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

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

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

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

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

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

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

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

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

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

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

9.2.2.3 Procedures

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

Regarding ASD VEWFD response operations, MCR Alarm Response Procedures (ARPs) must be available and accessible to guide the human response to a MCR alert or alarm. Personnel

should have immediate access to ARPs from the alarm location (Ref. 50). If procedures are not readily available or accessible, it may negatively impact performance by increasing the time to respond, thus decreasing the probability of fire prevention or prompt suppression.

Local actions (e.g., locating degrading components) are required in ASD VEWFD response operations. Typically, there are procedures available for local actions; however, some tasks may be considered “skill-of-the-craft”[6] and, thus, are not proceduralized. Project research did not yield information regarding the usage of procedures for local actions. If procedures are not used, a strong case must be made for labeling a task “skill-of-the-craft” to provide reasonable assurance of a safe operator response. Even when procedures do exist, it may not be practical to page through a procedure while performing a task. For example, if a technician is using a portable ASD to locate the degraded component, one hand would be used to hold the body of the device and the other would hold the probe, thus making paging through a procedure impractical. Thus, personnel must either be trained to perform the steps from memory or there must be a contingency plan for providing the procedural steps (e.g., via portable radio).

9.2.2.4 Training

Nuclear power plant personnel must receive training in accordance with current regulations. With regard to ASD VEWFD response operations, 10 CFR 50.120 applies to the non-licensed operators (FOs) and I &C technicians and10 CFR 55 applies to licensed operators. Both regulations identify a systems approach as acceptable methodology for training nuclear power plant personnel. A systems approach to training consists of the following five elements (10 CFR 55.4):

- systematic analysis of the jobs to be performed
- learning objectives derived from the analysis which describe desired performance after training
- training design and implementation based on the learning objectives
- evaluation of trainee mastery of the objectives during training
- evaluation and revision of the training based on the performance of trained personnel in the job setting

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

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

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

- training for MCR operators on ASD VEWFD ARPs
- training for FOs and technicians on any applicable procedures
- training for technicians on the operation of thermal imaging cameras and/or portable ASDs
- training for personnel who will serve as fire watch
- training for fire brigade personnel
- human performance training related to electrical safety for personnel involved in opening energized electrical cabinets

Special equipment operation training may be especially important, as it is the key to locating the degrading component. Portable ASDs have, more often, been used in other domains (e.g., telecommunications); licensees should be cognizant that vendor training may have been developed with domains other than nuclear in mind. Nuclear power plants may introduce unique elements that warrant domain-specific training. Project research yielded limited information with respect to the U.S. nuclear industry's current approach to special equipment training. Personnel at one site receive initial training followed by retraining every 2 years for portable ASDs. The training has classroom and practical aspects and lasts approximately 4 hours. The practical section consists of simulating a situation in which technician has to find a degrading component by placing a "smoking" wire in a room beforehand that trainees must locate. Another site reported that, although training has not yet been implemented, they expect that all operators will have specific training in the use of portable ASDs, with a qualification sign-off, as part of their basic operator training. In addition, one site reported that they receive several nuisance alarms per month, which allows personnel to gain experience in using the equipment and helps them maintain their level of proficiency. Regarding thermographic cameras, one site reported that personnel are required to complete a qualification card to use the thermographic camera which includes one week of offsite training and over 100 hours of working with the camera.

Training is also an important consideration with respect to fire-watch and fire-suppression activities. In some cases, the personnel may be trained in basic fire suppression using a fire extinguisher or may have fire brigade level training.[7] One licensee reported that approximately 95 percent of its field operators are fire brigade qualified, they receive specific incipient fire training and are qualified as incipient fire watch, and personnel receive refresher training yearly. Another licensee reported that all operators are trained in the proper use of fire extinguishers. It follows that more confidence can be placed in those with more extensive training to successfully suppress a fire.

7 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."

9.2.2.5 Staffing

According to NUREG-0711, Revision 3, staffing levels are an important consideration when plant modifications are undertaken. Plant modifications can impact important human actions, thus, applicants should assess staffing needs to assure that required actions can be successfully accomplished. Applicants should determine the following needs: 1) the type of staff (i.e., qualifications); 2) the number of staff and 3) the (required) availability of the staff. Information about regulations and guidance regarding staffing is provided in NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition,” Section 18 and NUREG-1764, “Guidance for the Review of Changes to Human Actions” (Refs. 53 and 54).

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

Non-MCR staff including an FO for initial fire watch duties, a DI&C technician to locate the degraded component, and potentially, additional personnel for a long-term fire-watch, are also needed for ASD VEWFD response operations. According to the distribution presented in Section 8.2, Figure 8-4, the incipient stage duration distribution is not narrowly defined (i.e., ranges from several minutes to several hours). With a large amount of variability in the duration of the incipient stage, it is a reasonable conclusion that personnel involved in response operations need to be available on site to ensure a timely response. If a sufficient number of qualified personnel are not available, the planned response should not be considered feasible.[8] The information gained from trip reports and expert consultation indicated that FOs and technicians are available on site continuously. However, level of staffing may be of concern with regard to a long-term fire-watch. The time between an incipient alarm and flaming conditions may be an extended period of time (refer to Section 8 for timing estimates), hence necessitating that licensees have personnel available for an extended fire-watch. Depending on staffing levels, this may affect whether or not the fire watch is roaming or constant. A roaming watch is not desirable as it could extend the timeline for detecting and suppressing a fire.

9.2.2.6 Communications

Much of the communication during ASD VEWFD response operations takes place between the MCR and personnel outside the control room. The MCR must dispatch FOs, technicians and the fire brigade. The MCR must also be in contact with the FO during the field investigation to provide pertinent information gained from monitoring the MCR computer. This communication is critical as the success of the alarm response operations rests with the FO and technician arriving at the fire location and completing their tasks in a timely manner. Communications equipment must be available, accessible and functional to ensure communication can occur.

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8 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)

According to NUREG-0700, Revision 2, "Where communications are critical, users should not be precluded from communicating with other plant personnel by the loss of one method" (Ref. 50). A complement of communications equipment for this context might include phone lines, the intercom system, sound-powered phones and portable radios. Sound-powered telephone systems do not require a separate electrical power supply to transmit signals; the force of the user's speech on the mouthpiece generates small electrical impulses, which are transmitted as a signal. They are beneficial for situations in which electricity is not available; however, it should be noted that training is required to operate them properly. Portable radio transceivers include battery-powered communication devices that transmit messages through the airways rather than through wires. However, there are places in the plant where radio usage is not permitted, thus, strengthening the case for having several diverse methods of communication. This complement of communications equipment provides a variety of equipment that uses various media for communication, and is a good example of establishing diverse communication methods. Guidance for speech-based communications regarding topics such as sound quality and area coverage is provided in NUREG-0700, "Human-System Interface Design Review Guidelines," Revision 2, Section 10.2.

9.2.2.7 Complexity

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

Sources of complexity that may affect task performance in VEWFD response operations include:

- ambiguity from difficult-to-interpret cues and indications
- the need to consider multiple variables simultaneously
- the need to perform many unfamiliar steps in rapid succession

The *indications* from portable ASDs and thermal images may be *ambiguous or difficult to interpret* because of the fact that, as stated previously, HSIs of special equipment often do not receive the same level of review as MCR HSIs. The equipment HSIs may be less than ideal, thus increasing the complexity of identifying the exact component that is degrading. Also, being *unfamiliar* with the necessary equipment and procedures/task steps can make the task more complex. If personnel use the portable equipment and perform the steps in VEWFD response operations rarely, this may result in a situation in which personnel are performing many *unfamiliar steps in rapid succession*. High-quality initial training and periodic refresher training along with well-designed procedures and equipment can help to mitigate complexity.

The decision to de-energize the affected cabinet may also be a complex task. There are *multiple variables* that personnel must take into consideration. First, personnel must have an understanding of the contents of a particular cabinet to determine the effect that de-energizing will have on the safe operation of the NPP. They must also consider the effort involved in the task of de-energizing. According to experts (see section 9.1), de-energizing equipment can be a very simple or a very involved and complex operation. For example, if an entire cabinet is being de-energized, there are instances in which it can be de-energized from the MCR within seconds. At one site, the logic for the cabinet power is laid out on the MCR control board, making the de-energization process simple. Alternatively, if only one breaker is being de-

energized (partial cabinet), local action may be required, and the task would likely require multiple steps. This is an important consideration because if the process takes an extended amount of time, it may not be possible to complete it before the transition to a flaming fire. Personnel must weigh the benefits of de-energizing to preserve equipment with the ancillary effects on the rest of the plant. Some of the complexity associated with this task can be mitigated by pre-planning the steps needed to de-energize the cabinets. One strategy would be to "pre-locate" the isolation devices for all ignition sources within each cabinet in an effort to speed up the process. This would include predetermining the isolation devices, conveniently displaying that information for use in response to VEWFD alerts, training responders to rapidly locate and operate the isolation device(s), and conducting drills to periodically demonstrate this ability.

9.2.2.8 Workload, pressure and stress

Workload, pressure and stress, collectively, refer to the extent to which personnel experience (time) pressure to perform an action, along with their overall sense of being threatened in some way with respect to accomplishing their task. The emphasis for this factor is on the amount of work that must be accomplished in the available time. If workload, pressure, and stress are too high, they may adversely impact personnel performance.

For ASD VEWFD response operations, it appears on the surface, that there would be little time pressure as this is *very early* warning fire detection. However, based on project research, personnel are trained to handle incipient alerts and alarms with urgency, such that they are to drop everything and respond. The value of these systems lies with the human reacting promptly to prevent a fire, or quickly suppress it. Thus, creating some time pressure is an important component of providing reasonable assurance of the feasibility and reliability of VEWFD response operations. However, while some time pressure may help provide a feasible reliable response, too much time pressure may result in degraded task performance (Ref. 56).

The fire itself can create time pressure because of the fact that the length of the incipient stage of a fire can vary widely (see Figure 8-4); thus, the time available for personnel to respond will also vary. It may be that being aware of the variability in the time available to respond, may alone, create pressure and stress for personnel.

Another source of stress during VEWFD response operations may be a concern for one's personal safety. If a VEWFD detector is being used for power distribution equipment, there is the potential for significant safety hazards (e.g., explosion upon opening a cabinet).

9.3 Area-wide Applications

Because of the considerable amount of unknown variables (e.g., room size, content of room, etc.) area-wide applications were not specifically addressed in the HF analysis as there is no "prototypical scenario" to be assessed. However, based on discussions with plant personnel, it is expected that the personnel response to an area-wide incipient alert and alarm will be fundamentally the same as for in-cabinet applications. The only difference is that the FO and technician will be sent to a room rather than a bank of cabinets, after receipt of an "alert." The technician will need to locate the incipient fire source within that room. The larger area that must be surveyed should be accounted for in the timing analysis.

10. HUMAN RELIABILITY ANALYSIS

10.1 Human Reliability Analysis (HRA) Approach

The objective of this section is to develop an improved, detailed HRA quantification to support a fire PRA quantification of VEWFD system performance. To accomplish this objective, existing HRA approaches will be used to the extent applicable to this particular context.

First, the HRA process (i.e., steps needed to perform HRA) used in this report is based on existing HRA processes. The Joint EPRI/NRC-RES Fire Human Reliability Analysis Guidelines (Ref. 49) and "A Technique for Human Event Analysis," (ATHEANA) (Refs. 57 and 58) describe two similar HRA processes. The HRA process given in NUREG-1921 is specific to a fire context. However, since the analysis in this report must address operator[1] 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 (Section 10.2.1).
2. Define the scope of analysis (Section 10.2.2).
3. Identify and define human failure events (HFEs) (Section 10.3).
4. Perform qualitative analysis (including feasibility assessment) (Sections 10.4 and 10.5).
5. Perform quantitative analysis to develop the human error probability (HEP) for each HFE (Section 10.6).
6. Perform dependency analysis (Section 10.7).
7. Perform recovery analysis (Section 10.7).
8. Perform uncertainty analysis (Section 10.8).
9. Complete documentation.

Second, as will be discussed further in Section 10.6, HRA quantification is 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 serves as the documentation portion of the process. Also, like NUREG-1921, HFE identification and definition is discussed before qualitative analysis (even though qualitative analysis must be performed to support this task). In addition, documentation of feasibility assessment, including the development of necessary timing inputs, is provided in a section separate from qualitative analysis.

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[1] For the application of very early warning 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 de-energization (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 11) provides the quantification for suppression activities.

10.2 Define Issue and Scope to Be Addressed

This section lays out the requirements of the HRA needed to support the overall quantification approach outlined in Section 10.6 and the quantification illustrative examples in Section 12.

10.2.1 Define issue

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. In particular, this analysis addresses VEWFD applications that:

- are focused on in-cabinet installations
- are intended to support quantification of fire non-suppression probabilities
- achieve such reductions by enabling quicker fire suppression response than is typically modeled in fire PRAs

From the discussions in Section 9 regarding human factors analysis, it can be inferred that the HRA task for supporting fire PRA for VEWFD applications will be different from that in traditional HRA/PRA contexts.

Some of the key differences are as follows:

- **All operator actions are taken before (or without) a reactor trip, but after a signal in the main control room (MCR).** HRA/PRA traditionally only addresses the time phase before a reactor trip with modeled operator actions that could result in system or component unavailability.[2] Consequently, the type of operator actions associated with VEWFD installations has not been addressed in the development or application of previous PRA studies.[3] Some low power and shutdown (LP&S) PRAs include operator actions that cause reactor trips (i.e., human-induced initiators), but these actions also differ from the exact context of VEWFD applications in that they occur before or simultaneous with reactor trip (rather than after); and they do not have as their goal to prevent a reactor trip or other worsening condition.

- **For VEWFD applications discussed in this report, human actions and activities involve the following personnel:** 1) MCR crew of operators and associated supervisor(s), 2) a field operator, 3) a technician (such as an Instrument and Control [I&C] technician), 4) the fire brigade, and 5) other plant personnel who may be needed for de-energization (e.g., electrical engineers, electricians). However, for simplicity, all of these human activities (except the fire brigade) are called "operator actions" in the context of the HRA, including definition of HFEs.

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2 Even those actions modeled in some fire PRAs that are preventative in nature, differ from those associated with VEWFD applications because, again, they occur following a reactor trip.

3 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 VEWFD system "alerts" is limited, so operators must respond with some urgency. This is not typically the case for support system initiating events.

- **There are no standard requirements for traditional job aids (e.g., procedures, training, human-machine interface) supporting the operator actions of interest.** While there are currently a few applications of VEWFD that are consistent with the objectives of this report, the operator response and supporting job aids have not been standardized either by regulation or common practice.

10.2.2 Define Scope

The scope of this HRA is limited and shaped by previous quantification efforts (described in Section 6.2) and current, existing VEWFD applications in NPPs and available supporting data.

These limiting and/or shaping factors include:

- **As discussed in Section 1, the typical objective of VEWFD system applications is reduction of the overall fire non-suppression probability for the fire PRA.** Consequently, this HFE defines success of operator actions as an end state that allows "enhanced" (i.e., quicker than usual) suppression of a fire that would otherwise eventually result in a reactor trip. Conversely, operator failure is defined as conventional fire suppression (i.e., normally used fire non-suppression probability). Section 11 discusses the use of non-suppression curves from NUREG/CR-6850 for the development of these failure probabilities.

- **Following the event tree discussed in Section 6.4, HFEs must represent: (1) main control room operator response, and (2) the combined response from a field operator and technician.** In the main control room (MCR), operators must acknowledge the incipient fire detector alert or alarm, then initiate and direct the field response. The field response is focused on the field operator being trained and positioned appropriately to provide fire suppression before flaming conditions occur.

- **The input data for this HRA are consistent with current VEWFD applications at NPPs, but do not represent any specific NPP.** To the extent possible, real operational experience for VEWFD applications is represented in this HRA. However, as illustrated by the plant interviews summarized in Appendix C, there was not always alignment among the NPPs that provided input. In general, a composite input was developed for the analysis. Examples of such inputs are how MCR operators are expected to respond to incipient fire detectors and the time required for various operator responses (including I&C technicians). Consequently, any plant-specific HRA would need to develop their own information for certain HRA inputs.

- **Inputs from NPPs with existing VEWFD installations have defined "enhanced fire suppression."** "Enhanced fire suppression" requires earlier than typical arrival of fire suppression capability at the location where an incipient fire detectors has alarmed.[4] Using the HF tabletop analysis described in Section 9 (an shown in Figure 9-1), this HRA is based on: (1) fire brigade training for all field operators (i.e., fire suppression capability), (2) special incipient fire and/or incipient fire detector training for all field operators, (3) field operator arrival at the relevant location before there is any visible evidence of a fire, (4) stationing of a field operator at the location until there is visible

[4] As discussed in Section 9.2.2.3, both VEWFD alerts and alarms require operator response fall under the broad definition of "alarm." Furthermore, whatever the signal in the MCR from the VEWFD system, it is expected that the operator response will be guided by Alarm Response Procedures (ARPs).

evidence of a fire, and (5) fire suppression equipment is available at the relevant location. The success or failure of fire suppression is addressed in a different event tree heading, as discussed in Section 11.

- **As discussed further in Section 10.4.1, the relevant success criteria, especially the time available after which operator actions are not helpful, have been difficult to establish.** Timing inputs are crucial to HRA. As discussed in NUREG-1921 (Ref. 49), for successful performance, there must be more time available for the action than the action requires; otherwise, the operator action is not feasible (i.e., guaranteed failure). In traditional HRA/PRA, success criteria are developed using plant-specific information and analyses. In the case of time available for HRA for VEWFD system applications, use of generic information, such as the timing analysis in Section 8, is likely to be the only option.

- **In this analysis, a distribution for the time available for operator action has been developed, rather than a single data point. To address this distribution, the HRA has evaluated feasibility and quantified human failure probabilities for multiple times available, each of which can have a different associated success criterion**. As shown in the event tree for fire suppression strategy for in-cabinet installations (see Figure 6-4), there are two event tree headings following the two operator responses: (1) enhanced suppression (π_1) and (2) conventional detection/suppression (η). As shown in Section 11, these factors are developed using non-suppression curves, with the associated timing inputs linked to the success (or failure) of field operator/technician response. Consequently, failure of the field operator/technician response essentially represents a failure to effectively use the “extra time” provided by the VEWFD system for fire suppression such that credit can be taken in the fire PRA.

These limitations indicate that a much more thorough qualitative HRA must be performed. In particular, the human factors analysis described in Section 9 is an important input to understanding the operational context (and potential variations with associated changes in human performance). For example, the tabletop analysis[5] (and associated Figure 9-1) described in Section 9.2.1 is an essential input to understanding what is required of operators and technicians to successfully implement VEWFD for fire PRA. In modern day, at-power, internal event Level 1 HRA/PRA studies, a formal task analysis is seldom required for any or all of the following reasons:

- Formal task analyses have already been performed in the development of the control room design and procedures (Ref. 59).

- Decades of simulator training and operating experience are available as inputs to the HRA analyst to understand the role and responsibilities of operators that are relevant to PRA.

- It is likely that any previously performed HRA/PRA study was supported by something resembling a “cognitive task analysis.”

5 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.

Overall, unlike the VEWFD application considered in this report, the HRA methods and approaches for addressing at-power, internal events Level 1 HRA/PRA are mature and supported with a wealth of relevant, realistic information.

Consequently, the development of an appropriate HRA approach for this study on VEWFD applications must recognize the following:

- There is no "standard" or requirement for how VEWFD is implemented (and, therefore, it resembles the equivalent of an "unconstrained, mathematical problem").
- There is very limited information on existing VEWFD applications in NPPs.
- HRA results must support VEWFD applications, in general, rather than a plant-specific HRA of a VEWFD implementation (as expected in HRA/PRAs that follow ANS/ASME PRA Standard (Ref. 60)).

In addition, this analysis, like the human factors discussion in Section 9, focuses on in-cabinet installations of VEWFD. Section 10.3 "Identification and Definition of HFEs" discusses the different types of installations and associated strategies for success.

10.3 Identification and Definition of Human Failure Events (HFEs)

In traditional PRAs, operator actions that mitigate an accident or that worsen plant conditions should be considered for representation in PRA models as HFEs. This analysis is similar, but not exactly the same as traditional HRA/PRAs. In particular, the objective of this analysis is to model operator actions whose success would result in **early** fire suppression. Consequently, an operator "failure" in this analysis is "no **early** fire suppression" (i.e., normal fire suppression).

NUREG/CR-6850, Supplement 1 (Ref. 61) identified two event tree headings associated with human actions for determining fire PRA. While this earlier work was an important input to this report, HFEs are identified herein by using the more thorough analysis of human actions and associated performance provided by the human factors analysis discussed in Section 9. In particular, the overall tabletop task analysis discussion and Figure 9-1 and Figure 9-2 has been the basis for the identification and definition of HFEs. In addition, this project included extensive coordination between the HRA team and the event tree developers on the structure, headings and success criteria associated with the event trees shown in Section 6.4. This event tree structure also requires close coordination with the task for assigning fire non-suppression probabilities (see Section 11).

In particular, Section 6.4 provides two event trees to address two different VEWFD applications:

(1) As shown in Figure 6-4, in-cabinet installations of VEWFD where the cabinet(s) are not targets of concern for the fire PRA (i.e., "success" for the operator action is achieved when a field operator (or other appropriately trained plant personnel) arrives at the fire location, providing fire suppression capability upon arrival, and the field operator begins fire suppression **as soon as flaming conditions are visible**. Figure 6-4 shows (and Sections 11.1 and 12.1 provide further discussion) that two different cases for operator success are considered for earlier fire suppression than normal fire suppression.

(2) As shown in Figure 6-5, area-wide installations of VEWFD are similar to the other installation types, but require additional time needed for the I&C technician to survey the entire room or fire area to identify the affected bank of cabinets or other equipment, especially since in-cabinet installations can be addressable (i.e., the specific alarming cabinet can be identified immediately if each cabinet is linked to its own detector).

Each of these installations will have different success criteria and, again, there will also be differences in the operator actions required. **The first type of installation is analyzed in detail in the remainder of the HRA discussion.** At the end of this section (i.e., Sections 10.6.4 and 10.6.5), some HRA-related notes are provided regarding de-energization strategies and area-wide applications, respectively.

10.3.1 Success criteria for in-cabinet, fire suppression strategy

Success criteria must be defined for each event tree heading, including identified HFEs. These criteria are:

- **MCR response**—After the detector "alert" signals in the MCR, MCR operators must dispatch both the field operator and technician to the correct location for the VEWFD system in "alert." This dispatching must be performed in a timely manner.

- **Field operator response**—Once the detector "alert" signals, this must result in the field operator 1) arriving at the correct location for the VEWFD system in "alert," 2) having the ability to initiate suppression in the absence of the fire brigade, and 3) positioning himself or herself, in a timely manner, in close proximity to the specific cabinets with the "alert" condition. In addition, the field operator must provide continuous fire suppression capability while degrading conditions occur, up through transition to flaming conditions or until the degraded component is de-energized, repaired, or replaced.[6]

- **Technician response**—The technician must 1) arrive at the correct location for the VEWFD system in "alert" with the required equipment, 2) correctly and timely identify the specific cabinet where the degraded component is located (especially for cases in which there is more than one cabinet associated with a detector, and 3) correctly identify the degraded components.

[6] The phrase 'continuous fire suppression capability' is used here rather than the more familiar phrase of 'continuous fire watch' because not all NPPs define 'continuous fire watch' in the same way.

There are a few important things to note:

(1) In Figure 6-4, the event tree heading for successful MCR response is "1-μ." Conversely, Figure 6-4 uses "μ" to represent MCR operator failure.

(2) For the purposes of quantification (as discussed in both Section 6 and Section 12), the field operator and technician response represented together as a combined outcome.

(3) Successful, combined response of the field operator and technician is represented as "1-ξ" in Figure 6-4. Conversely, the combined failure of the field operator and technician is represented as "ξ."

(4) According to Figure 9-1 (and the event tree shown in Figure 6-4), the overall objective of this VEWFD application is for the field operator to arrive at the "alert" location and provide fire suppression capability (earlier than would be provided by a fire brigade dispatch on "alarm").[7]

Timing inputs are almost always an important part of the success criteria defined for each operator action. First, the operator actions must be feasible (i.e., sufficient time available as defined in NUREG-1921). Second, shortness of time to complete actions also can influence the reliability (therefore, the failure probability) of operator actions. If time is limited for the PRA scenario modeled, operator actions must be completed before a worsened state occurs (e.g., equipment or plant damage). Discussion of timing and timing inputs is provided, first, in the qualitative analysis (i.e., Section 10.4), then in the feasibility assessment given in Section 10.5. Section 10.6 discusses all factors (including timing) that are considered relevant to HRA quantification. Overall, the critical timing inputs for this analysis are:

(1) the total time available for operator actions measured as the time starting from the VEWFD "alert" to when the incipient stage ends and a fire begins (as discussed in Section 8)

(2) the total time required to complete all operator actions, ending with the field operator positioned and ready to perform fire suppression activities

10.3.2 HFEs for "fire suppression" strategy, in-cabinet installations

The tabletop analysis provided in Section 9 describes in detail the operator and technician actions that could be performed to provide earlier than traditional fire suppression capability (per definition by the fire PRA). These actions are, in turn, aggregated or collected logically, then represented as HFEs and, for this analysis, shown as top events in event trees.

Specifically, the operator activities for the in-cabinet, fire suppression VEWFD strategy that are represented in event tree headings (see Section 6.4) are:

1. MCR operator response to VEWFD system signals ("μ" defines failure)

2. field operator and I&C technician response ("ξ" defines failure)

[7] A different event tree would be required if a VEWFD application was not focused on fire suppression and preventing fire damage to targets outside the affected cabinet.

3. fire suppression

    a. “Enhanced” fire suppression (for cases in which fire suppression capability is provided by the field operator (or other appropriately trained personnel) who is **already at the fire location when the transition from low-energy (incipient) fire to a flaming fire condition** occurs) (“π_1” defines failure)

    b. Conventional fire suppression (e.g., MCR operator response to VEWFD system signal fails, field operator/technician response fails) (“η” defines failure)

It is important to note that the suppression activities in the list above are not addressed explicitly by HRA. Instead, the failure probabilities for these activities are quantified using non-suppression curves as described in Section 11. Further details on the definitions of these two HFEs are given below.

10.3.2.1 HFE definition: MCR operator response (in-cabinet, fire suppression strategy)

Based on the tabletop analysis in Section 9, interviews with plant personnel from two NPPs with VEWFD installations, and the discussion of the qualitative analysis (in Section 10.4 below), the following are the key events and responsibilities for the MCR operator once the VEWFD system signals “alert” in MCR:

(1) VEWFD system signals “alert” in MCR.

(2) MCR operators immediately note “alert” and switch focus on this signal.[8]

(3) MCR operators find the appropriate alarm response procedure (ARP) for the VEWFD system “alert.”

(4) MCR operators consult main fire alarm control panel in MCR to identify which detector is signaling and the associated location, including specific cabinet or cabinet bank.

(5) MCR operators dispatch field operator[9] closest to the alerting detector, providing location information.

(6) MCR operators dispatch technician to alerting detector.

(7) MCR operators continue to monitor degrading conditions from the notification panel in the MCR and phone with the field operator with changing conditions.

(8) When VEWFD system signals “alarm,” MCR operators activate the fire brigade.

Alternative conditions (e.g., detector “alert” is not provided on the main fire alarm control panel, degrading conditions are displayed on a source other than a notification panel) can be addressed by HRA. However, the above combination of events, responsibilities, and conditions have been assessed in the HRA provided in this report to represent a realistic but fast and reliable MCR operator response.

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[8] Recall that no PRA credit for VEWFD system installations if a reactor trip or other similar higher priority event has occurred.

[9] Field operator is expected to have fire brigade training.

10.3.2.2 HFE definition: Field operator and technician response (in-cabinet, fire suppression strategy)

Based on the tabletop analysis in Section 9, interviews with plant personnel from two NPPs with VEWFD installations, and the discussion of the qualitative analysis (in Section 10.4 below), the following are the key events and responsibilities for the field operator and technician response in the fire suppression strategy for in-cabinet VEWFD installations:

(1) Upon dispatch, the field operator expeditiously travels to the fire location provided by the MCR operator.

(2) Upon dispatch, the technician expeditiously collects required equipment and travels to the fire location provided by the MCR operator.

(3) Upon arrival at the fire location, the field operator takes up the responsibility of fire watch (with suppression capability). If there is only one cabinet served by the VEWFD system, the field operator can have his/her attention immediately focused on changing conditions with and within this cabinet (even while the technician performs his survey - see the next step). If there are multiple cabinets served by the detector, the field operator draws upon his/her incipient fire detector training to monitor potentially changing conditions (e.g., smelling off-gases, seeing smoke, monitoring any local incipient detector notification panels in the room, taking phone calls from MCR operators with updates on changing conditions).

(4) Upon arrival at the fire location, the technician begins use of special equipment to identify the affected cabinet. In addition, the technician also is alert to the smell of off-gases, seeing smoke, and so forth that would provide more immediate evidence of a degrading component. The technician will change his/her survey plan to address cabinets that have these indications. With the “alert” signal locked in, the field operator remains at the fire location after the technician arrives and during the technician’s survey.

(5) The technician identifies the affected cabinet, using hand-held “sniffer.”

(6) The technician identified the degraded component, using hand-held “sniffer.” (It is assumed that the cabinet door will need to be opened for the “sniffer” to find the degraded component, and that the door will be closed after the technician has finished his/her survey.)

(7) The field operator provides continuous fire suppression capability, remaining alert to changing conditions in the cabinet where the degraded component has been identified. Changing conditions are monitored in multiple ways. The indications from the incipient detector will continue to be monitored. The MCR operators will be monitoring the VEWFD system display panel and communicating with the field operator by phone with changing conditions, especially as the setpoint for “alarm” is approached. In addition, there may be a display at the “alert” location that provides useful information. Finally, the field operator will be visually monitoring the cabinet, using his/her sense of smell, and generally monitoring for pre-flaming fire effects.

In this analysis, the field operator is trained to perform the simultaneous visual monitoring and detector monitoring[10] (as well as fire brigade trained), the multiple cabinet case can be treated similarly to the single cabinet case. In other words, the success of the field operator being prepared to provide fire suppression as soon as the incipient phase ends (and flaming conditions begin) does not depend on the identification of the affected cabinet by the technician (as long as there are a finite number of cabinets involved in the VEWFD installation).

Although the technician response is not necessary for success of the field operator, the identification of the affected cabinet and a degraded component is necessary in a practical sense. First, given the sensitivity of the incipient detectors, it is expected to be important to verify that the degraded component is within the cabinet (or bank of cabinets) served by the incipient detector, as opposed to somewhere else in the room, or even in a different room. From the standpoint of operational resources, the field operator is likely to be posted at the "alert" location to provide fire suppression capability only IF he is needed for this role. For example, if the technician's survey reveals that the source of degradation is elsewhere, then the field operator can return to his/her other duties. Second, although not addressed in this HRA and associated event tree, NPP personnel are expected to try de-energizing and repairing the degraded component, after it is identified and if flaming conditions do not occur first.

Section 10.4, HRA quantification, discusses these end states further and Section 11 continues this discussion with respect to which non-suppression curves are appropriate.

10.4 Qualitative HRA

As is described in NUREG-1921 (Ref. 49), HRA qualitative analysis is a vital step in HRA that provides the foundation for all other HRA products (i.e., identified and defined HFEs, human error probabilities developed through application of HRA quantification tools). Also, qualitative HRA is performed throughout the analysis, ending only when final outcomes/output have been produced or claimed. Consequently, for this report, the qualitative analysis step is listed ahead of all other purely technical tasks.

As noted above, one of the ways that this analysis is different from other HRAs is that it has not been performed for a specific NPP installation of VEWFD. Instead, this analysis is for a "representative plant" that:

- to the extent possible, uses the "real-world" information that was collected as part of this project, coupled with a general understanding of NPP operations and operators
- is consistent with the operational practices that support a "good" or "best case" with respect to successful and reliable operator performance for a VEWFD application
- is based on the human factors analysis provided in Section 9 (especially, the "tabletop analysis" of the steps required for VEWFD system response and the descriptions of contextual factors that either are licensing requirements or are common to the at-power internal events Level 1 PRA context)
- is based on the typical needs of HRA quantification tools so far as required inputs and underlying assumptions

10 If the field operator is NOT trained for such simultaneous monitoring, then "enhanced suppression" can be credited only AFTER the technician has identified the affected cabinet and degrading component. This situation is not addressed in this report.

Instead of collecting and interpreting plant-specific information through plant site visits and other interactions, this analysis has used, for example:

- a composite of information collected from three plants (e.g., a plant visit, NPP-supplied procedures, two plant surveys) for VEWFD applications
- general NPP information, such as conduct of operations (including protocols for communications), alert/alarm designs, alarm response procedures, control interfaces, fire brigade training
- a limited number of assumptions to take the place of information that is not available generically and was not supplied by the NPPs either visited or surveyed

For the "representative plant" analyzed, the subsections below provide descriptions of the MCR operator response and the responses of the field operator and technician at the plant location where a VEWFD system has detected a degrading component. Then, timing information for each operator action (both time required and time available) is discussed. The two most essential HRA timing inputs are: (1) the time available for operator action and (2) the time required for operator action. A plant-specific HRA would require the development of similar information, but based on that NPP's VEWFD application.

It should be noted that qualitative HRA described below for the "representative plant" is intended to represent a realistic, yet fast response, from MCR operators, as well as from field operators and technicians. As discussed in Section 8, the currently available timing information indicates that the time available for operator response (see Figure 8-4) can be quite short (i.e., 10 minutes or less), especially when compared to timing information regarding the time required for combined operator response, both in control room and ex-control room (see Section 10.4.3). Consequently, the qualitative analysis below also attempts to capture those factors that support a relatively fast operator response.

10.4.1 Qualitative analysis for all operator actions

General information on all operator responses is discussed below.

10.4.1.1 Qualitative analysis for MCR operator response

For the MCR operator response to in-cabinet installations of VEWFD, the keys to a fast response that can be addressed with existing HRA quantification tools are: (1) an overall plant philosophy that VEWFD response is "priority number one," supporting a quick, consistent, reliable, and predictable response, (2) procedures and training that support quick and immediate response to incipient fire detector alerts/alarms, and (3) any factors that support a response closely resembling that for post-reactor trip MCR operator response in at-power, internal events Level 1 PRA.

The following information provided by NPPs with existing VEWFD installations is used to define the "representative plant" for the MCR operator response:

- "MCR operator response" represents the collective effort of the MCR operating crew.
- VEWFD system alert/alarm annunciator panel(s) is/are located in the MCR on the front panel (i.e., where operators are accustomed to seeing critical alarms). There is a main

fire alarm annunciator panel[11] in the MCR, providing MCR operators with quick and easy access to information on both the specific fire area and location of the VEWFD system zone in “alert” or “alarm” condition and the specific cabinet or bank of cabinets where the detector is installed.

- Operators respond to VEWFD system alerts and alarms with urgency (that may be inconsistent with other alarms that occur during normal operating conditions). This sense of urgency is reinforced by training and procedures, and might be aided by distinguishing tape or other markings for VEWFD system alarm panels. In particular, MCR operators are trained to “**drop everything”** when a VEWFD system signals.[12]

- Alarm response procedures (ARPs), which are part of the emergency operating procedures set, guide MCR response, including consultation of the main fire alarm control panel and calls to the field operators, technicians, and fire brigade.

- MCR operators expeditiously dispatch the field operator closest to the detector in “alert,” providing essential location information.[13]

- MCR operators expeditiously dispatch a technician trained in portable ASD use, providing essential location information.

- MCR operators expeditiously dispatch the fire brigade when the detector is in “alarm” state, providing essential location information.

- Nuisance alarms for the VEWFD system are minimal (e.g., through appropriate initial testing and appropriate set points), such that MCR operator response is not slowed or questioned to be correct. In addition, the results of investigation into the causes of nuisance alarms (by technician surveys or other means) should increase confidence in the sensitivity of the plant-installed and hand-held incipient detectors.

- Accessibility is not a concern (as the VEWFD system in “alert” or “alarm” is outside the MCR).

- MCR operators are trained and directed by procedural guidance (i.e., ARPs) to continually monitor detector indications and to communicate these conditions (especially changing conditions and conditions approaching the “alarm” setpoint) to the field operator at the “alert” location.

This analysis also uses the following assumptions that: (1) are typical of an at-power, internal events Level 1 HRA, and (2) are based on generic information and a general understanding of NPP operations and operators (e.g., policies and practices given in “conduct of operations”

[11] 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.

[12] This specific response was provided by one of the licensees that provided input to this project.

[13] Again, this is consistent with information provided by one of the NPPs consulted in this project.

procedures, NRC requirements for MCR design and emergency operating procedures (EOPs), NRC requirements for operator licensing and training):

- VEWFD system alert/alarm signals are audible, according to other MCR alarm standards (see Section 9.2.2.2).

- The number of VEWFD system alert/alarms that require urgent response should be few as compared to other fire alarms, and measures are taken to avoid confusion of such alerts/alarms with other alarms that do not require such urgency.

- The instructions for VEWFD system response in the ARP are formatted and worded consistently with other instructions given in the ARPs.

- There is normal staffing, such that there is no shortage of manpower.

  - MCR operators use formal, three-way communication to describe the fire location to both the field operator and technician to minimize the likelihood of miscommunication. Three-way communication also can facilitate recoveries of miscommunication (e.g., repeat back from field operator while looking at the main fire alarm control panel can serve as a check). Or, other operators in the MCR, who also are looking at the main fire alarm control panel, can serve as an independent check.

- Peer checking and other activities that support reliable response by the MCR operators are used.

Changes to any of the above inputs are likely to change the timing of operator responses (and, therefore, feasibility) and/or the reliability of operator responses. For example, if the main fire alarm control panel in the MCR, does not provide the specific fire area and location of the VEWFD system zone in “alert” or “alarm” condition, and the specific cabinet or bank of cabinets where the detector is installed, then additional time will be needed for the field operator to travel to the panel where this information is provided.

10.4.1.2 Qualitative analysis for field operator response

For the field operator response to in-cabinet installations of VEWFD, the keys to a fast response that can be addressed with existing HRA quantification tools are: (1) an overall plant philosophy that VEWFD response is “priority number one,” supporting a quick, consistent, reliable, and predictable, response, (2) fire brigade training that results in the fastest possible arrival of fire suppression capability, and (3) any factors that support a response closely resembling that for post-reactor trip, operator response for field or local actions in at-power, internal events Level 1 PRA.

The following information provided by NPPs with existing VEWFD installations is used to define the “representative plant” for the field operator response:

- The field operator closest to the fire location is dispatched by the MCR operator.

- VEWFD system response is the highest priority job for the field operator (upon receiving dispatch from the MCR), such that no new activities will be started, and current,

non-critical activities will be suspended.

- The field operator is trained to travel expeditiously to the low-energy (incipient) fire location.
- The field operator is trained to suppress fires (e.g., fire brigade training).
- The field operator is trained regarding incipient fire detectors and associated response. This training includes initiation of fire suppression activities only AFTER there are visible effects of a fire (e.g., a flame).
- Required equipment (e.g., portable fire extinguisher) is available and accessible.
- Accessibility is not a concern (because the field operator is fire brigade-trained).

This analysis also uses the following assumptions that: (1) are typical of an at-power, internal events Level 1 HRA, and (2) are based on generic information and a general understanding of NPP operations and operators (e.g., policies and practices given in "conduct of operations" procedures, NRC requirements for MCR design and emergency operating procedures (EOPs), NRC requirements for operator licensing and training):

- Formal three-way communication is used between the MCR operator and field operator so that the likelihood of miscommunication is very small.
- There is normal staffing, such that there is no shortage of manpower.
- The time needed for the field operator to travel to the VEWFD installation in "alert" can be based on similar timing information that has been demonstrated for other analyses.

Three additional assumptions are important to this analysis:

(1) Based on his/her incipient fire detector training, the field operator actively assumes the role of on-site fire suppression capability immediately arrival at the "alert" location, and provides this fire suppression capability continuously until it is no longer needed. For example, the field operator will be alert to changes in degrading component conditions, both from changes in detector indications and from fire effects that he/she may be able to sense (e.g., see, smell). These responsibilities continue even while the technician is performing surveys with the hand-held "sniffer."

(2) The door to the affected cabinet does not need to be open (or unlocked) for the field operator to identify flaming conditions that require fire suppression.

(3) Although the plant-installed incipient detector is expected to produce nuisance alarms[14] (because of its sensitivity), the field operator is trained and procedurally driven to respond to any "alert" signal that is "locked in" as if the (potentially not-yet identified) degrading component can transition to flaming conditions within minutes from the start of the "alert" signal.

[14] One NPP's experience is approximately one nuisance alarm per month.

These last three assumptions and the provision of incipient fire detectors and fire brigade training for all field operators[15] are especially important. In particular, as discussed in the section on definition of HFEs and associated success criteria, the definition of operator "success" with respect to "enhanced" fire suppression is based on when plant personnel having fire suppression capability are in place for the VEWFD system in an "alert" or "alarm."

10.4.1.3 Qualitative analysis for technician response

From the discussion in of the HFE definition for the field operator and technician response (Section 10.3.2.2), it was identified that, for this HRA and conditions described in this report, the success of the field operator is not dependent on the success (or failure) of the technician.

However, analysis of the technician response is carried forward in this report because:

(1) Other analyses (with different conditions and assumptions) may need to include the technician's response as an integral part of the HFE defined for the field operator and technician response.

(2) Different analyses that consider, for example, de-energization (or repair) would require analysis of the technician response (as the identification of the affected cabinet and degraded component are essential to such strategies).

(3) Identification of the affected cabinet and degraded component are important operationally (either to minimize the field operator's time spent providing fire suppression capability when it is not needed or to support efforts to de-energize or repair the degraded component).

For the technician response to in-cabinet installations of VEWFD, the keys to a fast response that can be addressed with existing HRA quantification tools are: (1) an overall plant philosophy that VEWFD response is "priority number one," supporting a quick, consistent, reliable, and predictable, response, and (2) any factors that support a response closely resembling that for post-reactor trip, operator response for field or local actions in at-power, internal events Level 1 PRA.

The following information provided by NPPs with existing VEWFD installations is used to define the "representative plant" for the technician response:

- VEWFD system response is the highest priority job for the technician (upon receiving dispatch from the MCR); such that no new activities will be started, and current, non-critical activities will be suspended. In addition, work activities that are interrupted by dispatch from the MCR will be secured quickly.

- The technician is trained to expeditiously collect necessary equipment and travel to the low-energy (incipient) fire location.

[15] Section 9.2.2.4 discusses variations between plants on what, if any, fire training is provided to field operators.

- If cabinets that require survey are locked, the technician will travel to the MCR to obtain keys for these cabinets (allowing the field operator to travel directly to the "alert" location.

- If cabinets that require survey are locked, the technician will unlock the cabinet and open the cabinet doors for the survey with the hand-held "sniffer." When the technician completes his/her survey, cabinet doors will be closed and re-locked. Also, the technician will return the cabinet keys to the MCR.

- Required equipment is available and accessible.

- The technician is trained in using special equipment for identifying low-energy (incipient) fire conditions, including detection of both the relevant cabinet (if the VEWFD installation is for a bank of cabinets) and the degrading component in the cabinet.

- Although the technician's main function is to identify the affected cabinet and degrading component with the hand-held "sniffer," he/she also will be alert to any fire effects that can be detected by observation or smell.

- Accessibility is not a concern (because the field operator, who is fire brigade-trained, is responsible for operator response if the degraded conditions transition to a fire).

- Although nuisance alarms can be expected because of the sensitivity of the plant-installed equipment[16], technician response to these alarms, and subsequent discovery of the root causes of such alarms (e.g., adjacent overheating equipment), provides an on-the-job mechanism for understanding the sensitivity of plant-installed and hand-held incipient detectors and general confidence in their effectiveness.

This analysis also uses the following assumptions that: (1) are typical of an at-power, internal events Level 1 HRA, and (2) are based on generic information and a general understanding of NPP operations:

- Formal three-way communication is used between the MCR operator and technician so that the likelihood of miscommunication is very small.

- There is normal staffing, such that there is no shortage of manpower.

- Overall, technician activities for VEWFD are similar to that for instrument calibration (which are often represented in traditional HRA/PRAs) with respect to "operator" reliability (e.g., the technician is adequately trained).

Interactions with NPPs for this project indicated that there is limited experience and understanding of the technician activities for VEWFD applications in NPPs. Consequently, the final assumption above is likely to be the most crucial to this analysis.

10.4.2 Time available for operator actions

[16] As noted in the qualitative analysis for the field operator, one NPP's experience is approximately one nuisance alarm per month.

HRA typically relies on inputs developed by and for other PRA tasks. While this research does not involve a formal PRA study, it follows the traditional path in that several inputs to the HRA are developed by other analysts. In particular, HRA/PRA requires determination of the "system time window," or the time from the start of "event" to the operator action is no longer beneficial.[17] Another term used in HRA for "system time window" is "time available for operator response." Figure 8-1 shows several timelines that are used in this report, including the time available for the combined operator response.

In typical PRAs, the "event" is a reactor trip and the system time window is determined with thermal-hydraulic calculations for when, for example, core damage occurs. The context for this analysis is very different. In particular, the "plant damage" of significance is flaming conditions for a component(s) in the electrical cabinet(s) being monitored by VEWFD. Therefore, the component degradation and associated VEWFD response provide the basis for determining the system time window. Section 8 discusses the limited, appropriate data on the duration of the incipient phase (i.e., component degradation before flaming), while the first part of this report provides results of how various VEWFD respond to degrading components. Consequently, unlike traditional PRAs where plant-specific calculations are used to determine the system time window, this analysis, as well as any other similar analysis, must use the timing information developed in Section 8.[18]

10.4.2.1 How time available determination is different for VEWFD applications

In this analysis, system time window, or time available for operator action, is defined as the time from when an "alert" signal from the VEWFD system is displayed in the MCR (i.e., when the cue for action is received) until the incipient stage ends (e.g., flaming conditions begin). Section 8 discusses how the timing of the "alert" signal is dependent on the type of VEWFD system, as reported in Section 5 "Experimental Results." Consequently, the time available for operator actions will be different, depending on which detector is being used. Figure 10-1 shows three different timelines (fire, VEWFD, and conventional response) and how the time available is determined.

[17] NUREG-1921 defines the system time window in this way, drawing upon long-time HRA/PRA conventions.
[18] The timing information in Section 8 might be updated by future data collection efforts on VEWFD response and the duration of the incipient phase for degrading components of various types. Refer to Section 12.3 for further discussion.

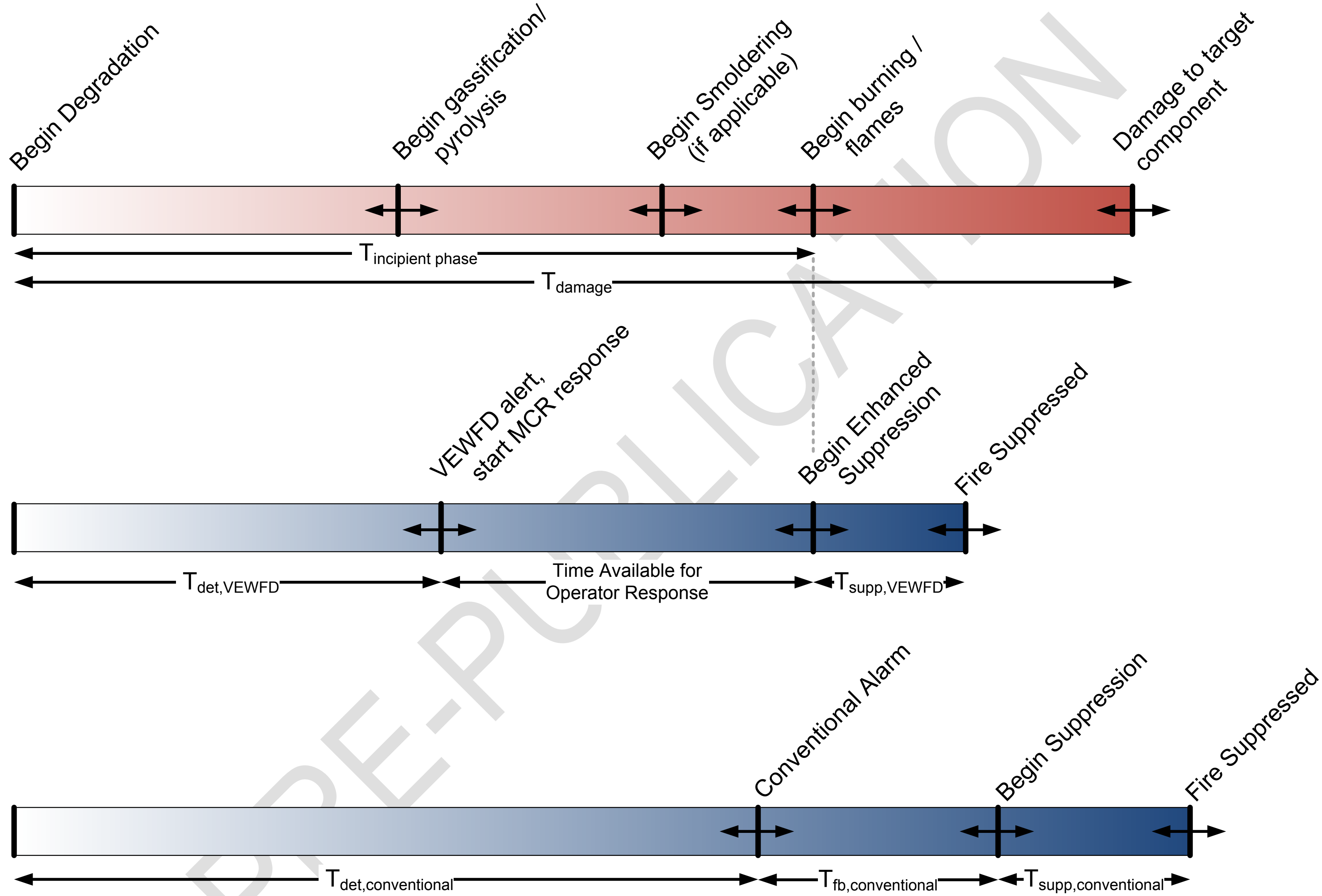

Figure 10-1. Timeline showing difference between time available and entire incipient phase.

Figure 8-4 (and the associated raw data given in Appendix D) shows how the time available for operator actions varies between the four types of fire detection technology tested and shown in the form of complementary cumulative probability distribution function (i.e., survivor function). These four distributions represent five fire detection technologies, include three VEWFD systems and two conventional fire detectors; respectively:

VEWFD systems
(1) air-aspirated VEWFD (cloud chamber)
(2) air-aspirated VEWFD (light-scattering)[1]
(3) sensitive spot-type VEWFD (light-scattering)

Conventional spot-type detectors
(4) spot detector (ionization)
(5) spot detector (photoelectric)

Typically, a single value for the system time window, or time available, is developed for defining the success criteria in HRA/PRA. Also, if timing ranges or distributions are developed, the shape of the distribution resembles either a normal distribution with small error factors (or another distribution with small "tails" at the low and high probability ends), justifying the use of a single value.

For this analysis, Figure 8-4 illustrates why a single value is not an appropriate way to represent the distribution of operating experience for component failures having an incipient phase. In particular, the existing data is sparse and this data is equally distributed in time between relatively short times available (e.g., less than 1 hour) and longer times available (i.e., longer than 1 hour).

In summary, the figures cited above provide several important insights for the HRA analyst:

(1) The input for the system time window is a probability distribution, rather than a single data point, providing an indication of the sparseness of data for the incipient phase and how it is distributed.

(2) The input for the system time window is different for different detectors.

In turn, there are several implications for this HRA:

(1) The HRA will need to address the system time window as a distribution, rather a single data point.

(2) Separate analyses will be required for each detector.

The probability distributions for the amount of time available for operator action (i.e., the system time window) shown time available is not necessarily very long (e.g., less than 1 hour), making all operator actions time critical.

[1] Note that the performance of the ASD VEWFD LS and the non-ASD VEWFD LS sensitive spot (SS) were very similar. As such, there response time characteristics were combined and represented as a single distribution for VEWFD light scattering type detectors.

10.4.2.2 Determining time available for operator response in VEWFD applications

To treat time available as a distribution, one approach occasionally used in PRA is to "sample" the distribution, then to assign split fractions associated with the sample points. In quantification, human failure probabilities will be developed for the time available associated with each sample point and split fraction.

In this analysis, cumulative probability distributions are used to determine sample points. Figure 10-2 shows such distributions for each of the four detectors investigated. These cumulative distributions are based on the same data and curves fit as the complimentary cumulative density functions are shown in Figure 8-4 and discussed further in Appendix D. In particular, both the probability of the incipient phase ending AND the sensitivity of the detector to gases emitted during the incipient phase are represented. The differences in the curves are related to the sensitivity in the detectors. The fact that a probability distribution is needed to show these differences is related to the uncertain nature of the data on the incipient phase. Two points to note that are illustrated by Figure 10-2 are that:

(1) Based on the test data presented in Section 5 and the smoke source materials tested, the PHOTO spot detector was generally not capable of detecting an incipient phase prior to transition to a flaming fire state, while the other detectors provide more advanced warning (see Figure 5-56).

(2) For even the earliest responding detector (i.e., ASD CC), the probability of the incipient stage transitioning to a flaming significant through and up to an hour.

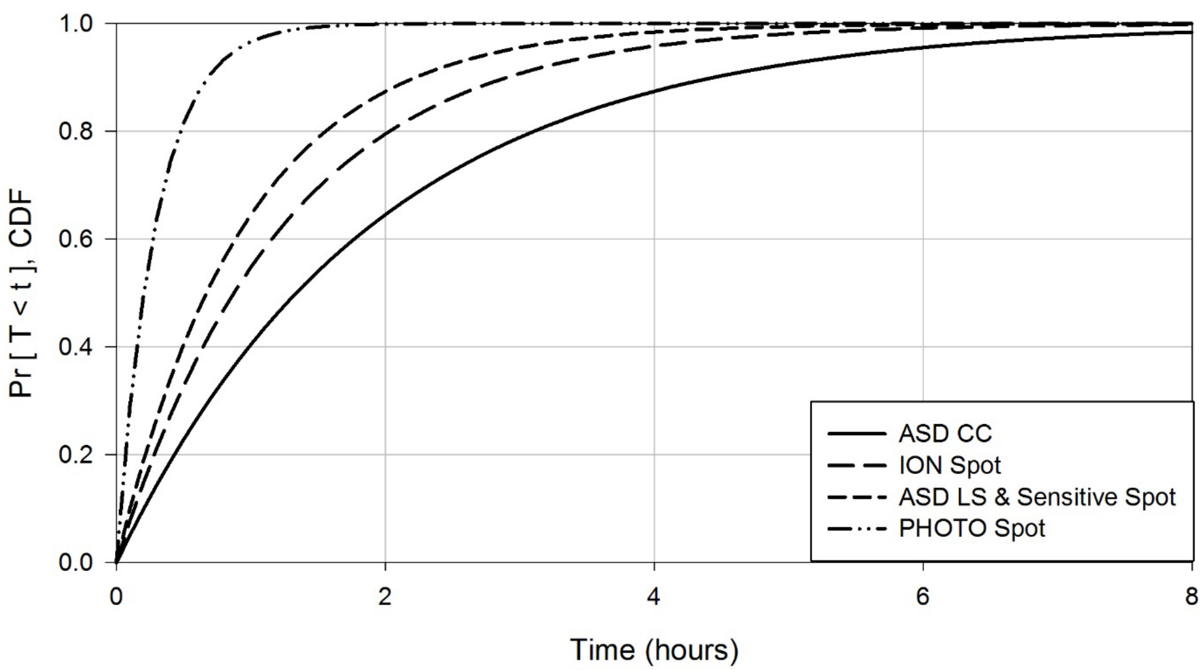

Figure 10-2. Cumulative distribution function of time available for operator response by detection type

For this analysis, the selection of time available points was driven by the need for the following:

- representation of the "most likely" situation with respect to duration of the time available for operator response following an VEWFD system "alert" signal
- representation of the situations in which all variations of in-cabinet, VEWFD installations are feasible (i.e., the time available is equal to or less than the total time required for all operator responses)
- representation of the mean of the probability distribution and/or the approximately 1 hour time available duration (which represents more time available than time required for all cases of operator response)

Using both the time required information (developed in Section 10.4.3 below) and the cumulative probability distributions, the following cases were chosen with respect to the duration of the time available (from "alert"):

- the time from "alert" that corresponds with a 90 percent likelihood that the transition to a fire has **NOT** occurred
- 30 minutes after "alert" (from Section 10.4.3 below) is approximately the maximum amount of time for the field operator to be positioned for immediate fire suppression
- 1 hour

The cumulative probability distributions for each of the four detectors investigated is shown in Figure 10-2 (These cumulative distributions are based on the same data and curves fit as the complimentary cumulative density functions are shown in Figure 8-4.) In addition, Appendix D provides minute-by-minute cumulative probabilities for each of the detectors. This information from Appendix D was used to develop Table 10-1, Table 10-2, and

Table 10-3 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 Sections 10.6.1 and 10.6.2, human error probabilities are developed to be paired with each of these split fractions.

The four sample points selected for this analysis are as follows:

- Sample 1: Incipient stage ends in only 10 percent of cases
- Sample 2: Incipient stage ends by 30 minutes after “alert” for VEWFD, “alarm” for conventional ION
- Sample 3: Incipient stage ends after 30 minutes but before approximately1 hour
- Sample 4: Incipient stage ends after approximately 1 hour

Note that, with these selections, the cumulative probability is fixed for one sample point (i.e., time available for operator response ends in 10 percent of cases) but the time from alert is not. All other sample points are associated with certain times and, therefore, the cumulative probabilities will be different for different detectors.

Feasibility assessments for each detector type and associated sample points are shown in Section 10.5. For those human error probabilities for each of the four distribution sample points and their associated-split fractions are developed in Section 10.6.

Table 10-1. 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	0-12 minutes*	0.10
2	0.23	>12 minutes AND < 30 minutes**	0.13
3	0.40	> 30 minutes AND < ~1 hour**	0.17
4	1.0	> ~ 1 hour**	0.60

* From the text above, this is the result from the cumulative distribution function associated with the definition of this sample point

** From the text above, this is the definition of this sample point

Table 10-2. Fractions of Probability Distribution for Conventional Spot-Type, ION Detector

Sample	Cumulative probability for Incipient stage ended	Time from alert	Fraction of probability distribution (split fraction)
1	0.10	0-8 minutes*	0.10
2	0.33	> 8 minutes AND < 30 minutes**	0.23
3	0.55	> 30 minutes AND < ~1 hour**	0.22
4	1.0	> ~ 1 hour**	0.45

* From the text above, this is the result from the cumulative distribution function associated with the definition of this sample point

** From the text above, this is the definition of this sample point

Table 10-3. 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	0-6 minutes*	0.10
2	0.41	> 6 minutes AND < 30 minutes**	0.31
3	0.65	> 30 minutes AND < ~1 hour**	0.24
4	1.0	> ~ 1 hour**	0.35

* From the text above, this is the result from the cumulative distribution function associated with the definition of this sample point

** From the text above, this is the definition of this sample point

10.4.3 Time required for all operator actions

Figure 10-3 expands upon the operator response timeline included in Figure 8-1, showing separate timelines for MCR operators, the field operator, and the technician.

For this analysis, time required for operator actions is defined to be the time from when the “alert” is received in the MCR until all operator actions, both those in the MCR and those taken by the field operator and technician locally, are expected to be completed.

HRA-specific timing inputs for a “representative plant” were developed from information collected through interviews of operations and fire protection personnel at NPPs that have installed VEWFD. To the extent possible, the NUREG-1921 (Ref. 49) guidance was used to develop of these inputs. For example, as recommended in Section 4.6.2 of NUREG-1921, inputs from the two NPPs have been used to develop a range of times, rather than a point estimate. (See Appendix C for details of the interviews and the development of these ranges

which recognize variabilities in timing.) However, timing information from both NPPs for and technician response was not based on walkdowns or demonstrations.

HRA analysts who perform a similar analysis would need to collect their own plant-specific information for the time required for completing operator actions.

For this analysis, time required for operator actions is defined to be the time from when the "alert" is received in the MCR until all operator actions, both those in the MCR and those taken by the field operator and technician locally, are expected to be completed. Estimates for time required for all of those operator actions were developed using information provided by NPPs with existing VEWFD installations. (See Appendix C for the details of the interviews and surveys used to developing this timing information.) In particular, a range of times is used to define the "representative plant" for each type of action. A plant-specific analysis should be based on similar plant-specific demonstrations and/or estimates of these required times.

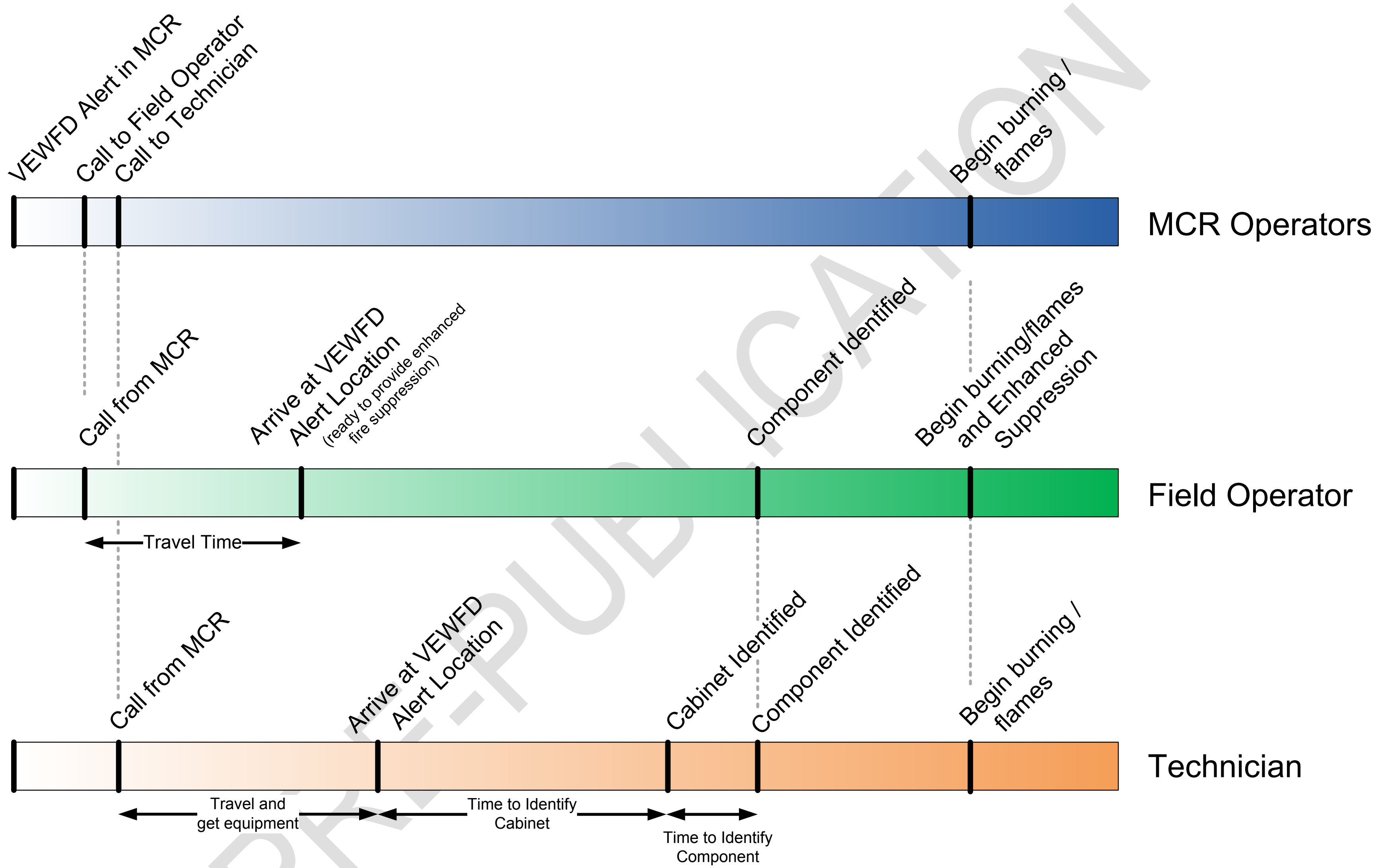

Figure 10-3. Timelines for MCR operators, field operators, and technician for incipient detector response.

Figure 10-3 shows individual timelines for the MCR operators, field operator, and technician. Important features of this figure are:

- Each of the three timelines represent the total time available for operator actions, starting with the “alert” signal at the far left and ending with “begin burning/flames” when fire suppression starts (and also the endpoint of the operator actions).
- t=0 for the MCR operator response starts with the “alert” signal, as shown by the leftmost start of all three timelines.
- Start times for field operator and technician responses start with a call from the MCR operators, which occurs at different times.
- For the field operator, another key time on the timeline is arrival at the “alert” location, at which time suppression capability is provided.
- The technician is always expected to arrive at the “alert” location after the field operator because:
  - The MCR operators call the technician after the field operator
  - In addition to travel time, the technician also must collect the hand-held detector equipment from its storage location (and may need to collect keys from the MCR)
- For the technician, other key features on the timeline are:
  - time to identify the affected cabinet
  - time to identify the degraded component

Table 10-4 below summarizes the HRA timing inputs developed. The ranges of times are either directly provided by plant personnel or are interpretations of more informal estimates (e.g., a “few” minutes can be translated into 3 or 4 minutes). Also, the durations of the field operator response and technician response shown in Table 10-4 represent the range of time estimates provided by both NPPs. For example, the duration of the field operator response (i.e., average time between when the field operator receives dispatch call to arrival at the appropriate location) was reported as 2 to 8 minutes for Plant X and 3 to 4 minutes for Plant Y, while Table 10-4 uses the broader range of times provided by Plant X for this analysis. Although the information sources for this timing data are limited, it was the only such information available when this analysis was performed and is adequate for this particular analysis.[1]

[1] For a plant-specific analysis, it is recommended that timing estimates be developed for each detector location. Such plant-specific and location-specific timing estimates may have a narrower range. However, it is still recommended that a range of timing estimates be developed, rather than a point estimate.

Table 10-4. Summary of Timing Inputs for Operator Actions after "Alert" Signal

Start of response	Who and Where?	Action(s) required for success	Time required (minutes)
Alert signal	MCR operator; MCR	Detect signal, use alarm response procedures, identify location of detector, and call to dispatch field operator	1-2
Alert signal	MCR operator; MCR	Dispatch technician to detector location	1
Call from MCR	Field operator in plant	Travel to location of VEWFD system in "alert": standby as fire watch by cabinet(s)	2-8
Call from MCR	Technician	Obtain necessary equipment and travel to location of VEWFD system in "alert"	5-11
Arrival at location	Technician	Uses equipment to identify cabinet	1 cabinet: 0 3 cabinets: 5 6 cabinets: 10 10 cabinets: 15
Cabinet identified	Technician	Uses equipment to identify degraded component in cabinet	3-4

Feasibility assessments (Section 10.5) and HRA quantification (Section 10.6) need to consider the appropriate <u>combination</u> of required times for the MCR operators, field operator, and technician. For this analysis, the total time required is for only the MCR operators and field operator actions. In particular, the total time required for these two actions starts from the "alert" signal and ends when the field operator arrives at the "alert" location and provides fire suppression capability.

The total time required can be calculated with the following:

$$t_{\text{total time required}} = t_{\text{MCR to field op}} + t_{\text{travel for field op}}$$

where:

$t_{\text{MCR to field op}}$ = total time from "alert" to ending the call to field operator (i.e., 1 to 2 minutes)

$t_{\text{travel for field op}}$ = 2 to 8 minutes (per Table 10-4 above)

Consequently,

$$t_{\text{total time required}} = (1 \text{ to } 2 \text{ minutes}) + (2 \text{ to } 8 \text{ minutes})$$

or,

$$t_{\text{total time required}} = 3 \text{ to } 10 \text{ minutes}$$

Note that from the discussion above and that regarding success criteria in Section 10.3, this total time required applies to all cabinet configurations considered in this analysis (e.g., single cabinets or 3-, 6-, or 10-cabinet installations).

10.5 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 total time required for operator actions calculated in the previous section, Section 10.4.2 (i.e., 3 to 10 minutes) must be compared with the time available shown in Table 10-1,Table 10-2, Table 10-3 for the different detectors, using the four sample points selected for this analysis, i.e.,

- Sample 1: Incipient stage ends in only 10 percent of cases
- Sample 2: Incipient stage ends by 30 minutes after "alert"
- Sample 3: Incipient stage ends after 30 minutes but before approximately1 hour
- Sample 4: Incipient stage ends after approximately 1 hour

Tables Table 10-5, Table 10-6, and Table 10-7 show the feasibility assessment results for the cloud chamber, ION, and light-scattering detectors, respectively, which apply to all cabinet configurations considered in this analysis. These tables show that:

- All sample points are feasible for the cloud chamber.
- Sample points #1 and #2 are only partially feasible for the ION and light scattering detectors because the upper bound on the total time required (i.e., 10 minutes) is greater than the ranges for time available, i.e.,
    - For the ION detector:
        - Sample point #1: Upper bound of time available (i.e., 8 minutes) is less than 10 minutes
        - Sample point #2: Lower bound of time available (i.e., 8 minutes) is less than 10 minutes

- For the light-scattering detector:
    - Sample point #1: Upper bound of time available (i.e., 6 minutes) is less than 10 minutes
    - Sample point #2: Lower bound of time available (i.e., 6 minutes) is less than 10 minutes

Table 10-5. Feasibility Assessment for ASD VEWFD, Cloud Chamber

Time required	Sample	Time available from alert	Feasible?
3-10 minutes	1	0-12 minutes*	Yes
	2	>12 minutes AND < 30 minutes**	Yes
	3	> 30 minutes AND < ~1 hour**	Yes
	4	> ~ 1 hour**	Yes

* From Section 10.4.2.1, this is the definition of this sample point.

** From Section 10.4.2.1, this is the result from the cumulative distribution function associated with the definition of this sample point

Table 10-6. Feasibility Assessment for Conventional Spot-Type, ION Detector

Time required	Sample	Time available from alert	Feasible?
3-10 minutes	1	0-8 minutes*	Partial
	2	> 8 minutes AND < 30 minutes**	Partial
	3	> 30 minutes AND < ~1 hour**	Yes
	4	> ~ 1 hour**	Yes

* From Section 10.4.2.1, this is the result from the cumulative distribution function associated with the definition of this sample point

** From Section 10.4.2.1, this is the definition of this sample point

Table 10-7. Feasibility Assessment for VEWFD Light-Scattering Detector (ASD & Spot)

Time required	Sample	Time available from alert	Feasible?
3-10 minutes	1	0-6 minutes*	Partial
	2	> 6 minutes AND < 30 minutes**	Partial
	3	> 30 minutes AND < ~1 hour**	Yes
	4	> ~ 1 hour**	Yes

* From Section 10.4.2.1, this is the result from the cumulative distribution function associated with the definition of this sample point

** From Section 10.4.2.1, this is the definition of this sample point

10.6 HRA Quantification

Because HRA quantification methods and associated human error probabilities (HEPs) were principally developed by and for post-initiator operator response, the overall strategy for quantification of the operator actions in this report is to either describe or prescribe operational conditions for the low-energy (incipient) fire response actions that are similar or parallel to the more familiar post-initiator operator actions. Section 10.4 (HRA Qualitative Analysis) is the starting point for the assumptions that will be used in HRA quantification to follow this strategy.

10.6.1 Basis for human error probabilities

Since the objective of the VEWFD installations for the scope of this analysis is to provide earlier than traditional fire suppression, by definition of a fire PRA, the context for operator response is very different than that typically 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 HEPs, are intended for post-reactor trip response, the strategy for identifying appropriate HEPs for this fire suppression 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 set of conditions, realistic yet representing fast operator responses, 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)

10.6.1.1 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. monitor detector output for changing conditions

   iv. notify field operator at "alert" location with important changes in detector output (e.g., detector output that is approaching the "alarm" set point)

   v. finally (on alarm), to the fire brigade response

In the context of post-reactor trip for at-power, internal events PRA, alarm detection and use of procedures to guide response are typical activities for MCR operator response. In general, these MCR operator activities comprise the cognitive (or diagnostic) portion of overall operator response. Communication between operators in the crew is most typical, but occasionally, emergency operating procedures (EOPs) will require MCR operators to make a phone call to a dispatch field operator. Explicit concerns for such communications to personnel outside the MCR have been more thoroughly considered in the context of fire PRA (e.g., NUREG-1921).

In the context of post-reactor trip MCR operator actions, there are many design requirements and associated guidance for supporting such MCR operator actions (as discussed in Section 9). This analysis assumes that these same requirements are used to support the pre-trip, "fire suppression" MCR operator responses. As a result, failure modes associated with diagnosis or cognition are expected to be the dominant contributor to these MCR operator activities.

THERP is not appropriate to use directly for this analysis (and, often, generally, for current NPP designs) because it does not explicitly address cognition or diagnosis as most modern HRA methods do; and it was developed before the Three Mile Island 2 accident (Ref. 59) and the ensuing upgrades to NPP control room designs, operating procedures, operator licensing and training programs. In addition, THERP's "annunciator response model" does not appropriately take into account the pattern-matching of annunciator tiles that modern NPP operators do when responding to an event. HEPs for THERP's "annunciator response model" (shown in Table 20-23 of NUREG/CR-1278) range from 1×10^{-04} to 2.5×10^{-01}.

The EPRI HRA approach includes two quantification methods that address cognitive failures. EPRI HCR/ORE method is a time reliability correlation and typically used when available time is relatively short. However, the HCR/ORE method should not be used for operator actions that are extremely well-practiced or skill-based, such as manual reactor trip after trip signals and alarms are received. The qualitative analysis in Section 10.4 is intended to describe a similar operator response. Consequently, for this reason (and because of the HCR/ORE method provides little insight on the potential causes of operator failure), EPRI's CBDTM method is used to calculate the cognitive contribution to operator failure.

EPRI's CBDTM model consists of eight decision trees, four of which address failures in the plant information-operator interface and another four that address failures in operator-procedure interface. Both sets of these decision trees match well with the MCR operator actions described above. The contextual factors assumed in Section 10.4 (as they relate to the VEWFD system

alarm in the MCR, the ARP used, the interface used to identify the fire and cabinet bank location, and the phone calls made to the FO, I&C technician, and brigade) are used to apply the CBDTM decision trees.

Table 10-8 summarizes these assessments and shows the resulting HEP assignments. For instance, EPRI's CBDTM assigns as "negligible" the contribution from all of the "data" decision trees, and all but one of the "procedure" decision trees. The results in Table 10-8 also show that the contribution from "procedures" for this HFE is the lowest possible HEP (i.e., 1×10^{-03} in decision tree pc-e). If CBDTM recovery factors (e.g., self-recovery and other, or extra crew) are applied, this HEP can be reduced to an HEP in the 1×10^{-4} range.

A similar analysis using SPAR-H for at-power contexts and the qualitative analysis in Section 10.4 would result in the following assessments:

- Available time is nominal.
- Stress from stressors is nominal.
- With respect to complexity, it is an "obvious diagnosis" (i.e., better than nominal).
- Experience and training are nominal.
- Procedures are diagnostic/symptom-oriented (i.e., better than nominal).
- Ergonomics/HMI is good (i.e., better than nominal).
- Fitness for duty is nominal.
- Work processes are good (i.e., better than nominal).

Using the worksheets in Appendix A of NUREG/CR-6883 with the information above, an HEP of 2×10^{-04} is obtained.

Table 10-8. MCR Operator Response (without recovery) Assessed with EPRI's CBDTM HRA Method

Decision Tree Type	Decision Tree Branch	Decision Tree Branch Assessment	Associated HEP Assignment
Plant Information (regarding VEWFD system "alert" and "alarm"	Pc-a (Data not available)	• is available in the MCR • is accurate (e.g., no spurious signals or nuisance alarms) • is trained upon	negligible
	Pc-b (Data not attended to)	• occurs during low workload conditions • is a "check" (by virtue of this cue being an "alarm") • is on the MCR front panel	negligible
	Pc-c (Data misread or miscommunicated)	• is easy to locate • is a "good" indicator with respect to HSI concerns • is communicated to the crew using formal, 3-way communications	negligible
	Pc-d (Information missing)	• cue is "as stated"	negligible

Table 10-8. MCR Operator Response (without recovery) Assessed with EPRI's CBDTM HRA Method (Continued)

Decision Tree Type	Decision Tree Branch	Decision Tree Branch Assessment	Associated HEP Assignment
Procedure	Pc-e (Relevant step in procedure missed)	• is obvious (i.e., stand-alone step) • is the only guidance being used at this time (i.e., no other procedures or activities are in play) • is graphically distinct (e.g., typical HSI concerns with respect to procedure formatting have been addressed) is followed using place keeping aids	1×10^{-3}
	Pc-f (Information misleading)	• uses standard, unambiguous wording contains all required information	negligible
	Pc-g (Error in interpreting logic)	• does not contain "NOT" statements • does not contain "and" or "or" statements does not contain both "and" and "or" statements	negligible
	Pc-h (Deliberate violation)	• is relevant for a practiced scenario is appropriate to the situation	negligible

10.6.1.2 HEP basis for field operator and technician response (in-cabinet, fire suppression)

As has already been discussed, the principal activities for the field operator are as follows:

- Take call from MCR operator
- Travel to low-energy (incipient) fire location
- Actively monitor conditions at the "alert" location, including:
  - monitoring output from incipient detector, by local panels present at the "alert" location and/or by information provided by phone calls from MCR operators who are monitoring incipient detector signals in the MCR
  - monitoring cabinets for any fire effects, such as visible signs of smoke or burning smells
- Stand at-ready to perform fire suppression[2] at first sign of flaming conditions inside any of the cabinets covered by the detector in "alert."

These activities are similar to those that might be modeled for an ex-control room action modeled in an at-power, post-reactor trip Level 1 PRA, including some time urgency. However,

[2] This analysis is based on the expectation that fire suppression capability will need to be continuously present until either the incipient stage ends or the degraded component and/or cabinet is de-energized.

typically, such field operator activities also would involve some sort of equipment manipulation. In this case, however, the only “execution” modeled for the field operator is the success or failure of fire suppression (which is addressed in Section 11 with the assignment of appropriate non-suppression curves). Therefore, the field operator activities modeled in this HRA represent only part of what is typically modeled in HRA/PRA. Consequently, only the general HEP guidance given in THERP or ATHEANA associated with “unlikely” or “very unlikely” failure probabilities (i.e., 1×10^{-2} or 1×10^{-3}, respectively) is appropriate.

Following the discussion given in Section 10.3.2.2 on the definition of this HFE for this analysis, the technician does not need to identify the affected cabinet or degrading component for the overall success of the combined field operator/technician response, provided the field operator is appropriately trained to perform the activities described above. However, for completeness (and in case a different analysis scope is addressed), the technician response is discussed here. So, for the technician, the principal activities are:

- Take call from MCR operator.

- Gather necessary equipment (including keys for locked cabinets, if necessary).
- Travel to low-energy (incipient) fire location.
- Use portable ASD equipment to identify affected cabinet (only needed for installations involving more than three cabinets).

These activities are very different than those usually modeled in at-power, post-reactor trip Level 1 HRA/PRA. Instead, these activities are similar to those modeled with pre-initiator HFEs (e.g., test or maintenance activities), except these actions may be performed with some urgency, and there is no opportunity to verify the actions. Consequently, an HEP (more) typical of THERP or ASEP (Ref. 65) is the best fit (e.g., 1×10^{-3}).

10.6.2 Results: HFE quantification for in-cabinet, fire suppression strategy

This section presents the HRA quantification results for operator actions associated with the in-cabinet, VEWFD system installations (ASD VEWFD cloud chamber, conventional spot-type ionization, and VEWFD light-scattering detectors), using the fire suppression strategy. These results only apply to the analysis scope and operational factors that have been described in this report.

10.6.2.1 MCR operator response, μ

The HEP for the MCR operator response (μ), in all cases, is assigned as 1×10^{-04}. The basis for this assignment is described below.

The state-of-practice in HRA currently is to treat each HFE, and its associated operator actions, holistically, rather than analyzing a breakdown of the various subtasks and individual influencing factors then “adding them up.” In particular, operator response in an existing U.S. NPP, in the MCR, following a reactor trip, and using the existing emergency operating procedures (EOPs), is understood to be supported by, for example (Note: this is not a complete or comprehensive list):

- a well-designed control room (including alarm panel placement and layout, clear indication of different trains, appropriate lighting and ventilation)
- effective training and certifications
- job aids (such as procedures that follow human factors guidance with respect to content, presentation and format)
- communication protocols
- a co-located crew and adequate and qualified staffing
- a strong safety culture

The combination of factors such as those given above may result in a certain expectation and reliability of operator performance. Because of differences between NPPs and even operator crews, there is no set combination of factors or features, or right or wrong implementation of job aids or designs except that they must be demonstrated (via operating experience, namely); each NPP's combination of job aids, influential factors and EOPs achieves the level of performance expected. If a plant design (e.g., size of steam generators) is such that faster response is required, then certain steps, training and procedures may be altered to compensate for or address this need.

Consequently, the "right" set of design features, job aids, and so forth cannot be definitively identified as it may come in a variety of forms. However, certain factors are expected to be important to successful operator response (since they underlie operator response for post-reactor trip events and using EOPs). For the purposes of this analysis, the qualitative analysis described in Section 10.4 are taken to be adequate to describe a context in which the MCR operator response is similar to that for post-reactor trip response. Thus, under those conditions described and assumed above, MCR operators are expected to act quickly, and with a reliability consistent with alarm response and procedural use traditionally addressed by PRAs for post-initiator actions.

Overall, given the qualitative analysis results, and the implication that MCR operator response for the fire suppression strategy of in-cabinet VEWFD installations, should mirror that for alarm response in HRA:

- does not consider any failure modes associated with detection
- considers only potential failure modes for situation assessment or diagnosis (which would result either in delayed MCR operator response or difficulty in identifying the specific cabinet(s) associated with the VEWFD system signal, which is expected to result in delayed MCR operator response)
- does not consider any failure modes associated with response planning
- considers only delays as potential modes associated with execution

Based on this discussion, an HEP for this HFE is justified in being similar to those HEPs developed in Section 10.6.1.1; namely, an HEP of 1×10^{-04} is assigned (which is independent

of the number of cabinets per bank in the installation and type of VEWFD system) for failure of MCR response.

10.6.2.2 Field operator and technician response, ξ

As discussed earlier, the key to the success of this HFE for the field operator to arrive quickly at the “alert” location and immediately provide fire suppression capability. Consequently, the only contribution to the failure probability for this HFE is from the assessment of the field operator response.

The HRA quantification results for the field operator response, ε, are shown in Tables 10-9, 10-10, and 10-11 for the cloud chamber, ION, and light-scattering detectors, respectively. The results for “total HEP” (along with the results of Section 11) are used to quantify the event trees shown in Section 6.4. (Note that these results, per this particular analysis, are for all cabinet configurations — single, 3-, 6-, or 10-cabinet installations.)

Table 10-9. HEP Calculations for ASD VEWFD, Cloud Chamber

Sample	Time available from alert	Split Fraction from Table 10-1	Base HEP	Base HEP x Split Fraction
1	0-12 minutes*	0.1	1×10^{-03}	1.0×10^{-04}
2	>12 minutes AND < 30 minutes**	0.13	1×10^{-03}	1.3×10^{-04}
3	> 30 minutes AND < ~1 hour**	0.17	1×10^{-03}	1.7×10^{-04}
4	> ~ 1 hour**	0.60	1×10^{-04}	6.0×10^{-05}
TOTAL HEP (ξ)				4.6×10^{-04}

* From Section 10.4.2.1, this is the definition of this sample point

** From Section 10.4.2.1, this is the result from the cumulative distribution function associated with the definition of this sample point

Table 10-10. HEP Calculations for Conventional Spot-Type, ION Detector

Sample	Time available from alert	Split Fraction from Table 10-2	Base HEP	Base HEP x Split Fraction
1	0-8 minutes*	0.10	0.10***	1×10^{-02}
2	> 8 minutes AND < 30 minutes**	0.23	3×10^{-02}***	6.9×10^{-03}
3	> 30 minutes AND < ~1 hour**	0.22	1×10^{-03}	2.2×10^{-04}
4	> ~ 1 hour**	0.45	1×10^{-04}	4.5×10^{-05}
TOTAL HEP (ξ)				1.7×10^{-02}

* From Section 10.4.2.1, this is the result from the cumulative distribution function associated with the definition of this sample point

** From Section 10.4.2.1, this is the definition of this sample point

*** Partially feasible.

Table 10-11. HEP Calculations for VEWFD, Light Scattering Detector

Sample	Time available from alert	Split Fraction from Table 10-3	Base HEP	Base HEP x Split Fraction
1	0-6 minutes*	0.10	0.30***	$3.0x10^{-02}$
2	> 6 minutes AND < 30 minutes**	0.31	$5x10^{-02}$***	$1.6 x10^{-02}$
3	> 30 minutes AND < ~1 hour**	0.24	$1x10^{-03}$	$2.4x10^{-04}$
4	> ~ 1 hour**	0.35	$1x10^{-04}$	$3.5x10^{-05}$
TOTAL HEP (ξ)				$4.6x10^{-02}$

* From Section 10.4.2.1, this is the result from the cumulative distribution function associated with the definition of this sample point

** From Section 10.4.2.1, this is the definition of this sample point

*** Partially feasible.

As summarized in the timing input tables and feasibility assessments (Sections 10.4 and 10.5, respectively), the assignment of HEPs for the field operator is more complicated than that for the MCR operator response because of variations in HRA inputs, namely:

- differences in the sensitivity of detectors, which results in different times available
- different "branches" that represent different times available (i.e., durations of the time available for operator response measured from "alert"), as a function of probability distributions
- feasibility assessments for each combination of timing inputs

Using the base HEP of $1×10^{-03}$ developed in Section 10.6.1, the following considerations were used to develop the "Base HEP" values shown in Tables 10-9, 10-10, and 10-11:

- If the overall operator response is not feasible, then an HEP of 1.0 is assigned. (Per Section 10.5, there are no cases where complete unfeasibility has been assessed.)
- If partial feasibility has been assessed (i.e., one of the endpoints in the range of times available for a particular sample point is less than the time required),the following HEP assignments are made:
  - For the ION detector:
    - The range of times available for Sample Point #1 (i.e., 0 to 8 minutes) is less than the range of times required (3 to 10 minutes) with a "gap" of 2 minutes. An HEP of 0.1 is assigned for this particular Sample Point.
    - The range of times available for Sample Point #2 (i.e., 8 - 30 minutes) is less than the range of time required (3 -10 minutes). Although this "gap" (i.e., 2 minutes) is the same as for Sample Point #1, the ratio of this time gap with the range of times available is smaller than that for Sample Point #1. Consequently, an HEP of 3.0E-2 is assigned for this case.

- For the light scattering detectors (i.e., ASD VEWFD and SS light scattering):

    - The range of times available for sample point #1 (i.e., 0 - 6 minutes) is less than the range of time required (3 -10 minutes) with a “gap” of four minutes. An HEP of 0.3 is assigned for this particular Sample Point.

    - The range of times available for Sample Point #2 (i.e., 6 - 30 minutes) is less than the range of time required (3 -10 minutes). Although this “gap” (i.e., 4 minutes) is the same as for Sample Point #1, the ratio of this time gap with the range of times available is smaller than that for Sample Point #1. Consequently, an HEP of 5.0E-2 is assigned for this case.

- If the time available is more than the time required, then an HEP of 1×10^{-03} is assigned (which is the recommended base HEP from Section 10.6.1).

- If the time available is significantly more than the time required (e.g., time available is greater than 1 hour), an HEP of 1×10^{-4} is assigned.

- An HEP floor of 1×10^{-4} is used.

In each table (for each detector type), the “Total HEP” is calculated by summing the results of all four sample points (i.e., the product of “Base HEP x Split Fraction” for each sample point).

10.6.3 Exploration of a variation in HRA quantification

From the discussion above, it is apparent that the HRA quantification results for the HFE representing the field operator response are extremely sensitive to the comparison between the time required for operator actions, and the time available from VEWFD system “alert” to when the incipient stage ends. For this reason, this section explores how a variation in HRA timing inputs would influence HRA quantification results.

Three variations are explored:

1. Variations in the time required for field operator response,

2. Variations in the time available data for the cloud chamber:

    a. under the most sensitive setting tested (i.e., 150,000 particles/cm^3)

    b. under the least sensitive setting tested (i.e., 9,000,000 particles/cm^3)

10.6.3.1 Variation in the time required

As discussed in Section10.4.3, the time required for the field operator to arrive at the location where the VEWFD system is in “alert” varies from 2 to 8 minutes. In addition, the answers to Question #14 in Section C.1.1 were:

- Plant X: varies but typically, 2 to 8 minutes
- Plant Y: 3 to 4 minutes

These variations in reported times could be explained by a variety of factors (principally related to the field operator travel time), including:

- plant-to-plant differences in layout of fire areas
- for a specific plant, differences in field operator travel times, depending on the specific location of the VEWFD system and where the field operator is located when the MCR operator calls
- lack of operational experience with this field operator action

The qualitative analysis chapter in NUREG-1921 (Ref. 49) provides guidance on the development of timing inputs for fire HRA, especially the discussions of sufficient time as a feasibility assessment criterion (see Section 4.3.4.1 in NUREG-1921) and of timing as a performance shaping factor (see Section 4.6.2 in NUREG-1921). This guidance, along with the possible explanations for variations given above, points to a corresponding selection of ways to explore variations in this timing input, such as:

1. The "Plant Y" data could be used as a plant-specific input (rather than a generic representation of this input), or
2. Uncertainty in the estimate of this timing input could have been reduced by either:
   a. collecting a more robust set of operational experience that reduces such variations, or
   b. establishing a job performance measure for this field operator action (or, even better, for the integrated response of the MCR operators and the field operator) that requires operator performance to meet certain targets (usually time required for performance.)

Despite uncertainties regarding the time required for field operator actions, this analysis explores the change in HRA quantification results if the time required for the field operator to arrive on location is assumed to be four minutes , plus an additional one minute for the MCR operator dispatch of the field operator. In other words, the total time required in this variation is 5 minutes (rather than the 3 to 10 minutes used in the quantification shown in Section 10.6.2).

Table 10-12 shows the results of this variation (in which all sample points are assessed to be feasible). In particular, the total HEP for this variation case is almost a factor of 20 smaller than that shown in Table 10-10.

Table 10-12. Time Required Variation (4 minutes): Revised HEP Calculations for Conventional Spot-Type, ION Detector

Sample	Time available from alert	Split Fraction from Table 10-2	Base HEP	Base HEP x Split Fraction
1	0-8 minutes*	0.10	1×10^{-03}	1×10^{-04}
2	> 8 minutes AND < 30 minutes**	0.23	1×10^{-03}	2.3×10^{-04}
3	> 30 minutes AND < ~1 hour**	0.22	1×10^{-03}	2.2×10^{-04}
4	> ~ 1 hour**	0.45	1×10^{-04}	4.5×10^{-05}
TOTAL HEP (ξ)				1×10^{-03}

* From Section 10.4.2.1, this is the result from the cumulative distribution function associated with the definition of this sample point

** From Section 10.4.2.1, this is the definition of this sample point

10.6.3.2 Variation in cloud chamber sensitivity – more sensitive

Section 5 discusses the various test cases for the cloud chamber and their results. Specifically, the most sensitive cloud chamber detector setting tested was 150,000 particles/cc.

The most important change from the HRA perspective is how the time available distribution changes with the detector on the most sensitive setting. Table 10-13 provides the results for this variation, showing, as expected, that there is more time available for the first sample point than was calculated in Section 10.6.2 (i.e., 0 to 15 minutes in the revised case versus 0 to 12 minutes in Section 10.6.2). Also, the split fractions for each sample are changed, shifting an even larger bulk of the distribution to longer times.

The base HEPs multiplied for each split fraction/sample point are unchanged.

Although the time available ranges are significantly changed, the revised total HEP is not much changed from that calculated in Section 10.6.2 (i.e., 4.2×10^{-04} in the revised cases versus 4.6×10^{-04} in Section 10.6.2).

Table 10-13. More Sensitive Detector Setting Variation: Revised HEP Calculation for ASD VEWFD, Cloud Chamber

Sample	Time available from alert	Split Fraction from Section B.4	Base HEP	Base HEP x Split Fraction
1	0-15 minutes*	0.10	1×10^{-03}	1×10^{-04}
2	>15 minutes AND < 30 minutes**	0.09	1×10^{-03}	9×10^{-05}
3	> 30 minutes AND < ~1 hour**	0.16	1×10^{-03}	1.6×10^{-04}
4	> ~ 1 hour**	0.65	1×10^{-043}	6.5×10^{-05}
TOTAL HEP (ξ)				4.2×10^{-04}

* From Section 10.4.2.1, this is the definition of this sample point

** From Section 10.4.2.1, this is the result from the cumulative distribution function associated with the definition of this sample point

10.6.3.3 Variation in cloud chamber sensitivity – less sensitive

Section 5 also discusses the least sensitive cloud chamber detector setting tested (i.e., 9,000,000 particles/cc.)

As in the variation with test results using the most sensitive setting, the most important change from the HRA perspective for the least sensitive test setting is changes to the time available range for the first sample point, and changes to the split fractions for all sample points.

Table 10-14 shows:

- the revised time available range for Sample Point #1
- the revised split fractions for all split fractions
- the same “Base HEP” assignments as in Section 10.6.1
- the revised HEP x split fraction calculations
- the revised total HEP

As for the more sensitive detector setting test results, the revised total HEP for this variation is not much changed from that calculated in Section 10.6.2 (i.e., 5.4×10^{-04} in the revised cases versus 4.6×10^{-04} in Section 10.6.2).

Table 10-14. Less sensitive detector setting variation: Revised HEP Calculation for ASD VEWFD, Cloud Chamber

Sample	Time available from alert	Split Fraction from Section B.4	Base HEP	Base HEP x Split Fraction
1	0-9 minutes*	0.1	1×10^{-03}	1×10^{-04}
2	>9 minutes AND < 30 minutes**	0.19	1×10^{-03}	1.9×10^{-04}
3	> 30 minutes AND < ~1 hour**	0.20	1×10^{-03}	2×10^{-04}
4	> ~ 1 hour**	0.51	1×10^{-04}	5.1×10^{-05}
TOTAL HEP (ξ)				5.4×10^{-04}

* From Section 10.4.2.1, this is the definition of this sample point

** From Section 10.4.2.1, this is the result from the cumulative distribution function associated with the definition of this sample point

10.6.4 HFE quantification notes for de-energization strategy

As stated earlier Section 10.1, the discussion given in this report is intended to be a guide for HRA analysts and reviewers. It is not intended to be a complete illustration of the detailed HRA that would be required for this application. The notes given in this section are even more simplified so far as HRA and its documentation, principally because de-energization strategies will be very plant-specific and no such details support this report. Consequently, the reader should view the discussion below as a general guide, but follow other guidance (e.g., NUREG-1921 [Ref. 49], the ASME/ANS PRA Standard [Ref. 60]) for the level of detail in their plant-specific analysis.

10.6.4.1 General HRA Notes on De-energization Strategies

As described in the HF tabletop analysis (Section 9.2.1), in-cabinet installations of VEWFD systems that use a de-energization strategy will involve additional operator actions and associated times, all of which must be performed before the incipient stage ends to credit fire prevention. Addressing both cabinet and component de-energization strategies, these additional actions include:

1. The technician must identify the degraded component first.

2. The field operator must communicate to the MCR operators what component is degraded.

3. MCR operators must:

   a. Determine **if** the degraded component can be de-energized.

   b. Determine **how** (e.g., with what steps and by whom) the degraded component can be safely de-energized (and without reactor trip).

4. The degraded component must be de-energized by plant personnel, such as:

   a. electrical engineers or electricians (who may assist in developing the de-energization strategy and in actually performing de-energization steps.

5. The field operator may assist in the de-energization.

Based on NPP interviews conducted for this project (see Appendix C), the complexity and associated amount of time needed to de-energize can vary widely (e.g., from minutes to a "research project" that takes days or more).

Similarly, the determination **of whether or not** a degraded component can be de-energized is not always straightforward.

10.6.4.2 Recommended Approaches for De-Energization Strategies

Based on the general notes immediately above (especially regarding the amount of time required versus the time available), it is apparent that de-energization strategies would be most successful in terms of HRA/PRA risk reduction, if:

1. The de-energization strategy is pre-planned, including the decision to de-energize (whether cabinet or component) and specific instructions for what operator actions must be taken.

2. The amount of time needed to identify the affected cabinet, and degraded components within a cabinet is minimized.

3. The amount of time needed to de-energize the affected cabinet, and degraded components within a cabinet is minimized.

4. All times required for operator actions are demonstrated.

The sub-sections that immediately follow provide further discussion on how to address de-energization strategies with detailed HRA, using these recommendations in the following way:

1. The alarm response procedure (ARP) used to response to a VEWFD "alert" also contains the necessary instructions for de-energization. (Also, if de-energization is performed locally, instructions are available at that location.)

2. A single-cabinet installation (e.g., addressable cabinet) is assumed in this discussion.

3. A cloud chamber VEWFD installation is assumed, providing the most time available (see Figure 10-2).

4. Only those de-energization strategies that are very simple to carry out are considered (e.g., only 1 to 3 simple and quick steps).

5. Only MCR operators, the field operator, and technician are required to perform all actions; no additional personnel are needed.

6. All actions are proceduralized and trained such that both speed and high reliability can be expected in task performance.

10.6.4.3 Issue / Scope

The issue and scope described in Section 10.2 are adjusted to represent the three different de-energization strategies considered, namely:

- Focused on in-cabinet VEWFD installations that are ***addressable devices***[3] (i.e., unique "alert" signals) for each cabinet

- Intended to support quantification of cabinet or component de-energization

- Allows credit fire suppression if de-energization fails

- Assumes that the MCR operators, field operator, and technician (rather than other plant personnel) can perform all actions needed to support the de-energization strategy and that these actions can be performed either at the "alert" location or in the MCR

[3] "addressable device" is defined in Section 16, "Definitions"

10.6.4.4 Success Criteria

Success criteria must be defined for each event tree heading (such as those shown in Figure 6-6), including identified HFEs. These criteria, which are similar but not the same as those stated in Section 10.3.1, are:

- **MCR response:**[4] After the detector "alert" signals in the MCR, MCR operators must dispatch both the field operator and technician to the correct location, including the specific cabinet, for the VEWFD system in "alert." This dispatching must be performed in a timely manner.
    - **Local de-energization:** In addition to the actions above, the MCR operators must direct the field operator to perform actions for de-energization immediately upon arriving at the correct location (i.e., cabinet).
    - **In-MCR de-energization:** A board operator is assigned the task of performing de-energization steps expeditiously from the MCR.
- **Field operator/Technician response:**
    - **Cabinet de-energization:** Once the detector "alert" signals, field operator must:
        1) arrive at the correct location, including the specific cabinet, for the VEWFD system in "alert,"
        2) confirm that the VEWFD "alert" is valid locally,
        3) perform necessary actions for de-energizing the cabinet in a timely manner, and
        4) provide continuous fire suppression capability while degrading conditions occur, in case there is a transition to flaming conditions before de-energization actions are complete.
    - **Component de-energization:**

      Once the detector "alert" signals, the field operator must:
        1) arrive at the correct location, including the specific cabinet, for the VEWFD system in "alert," and
        2) confirm that the VEWFD "alert" is valid locally.

[4] The decision to de-energize is not addressed here because it is assumed that pre-planning addresses this decision, per the recommendations in Section 6.4.2 which are the basis of these illustrative examples. If the decision to de-energize is NOT pre-planned, then procedures, training, and cues must be provided to support decision-making. Also, the time required for MCR operator response must be increased to account for the additional time required to make the decision.

The technician must:

3) arrive at the correct location,[5] and
4) locate the degraded component (using, for example, a “sniffer” tool, visual inspection, or thermography).

Then the field operator must:

5) perform necessary actions for de-energizing the component in a timely manner, and

6) provide continuous fire suppression capability while degrading conditions occur, in case there is a transition to flaming conditions before de-energization actions are complete.

10.6.4.5 Identify and define HFEs

Two HFEs can be used to represent the required operator actions for de-energization strategies, as has been done throughout Section 10. The HFE definitions for this de-energization strategy are somewhat different than those given in Section 10.3.2. The revised and new aspects of both HFEs are:

1. *HFE definition*: *MCR operator response (in-cabinet, addressable cabinet de-energization strategies)*

    a. MCR operators find the appropriate alarm response procedure (ARP) for the VEWFD system “alert,” and the specific cabinet. The ARP provides clear indication that this cabinet (or any degraded component in the cabinet) is to be de-energized when the VEWFDS is in “alert.”

    b. MCR operators consult main fire alarm control panel in MCR to verify which detector is signaling and the associated location, including specific cabinet.

    c. MCR operators:

        - Local de-energization: i) dispatch field operator closest to the alerting detector, providing both location and cabinet information, ii) direct the field operator to de-energize the identified cabinet or degraded component, iii) dispatch the technician to the location of the cabinet in "alert."

        - In-MCR de-energization: i) direct a board operator to de-energize the identified cabinet, ii) in parallel, dispatch field operator2 closest to the alerting detector, providing both location and cabinet information, iii) dispatch the technician to the location of the cabinet in "alert."

[5] The time required for the technician to arrive at the location must include the time required to retrieve the required equipment to identify the degraded component in the component de-energization case (e.g. the “sniffer” tool, thermography equipment, etc.).

d. Local de-energization: Depending on the field operator's success/failure, MCR operators:

  - receive verification from the field operator that the cabinet is de-energized,
  - receive verification from the field operator that a fire was suppressed, or
  - activate the fire brigade when VEWFD system signals "alarm,"

2. *HFE definition*: *Field operator and technician response (in-cabinet, addressable cabinet de-energization strategies)*

   a. Upon arrival at the fire location:

      - Local cabinet de-energization- The field operator: i) locates the cabinet in "alert" and any necessary procedure guidance for de-energizing the cabinet, and ii) then performs de-energization steps expeditiously.
      - Local component de-energization - i) The field operator locates the cabinet in "alert" and any necessary procedure guidance for de-energizing degraded components in the cabinet, ii) the technician performs necessary actions to identify the degraded component within the affected cabinet (for example, using "sniffer" tool, visual inspection, thermography), iii) then the field operator performs de-energization steps expeditiously.

   b. The field operator takes the responsibility of fire watch (with suppression capability. [both in-MCR and local de-energization]

   c. The field operator calls the MCR when the cabinet or component is de-energized (or fire is put out, if transition to flaming occur before de-energization steps have been completed.) [local de-energization only]

10.6.4.6 Qualitative HRA

All of the information and assumptions presented in Section 10.4 still applies for this de-energization strategy. However, there are some key, new assumptions for the MCR and field operators, including:

- MCR operator is trained on ARPs, especially if different responses are required for VEWFD system in "alert" (i.e., some, but not all, cabinets have instructions for de-energization)
- De-energization steps have been pre-planned and documented in appropriate procedures
- field operator is trained on both de-energization steps and fire suppression such that "high reliability" is expected for these actions

- the cabinet being de-energized is not locked (or there are other provisions made so that there is no additional time required to obtain keys)

- there are few (e.g., 1-3) steps required for de-energization and these steps are either memorized, skill-of-the-craft, or posted at the “alert” location (such that no additional time is required to find procedure binders and locate necessary procedure)

- de-energization steps require only 1-2 minutes to complete

In addition, while the time available has not changed for the VEWFD system – cloud chamber, there is a minor adjustment to time required for operator actions (as shown in Table 10-4), namely:

- MCR operators:

    - All de-energization strategies (cabinet / component): Additional time is needed to review ARP instructions for de-energizing cabinet or component and communicating these instructions to the field operator. For illustrative purposes, a time required of two minutes (i.e., the maximum time required shown in Table 10-4) is used in the examples below.

    - In-MCR de-energization strategy: For the examples below, the time required for de-energizing is assumed to be 1-2 minutes in addition to the two minutes needed to review the ARP and dispatch the field operator/technician.

- Field operator/technician:

    - Local cabinet de-energization: The time required for the field operator is adjusted to account for additional time needed to perform de-energization (i.e., 1-2 minutes for de-energizing added to 2-8 minutes required for the field operator's travel time), resulting in 3-10 minutes time required.

    - Component de-energization: The time required is adjusted to account for additional time associated with locating the degraded component AND performing de-energization, in addition to the technician's travel time to the location. From the notes above and Table 10-4, the technician requires 5-11 minutes to arrive at the location and 3-4 minutes to identify the degraded component in an affected cabinet, resulting 8-15 minutes required for the technician plus 1-2 minutes for the field operator to de-energize the degraded component, resulting in 9-17 minutes of time required for both the field operator and technician.

Consequently, the total time required (i.e., sum of time required for MCR operators and field operator/technician) for each de-energization strategy is:

- Local cabinet de-energization: 5-12 minutes
- In-MCR cabinet de-energization: 3-4 minutes
- Local component de-energization: 11-19 minutes

This example is not intended to be a complete illustration of the detailed HRA that would be required for this application. The timing assumptions given above are for a simple-optimized scenario, principally because de-energization strategies will be very plant-specific and no such details support this illustrative example.

10.6.4.7 Feasibility Assessment

All of the same assumptions made in Section 10.5 are assumed to be valid for these ***illustrative de-energization examples***.[6] In addition, the feasibility assessments for these illustrative examples (using the cloud chamber VEWFDS to determine the time available) will be similar to that shown in Table 10.5. However, the total time required for MCR operator and field operator/technician actions has changed for the de-energization strategies, resulting in the following feasibility assessments:

- Local cabinet de-energization: All cases remain feasible (however, only barely so for the first sample point of the time available probability distribution).

- In-MCR cabinet de-energization: All cases remain feasible.

- Local component de-energization:
    - Sample point #1: Not feasible
    - Sample point #2: Partially feasible
    - Sample point #3: Feasible
    - Sample point #4: Feasible

10.6.4.8 HRA Quantification

The discussion provided in Section 10.6.1 and 10.6.2 still applies to these illustrative examples. However, adjustments to the analysis and associated HEPs need to be made in order to address the specifics of each de-energization strategy (all for an addressable cabinet). Each de-energization strategy is considered separately in the sections below.

10.6.4.8.1 HRA Quantification for Local, Cabinet De-energization

The following adjustments are needed for the local, cabinet de-energization strategy:

- **MCR operator response** – It is assumed that the same assessments and assumptions made previously still apply. However, to account for the additional ARP instructions and communication with the field operator, an HEP of 2E-4 (instead of 1E-4) is used.

- **Field operator response** – Again, the same assessments and assumptions made previous still apply. In this case, the HFE for the field operator represents actual equipment manipulation, i.e., an execution task. There are variety of unknown potential

[6] For these illustrative de-energization examples, the same partitioning of the cumulative distribution function curve for time available was used. However, if the time required for a de-energization strategy was 1.5 hours (e.g., a time required greater than the lower limit of the fourth bin used in previous example) then it would be appropriate to establish additional partitions (and associated sample points) in the time available distribution (e.g., two additional sample points corresponding with time frames of: 1) greater than1 hour to less than 2 hours, and 2) greater than 2 hours.

influencing factors (that would be known for the HRA analyst in a plant-specific analysis), such as environmental factors (e.g., lighting), ergonomics (e.g., layout of items to be manipulated), and potential offsetting factors for the short time available for operator actions, that would be important inputs to determining the appropriate HEP. As noted above, for the first sample point of the time available probability distribution, there is only just enough time available to perform required actions. The scoping HRA quantification approach in NUREG-1921 and SPAR-H address concerns about adequate time for performing operator actions. EPRI's HCR/ORE HRA method, a time-reliability correlation, is not likely to be appropriate in this case since its estimates can be too high for high-practiced and memorized actions taken in short time frames. For these reasons, no attempt is made here to formally assign an HEP to this modified HFE. However, for illustrative purposes, the inputs used in Table 10-9 are modified to produce Table 10-15. The base HEP of 5E-2 shown in Table 10-15 represents a THERP-like HEP for multiple, possible failure modes (e.g., errors of omission and commission), plus an adjustment for barely enough time. As a result, the overall HEP for the field operator de-energization ($\xi_{de\text{-}ss}$) shown in Table 10-15 (i.e., $6.4x10^{-03}$) is larger than that shown in Table 10-9 (i.e., $4.6x10^{-04}$) by a factor of 10. These HEPs can be used in an event tree, such as that shown in Figure 6-6, for failure of the MCR operator actions and of "prevention," respectively.

Table 10-15. HEP Calculations for Cloud Chamber - Local Cabinet De-energization

Sample	Time available from alert	Split Fraction from Table 10-1	Base HEP	Base HEP x Split Fraction
1	0-12 minutes*	0.1	$5x10^{-02}$	$5.0x10^{-03}$
2	>12 minutes AND <30 minutes**	0.13	$5x10^{-03}$	$6.5x10^{-04}$
3	> 30 minutes AND < ~1 hour**	0.17	$1x10^{-03}$	$1.7x10^{-04}$
4	> ~ 1 hour**	0.60	$1x10^{-03}$	$6.0x10^{-04}$
TOTAL HEP ($\xi_{de\text{-}ss}$)				$6.4 x10^{-03}$

* From Section 10.4.2.1, this is the definition of this sample point

** From Section 10.4.2.1, this is the result from the cumulative distribution function associated with the definition of this sample point

10.6.4.8.2 <u>HRA Quantification for In-MCR, Cabinet De-Energization</u>

This case is similar to that discussed immediately above except:

- MCR operators perform de-energization steps in the MCR
- Specifically, it is assumed that, for example, a board operator would be directed to perform the de-energization steps while either the shift supervisor or shift technical advisor would dispatch the field operator to "alert" location to provide fire suppression capability.
- It is assumed that operator performance influencing factors (e.g., ergonomic design with respect to possible errors of commission) in the MCR are more favorable than they would be at the cabinet with the "alert" condition.

In this case, the total time required for de-energization involves only MCR operator actions, i.e., 1-2 minutes for MCR operator response to the "alert" plus 1-2 minutes to perform de-energization steps. Consequently, not only would this set of be feasible, but a more than adequate amount of time is available for operator actions.

Based on the discussion immediately above and that for the context of de-energization locally, a base HEP of 1.0×10^{-03} is assigned for de-energization steps only in the MCR.

In order to use the event tree in Figure 6-6, assigned HEPs could be used as follows:

- the failure probability for MCR operator actions developed in Section 10.6.4.2 should be used in the same way for this case
- the failure probability for de-energization should include both the failure probability of MCR de-energization (i.e., HEP of 1.0×10^{-03}) and field operator positioning for fire suppression (i.e., HEP of 4.6×10^{-04})

Consequently, the overall HEP for de-energization ($\xi_{de\text{-}ss}$) in this case is 1.4×10^{-03}.

10.6.4.8.3 HRA Quantification for Local, Component De-energization

This case is similar the strategy for local cabinet de-energization, but more complicated due to the timeframes in which this strategy is not feasible.

Adjustments include:

- **MRC operator response:** The HEP assigned for the MCR operator response is the same as for the local cabinet de-energization (i.e., 2.0×10^{-04}).
- **Field operator/technician response:**
  - Field operator response: The considerations for this strategy are identical to that for the local cabinet de-energization strategy, except that there are sample points in the time available probability distribution where de-energization is either not feasible or partially feasible. An HEP of 1.0 is assigned for the infeasible case. The HEP assignment used in Table 10-10 was used as the basis for the partially feasible case. Table 10-15 was used as a guide to assign the remaining HEPs.
  - Technician response: Although considerable effort (including reviews and walkdowns of operational events) has been devoted to understanding the process involved in the technician identifying a degraded component within an affected cabinet, the failure modes (and reasons for success) for this activity are still not well understood. In principle, the identification of a degraded component should be successful, given adequate time available. This assumption is used in this illustrative example, but is recommended to be further supported in an actual plant-specific application.

Table 10-16. HEP Calculations for Cloud Chamber - Local Component De-energization

Sample	Time available from alert	Split Fraction from Table 10-1	Base HEP	Base HEP x Split Fraction
1	0-12 minutes*	0.1	1.0***	0.1
2	>12 minutes AND <30 minutes**	0.13	0.1****	1.3E-2
3	> 30 minutes AND < ~1 hour**	0.17	$5x10^{-03}$	$8.5x10^{-04}$
4	> ~ 1 hour**	0.60	$1x10^{-03}$	$6.0x10^{-04}$
TOTAL HEP (ξ_{de-ss})				0.14

* From Section 10.4.2.1, this is the definition of this sample point

** From Section 10.4.2.1, this is the result from the cumulative distribution function associated with the definition of this sample point

*** Not feasible.

**** Partially feasible.

10.6.5 HFE quantification notes for area-wide applications

HRA for area-wide applications of VEWFD would be similar to that for the in-cabinet, de-energization strategy, except that even more time will be needed for field operator and technician actions. A value of 1.0 was used to represent the HEP failure based on area-wide applications. That is, the timing information available for detecting fires before flaming conditions will vary widely on a room by room basis. To inform HEP's for area-wide application analysts should perform timing feasibility studies which take into account room factors such as; area (i.e. size, ceiling height), contents of room (i.e. number of cabinets protected, alternative fire sources), accessibility of room (i.e. ease of movement within the room, security, locked doors, radiation areas etc.).

10.7 HRA Dependency and Recovery Analysis

Dependencies between HFEs addressed in this analysis have been treated directly through the event tree representation.

Self- or within-crew recoveries have been addressed in the development of base HEPs (see Section 10.6.1). Recoveries, as traditionally defined by PRA, are only addressed with respect to fire suppression capability (i.e., "enhanced" versus "conventional").

10.8 HRA Uncertainty Analysis

The uncertainty analysis guidance provided in Section 6.3 of NUREG-1921 (Ref. 49) is appropriate for this study. However, because of the limitations in the information inputs for this project, new uncertainty sources could not be identified (and uncertainty sources identified in NUREG-1921 are assumed to be applicable). In particular, uncertainty in timing estimates are expected to be especially important to this analysis.

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 to NUREG/CR-6850 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.

The current approach takes credit for the fire suppression capability. This approach assumes appropriately trained personnel remain in place until the problem has been resolved. Success in this approach is ultimately judged based on the ability to suppress the fire rather than prevent it. So long as the fire is prevented from growing significantly, the adverse consequences related to a large cabinet fire, and the associated fire growth because of secondary combustibles, are prevented. Estimation of both the enhanced and conventional non-suppression probabilities necessitates the estimation of the manual suppression time. This quantity is estimated as described in Supplement 1 to NUREG/CR-6850 (see Section 14 *Manual Non-suppression probability)*. Mathematically, the manual suppression time is estimated as:

$$t_{ms} = t_{damage} - t_{det}$$

where:
- t_{ms} : time for manual suppression
- t_{damage} : time to target damage
- t_{det} : time to detection

The time to damage (t_{damage}) is based on scenarios specific information and fire modeling used to estimate the time of target damage. For quantification of VEWFD system performance, the time to detection (t_{det}) should be assumed to be zero minutes. No time should be added to the time to target damage (t_{damage}) or subtracted from the time to detection (t_{det}) to represent the advanced warning provided by the VEWFD system (detection during the incipient stage). The event tree parameters "α" and "ξ" along with the use of different manual non-suppression probability curves, as explained below, support quantification of the performance of the VEWFD system. Adjusting the manual suppression time to account for an incipient stage time would be non-conservative and inconsistent with the method described in this report. Thus, as stated in NUREG/CR-6850, *no* incipient stage duration is included in the time to damage estimate due to its uncertainty in duration and that it is not expected to generate thermal conditions that threaten the integrity of other targets in the room (emphasis added).

If a licensee desires to obtain more credit in this process, a more detailed evaluation of de-energization strategies, including adequate and appropriate justification in the form of a detailed human reliability analysis must be performed. One way a licensee could achieve additional benefit would be to "pre-locate" the isolation devices for all ignition sources within each cabinet in an effort to speed up the process. This would need to include predetermining the isolation devices, conveniently displaying that information for use in response to VEWFD system alerts, training responders so that they could rapidly locate and operate the isolation device(s), and conducting drills to periodically demonstrate this ability. Given the scenario specific details that

would need to be known to conduct such an analysis, the de-energization approach is beyond the scope of this study.

11.1 Enhanced Fire Suppression

Enhanced Fire Suppression is credited following the *success path* of the following branch points:

(1) very early warning fire detection (VEWFD) system availability, reliability, and effectiveness (β)

(2) fraction of fires that have an incipient stage of sufficient duration (α)

(3) system effective at detecting incipient stage (τ)

(4) main control room (MCR) response (μ)

(5) field operator and technician response (ξ)

The "π" factor in the event tree represents the enhanced suppression probability. The "π" factor differs between the two event trees (in-cabinet – π_1; area-wide – π_2).

The "π_1" factor is applicable for the in-cabinet event tree (see Figure 6-4) and represents the probability that, given **success** of the technician/field operator to respond to the VEWFD "alert," suppression has failed to limit the fire damage to the enclosure of origin. The field operator in the area of the cabinet responsible for the VEWFD system alert fails to promptly suppress the fire quickly enough to prevent damage to PRA targets outside the cabinet. The MCR curve (λ=0.324) should be used for this case. This is considered to be reasonable representation given that the field operator, a trained responder, will be near the bank of cabinets where the VEWFD system alert was initiated, actively searching for the source location of the alert.

The "π_2" factor is applicable for the area-wide event tree and represents the probability that, given **success** of the technician/field operator in the room responsible for the VEWFD system alert, suppression activities fail to prevent damage to PRA targets outside the cabinet.[52] This branch path takes into account that the field operator has arrived at the room causing the VEWFD system alert, but was unable to locate the source of the condition causing the VEWFD system "alert" before the low-energy (incipient) fire progresses to a flaming condition. A newly developed non-suppression probability curve should be used with λ = 0.194. This value is based upon an analysis of fire events from the Updated Fire Events Database (Ref. 63). All fires in electrical cabinets were sampled for occurrences in which personnel were present in the room of origin when a flaming condition began. The approximation for the non-suppression value to be used was then evaluated against the MCR suppression curve. Differences between the MCR and newly developed curve were sufficient to warrant a new suppression curve for this application. This is considered to be reasonable representation given that the field operator, a

[52] Due to the large variation among area-wide applications, including room size, ignition sources, ventilation conditions, and limited operator experience in locating ignition sources for area-wide application, the HEP for the area-wide application is assumed to fail (HEP = 1.0). The generic approach presented in this report assumes that the field operator fail to 1) arrive at the correct location, 2) initiate suppression, and 3) position him/herself in close proximity to the specific cabinet responsible for the 'alert' condition. Plant specific information and supporting justification and documentation may support an HEP estimate other than 1.0.

trained responder, will be in the room where the VEWFDS alert was initiated, actively searching for the source location of the alert.

The probability that the fire brigade or other first responders will fail to suppress the fire [Pr(Tsupp ≥ t)] is estimated with suppression probability curves developed using the suppression time data reported in FEDB. In EPRI 3002002936 (NUREG-2169), new non-suppression probability estimates are provided. These new estimates are used in Section 12 "Illustrative examples." These curves were developed using U.S. Fire Event Experience through 2009 where manual suppression was involved and suppression time information was available. Suppression time was defined as the time the fire was extinguished *or* the time the fire was reported to have been under control by the fire brigade on scene (Ref. 45). Events including self-extinguished fires, supervised burnouts, and fires extinguished with automatic fire suppression systems were excluded from the curves. If the time from detection to suppression was not known, but the duration of the fire event from start to suppression was known, then the reported fire duration was used instead.

The mathematical model to derive $Pr(T_{supp} \geq t)$ is described in NUREG/CR-6850 as follows:

> *The data for analysis consists of reported fire durations in commercial U.S. NPPs. These times are treated as being generated by an underlying probabilistic model. The final output of interest is the suppression curve, which gives the probability that a fire lasts longer than a specified time. If T is the random variable describing when the fire is suppressed, and λ(t) is the rate at which the fire is suppressed (possibly time-dependent), this probability of non-suppression is given by:*
>
> $$\Pr(T > t) = e^{\left(-\int_0^t \lambda(s)ds\right)}$$
>
> *In this equation, λ(t) is a function of the parameters of the probabilistic model chosen for T. The simplest model for T is the exponential distribution, whose probability density function is:*
>
> $$f(t) = \lambda e^{-\lambda t}$$
>
> *In this model, λ is estimated directly and is not a function of time, giving*
>
> $$\Pr(T > t) = e^{-\lambda t}$$
>
> *The non-suppression probability is calculated using the above equation, usually selecting t as the time to target damage.*

The same mathematical model was used to derive the non-suppression probability curve applicable to "π_2."

11.2 <u>Conventional Fire Suppression</u>

Conventional detection/suppression is credited following the *failure path* of the following branch points:

1. VEWFD system availability and reliability (β)
2. fraction that have an incipient stage of sufficient duration (α)
3. detector effectiveness (τ)
4. MCR response (μ)
5. field operator and technician response (ξ)

The "η" factor in the event tree represents the conventional suppression probability. There are two cases for this factor which are dependent upon the detection strategies used within the fire area. "$\eta 1$" represents the failure probability of redundant detection and/or automatic suppression systems, given that the VEWFD system has failed. "$\eta 2$" represents the failure probability of redundant detection and/or automatic suppression systems, given that the VEWFD system was not able to provide enhanced detection.

As used here, its estimated using the conventional Detection Suppression Event Tree in NUREG/CR-6850, Appendix P, using the electrical fire suppression curve for manual suppression as appropriate. The conventional detection suppression event tree is shown in Figure 11-1. The end points for conventional suppression are shown below in Table 11-1. When crediting automatic suppression systems, the analyst must first determine that the automatic suppression will actuate prior to the predicted time to fire damage or else auto suppression fails.

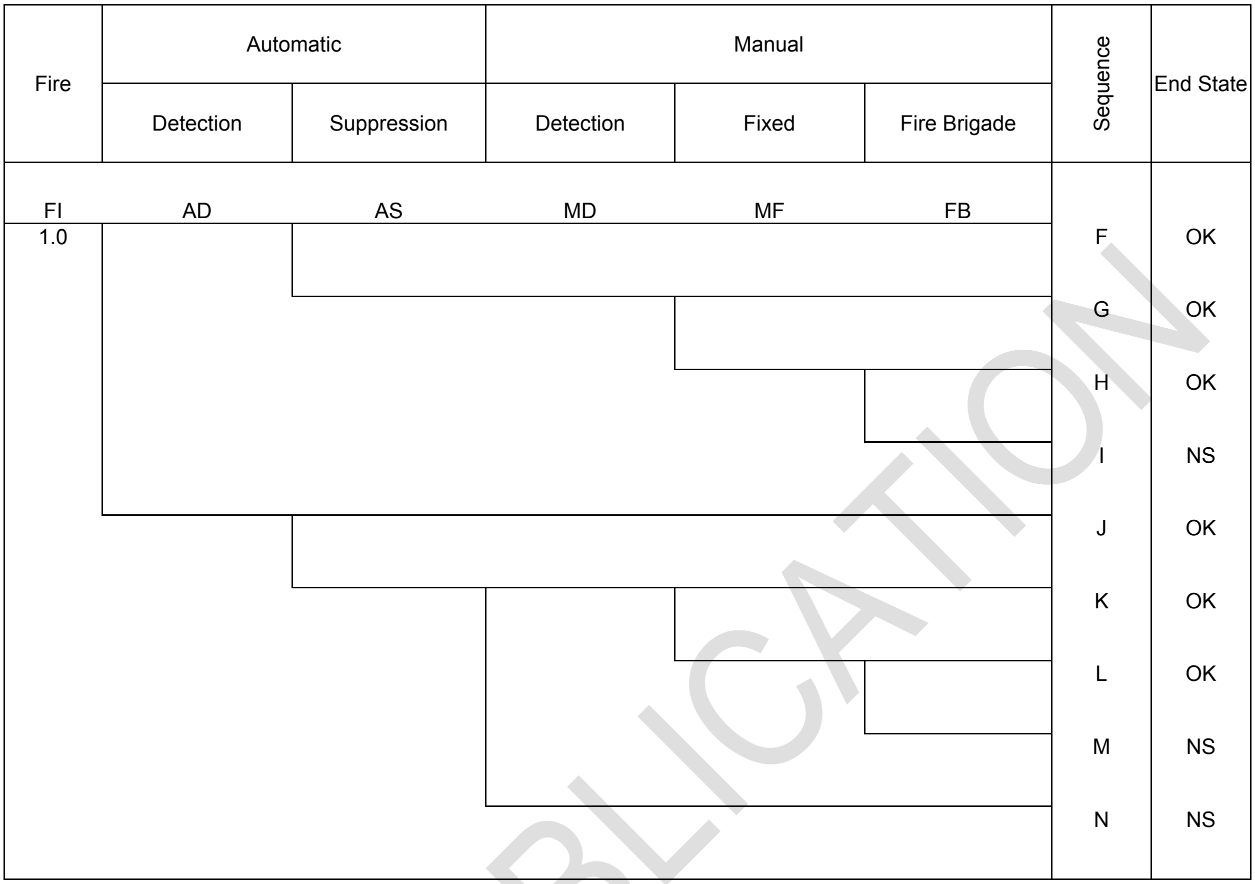

Figure 11-1. Conventional detection suppression event tree

Table 11-1. Conventional Detection Suppression Event Tree Outputs

Sequence	Detection	Suppression
F	Automatic detection by • Heat detectors • Smoke detectors	Fire suppression by an automatically actuated fixed system
G		Fire suppression by a manually actuated fixed system
H		Fire suppression by the fire brigade
I		Fire damage to target items
J	Delayed detection by • Roving fire watch • Control room verification	Fire suppression by an automatically actuated fixed system
K		Fire suppression by a manually actuated fixed system
L		Fire suppression by the fire brigade
M		Fire damage to target items
N	Fire damage to target items	

For **In-Cabinet** or **Area-wide** applications, in which redundant detection and/or automatic suppression systems are available in the area, “η_1” represents sequences F – N from Figure 11-1. That is, given a failure of the VEWFD system or MCR to respond, the redundant detection and/or automatic suppression capability still exists. From NUREG-6850, the probability of random failure of a conventional spot-type smoke detector system is assumed to be no larger than 0.05.

For **In-Cabinet** or **Area-wide** applications, in which redundant detection and/or automatic suppression systems are available in the area, “η_2” represents sequences F – I from Figure 11-1. That is, given a failure of the VEWFD system to provide sufficient advance warning, the VEWFD system will still provide prompt detection functions. Time to detection is assumed to be at ignition.

For **In-Cabinet** or **Area-wide** applications, “η_3” represents the failure of an independent automatic fire suppression system (including automatic detection system if the automatic suppression system is dependent on the automatic detection system) to suppress the fire prior to fire damage when the enhanced suppression capabilities fail. If an independent automatic suppression system is not present in the fire scenario, then “η_3” is assumed 1.0. For all other cases, the reliability of the independent automatic suppression system (and automatic detection system, if applicable) is modeled consistent with NUREG/CR-6850, including an evaluation of any timing considerations.

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 several different fire scenarios.

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 smoke detection, bank of 10 cabinets that are naturally ventilated

Case 2 Control cabinet ignition source, in-cabinet smoke detection, single cabinet that is forced ventilated

Case 3 Power cabinet ignition source, in-cabinet smoke detection, bank of 10 cabinets that are naturally ventilated

Case 4 Mix of control and power cabinets, area-wide air return grill mounted ASD VEWFD

Case 5 Mix of control and power cabinets, area-wide 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 or from NUREG-2178), 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 to reduce the number of variables, allowing for a more 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 FAQ 08-0046 simplified model approach on page 13-8 of Supplement 1 to NUREG/CR-6850, EPRI 1019259.

12.1.1 Case 1: In-cabinet smoke detection, 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. The cabinets are naturally ventilated. Each in-cabinet smoke detection system will be evaluated separately. It is assumed that a single zone of the ASD protects the entire cabinet bank and the spot-type detectors are addressable to a single cabinet.

The in-cabinet detection systems will be evaluated with and without crediting other detection and suppression systems in the room. The following information is necessary before proceeding with the analysis:

- Based on fire modeling analysis, the estimated time to target damage is 12 minutes.
- From fire drills records, the reasonable fire brigade response time is 10 minutes.
- Procedures to de-energize entire cabinets or specific components within the cabinet are not available.
- When a redundant ceiling mounted conventional area-wide smoke detection system is credited, fire modeling analysis has shown that the estimated time for conventional area-wide smoke detection is 2 minutes.

Based on the preceding information, the values presented in Table 12-1 are to be used in applying the in-cabinet ASD VEWFD event tree approach; each parameter estimate is provided with source information as to where the particular estimate value can be located. The results are presented in Table 12-2 as non-suppression probability estimates.

Table 12-1. Case 1 Input Parameters: Multi-Control Cabinet, In-Cabinet

Parameter	Estimate	Source
β	3.6×10^{-03} (ASD) 5×10^{-02} (Spot)	System unavailability (Table 7-4) and unreliability (Table 7-2) in Section 7.2 of this report for ASD VEWFD systems NUREG/CR-6850 – Appendix P
α	2.8×10^{-01}	Fraction of fires that have an incipient phase Table 7-1, Low Voltage Control Cabinets
τ	2.7×10^{-03} : ASD CC 5.3×10^{-01} : ASD LS1 1.9×10^{-01} : ASD LS2 2.6×10^{-01} : SS 1.0×10^{-01} : ION	System ineffectiveness Table 7-5, In-cabinet, Natural Ventilation
μ	1×10^{-04}	MCR operator response Section 10.6.2.1
ξ	4.6×10^{-04} : ASD CC 4.6×10^{-02} : ASD LS 4.6×10^{-02} : SS 1.7×10^{-02} : ION	Field operator response Section 10.6.2.2 Table 10-9 – ASD VEWFD CC Table 10-10 – Ionization Table 10-11 – ASD VEWFD LS and SS
π1	2.0×10^{-02}	See discussion below
η1	Varies with redundant systems credited in scenario.	
η2		
η3		

Table 12-2. Case 1 Results - Probability of Non-Suppression

In-Cabinet Detection Type	In-Cabinet Detection Only	In-Cabinet Detection with		
		Redundant Auto Detection	Auto Suppression [Halon]	Auto Suppression [Wet Pipe]
LS1	2.2×10^{-02} [4.6]	2.2×10^{-01} [4.6]	1.1×10^{-02} [92]	4.3×10^{-03} [231]
LS2	1.5×10^{-01} [6.6]	1.5×10^{-01} [6.7]	7.5×10^{-03} [134]	3.0×10^{-03} [335]
CC	1.1×10^{-01} [9.4]	1.0×10^{-01} [9.6]	5.2×10^{-03} [193]	2.1×10^{-03} [482]
SS	2.0×10^{-01} [4.9]	1.7×10^{-01} [5.7]	8.7×10^{-03} [115]	3.5×10^{-03} [287]
ION	1.7×10^{-01} [5.9]	1.4×10^{-01} [7.2]	7.0×10^{-03} [144]	5.6×10^{-03} [180]
None	1.0	**Without In-Cabinet Detection**		
		3.6×10^{-01} [2.8]	1.8×10^{-02} [56]	8.1×10^{-03} [123]

Note: non-suppression probability estimates presented in Table 12-2 are scenario dependent and not generic. Values in "[ ]" represent the inverse of the probability of non-suppression, sometime referred to as the "reduction factor."

The enhanced suppression parameter (π) is the probability that, given **success** of event ξ, the field operator in the area of the electrical cabinet responsible for the VEWFD system alert fails to promptly suppress the fire quickly enough to prevent damage to PRA targets outside the cabinet. This is calculated using the MCR non-suppression curve. For this case, both the time to detection of the VEWFD system and time to fire brigade response are set to 0 minutes, considering that the system has already gone into alarm and the field operator is present in the room. The 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 VEWFD 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 (π_1), once ignition has occurred, is calculated using the MCR curve (λ = 0.324) using a manual suppression time of 12 minutes as:

$$e^{(-\lambda_{MCB}*t)} = e^{(-0.324*12)} = 2.0 \times 10^{-02}$$

As identified in Table 12-1, the conventional detection/suppression estimates vary with the types of redundant detection and suppression systems credited in the fire scenario. Figure 12-1 and Figure 12-2, illustrate the solution of the detection suppression event tree from NUREG/CR-6850 for the scenario where only redundant fire detection is available.

Figure 12-1 represents η_1, the presence of redundant conventional ceiling mounted spot-type detection system is assumed for this example calculation. η_1 is calculated through sequences F to N of the conventional suppression/detection event tree. 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 12 - 2 = 10 minutes (t_{dam} - t_{det} = t_{ms}) as:

$$e^{(-\lambda_{electrical}*t)} = e^{(-0.098*10)} = 0.375$$

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.

Accordingly, the non-suppression probability is the sum of sequences I, M and N, which is 0.36 + 0.00 + 0.05 = 0.41.

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	0.625	H	OK	
					0.375	I	NS	3.6E-01
	0.05	0.0				J	OK	
		1.0	0.0	0.0		K	OK	
				1.0	0.0	L	OK	
					1.0	M	NS	0.0
			1.0			N	NS	5.0E-02
							Total	**4.1E-01**

Figure 12-1. Case 1, detection suppression tree for (η_1)

Figure 12-2 represents (η_2), the presence of in cabinet VEWFD system providing prompt detection for event sequences where a fast developing fire occurs or the VEWFD system is not effective in detecting the low energy fire in its incipient stage. That is, given a failure of the in-cabinet ASD VEWFD system to provide sufficient advance warning, the VEWFD system will still perform prompt automatic detection functions. That is, for in-cabinet applications, prompt detection assumes the ASD VEWFD system time to detect is 0 minutes. (η_2) is calculated through sequences F to I. The probability of failure for the fire brigade is calculated using the electrical suppression curve using a manual suppression time of 12 minutes as:

$$e^{(-\lambda_{electrical}*10)} = e^{(-0.098*12)} = 0.309$$

Accordingly, the non-suppression probability for (η_2) sequence I or 0.309.

Fire	Prompt Detection	Automatic Detection	Automatic Suppression	Manual Detection	Manual Fixed	Manual Fire Brigade	Sequence	End State	Pr(non-suppression)
FI	PD	AD	AS	MD	MF	FB			
1.0	1.0	1.0	0.0				F	OK	
			1.0		0.0		G	OK	
					1.0	0.691	H	OK	
						0.309	I	NS	3.1E-01
		0.0	0.0				J	OK	
			1.0	0.0	0.0		K	OK	
					1.0	0.691	L	OK	
						0.309	M	NS	0.0
				1.0			N	NS	0.0
								Total	3.1E-01

Figure 12-2. Case 1, detection suppression event tree (η_2)

"η_3" represents the failure of an independent automatic fire suppression system (including automatic detection system failure, if the automatic suppression system is dependent on the automatic detection system.) For scenarios where no independent automatic fire suppression systems are available or credited, "η_3" is set to 1.0. Where automatic suppression systems are available and credited and not dependent on an automatic detection system (such as wet pipe sprinklers), then the failure probability of that system should be represented by "η_3." Where automatic suppression systems are available and credited and dependent on an automatic detection system the combined failure probability of the suppression and detection system should be represented by "η_3." For example, if an automatic suppression system with a failure probability of 0.04 is dependent on an automatic detection system with a failure probability of 0.05, then the combined failure probability to use for η_3 should be (0.05) + (1-0.05) × (0.04) = 0.088.

12.1.2 Case 2: In-cabinet, single control cabinet, force ventilation high ACH

In this example, various in-cabinet smoke detection systems are evaluated for their ability to enhance the suppression capability for a potential fire hazard located in a single control cabinet with a high rate of forced ventilation (approximately 300 cabinet ACH). Each in-cabinet smoke detection system will be evaluated separately. It is assumed that a single zone of the ASD protects the cabinet and the spot-type detectors are addressable to a single cabinet. The in-cabinet detection systems will be evaluated with and without crediting other detection and suppression systems in the room. The following information is necessary before proceeding with the analysis:

- Based on fire modeling analysis, the estimated time to target damage is 12 minutes.
- From fire drills records, the brigade response time is 10 minutes.
- Procedures to de-energize entire cabinets or specific components within the cabinet are not available.
- When a redundant ceiling mounted conventional area-wide smoke detection system is credited, fire modeling analysis has shown that the estimated time for conventional area-wide smoke detection is 2 minute.

Based on the above information the values presented in Table 12-3 are to be used in applying the in-cabinet ASD VEWFD event tree approach; each parameter estimate is provided with source information as to where the particular estimate value can be located. The results are presented in as non-suppression probability estimates.

Table 12-3. Case 2, Input Parameters: Single Low Voltage Control Cabinet, In-Cabinet

Parameter	Estimate	Source
β	3.6×10^{-03} (ASD) 5×10^{-02} (Spot)	System unavailability (Table 7-4) and unreliability (Table 7-2) in Section 7.2 of this report for ASD VEWFD systems NUREG/CR-6850 – Appendix P
α	2.8×10^{-01}	Fraction of fires that have an incipient phase Table 7-1, Low Voltage Control cabinet
τ	1.9×10^{-02} : ASD CC 3.7×10^{-01} : ASD LS2 7.9×10^{-01} : ION	System ineffectiveness Table 7-5, In-cabinet, Forced Ventilation
μ	1×10^{-04}	MCR operator response Section 10.6.2.1
ξ	4.6×10^{-04}: ASD CC 4.6×10^{-02} : ASD LS 1.7×10^{-02} : ION	Field operator response Section 10.6.2.2 Table 10-9 – ASD VEWFD CC Table 10-10 – Ionization Table 10-11 – ASD VEWFD LS and SS
π1	2.0×10^{-02}	Same as Case 1
η1	Varies with redundant systems credited in scenario	
η2		
η3		

Table 12-4. Case 2 Results - Probability of Non-Suppression

In-Cabinet Detection Type	In-Cabinet Detection Only	In-Cabinet Detection with		
		Redundant Auto Detection	Auto Suppression [Halon]	Auto Suppression [Wet Pipe]
LS2	1.9×10^{-01} [5.4]	1.8×10^{-01} [5.4]	9.2×10^{-03} [108]	2.0×10^{-02} [271]
CC	1.1×10^{-01} [9.2]	1.1×10^{-01} [9.3]	5.4×10^{-03} [187]	2.1×10^{-03} [467]
ION	3.0×10^{-01} [3.3]	2.7×10^{-01} [3.7]	1.4×10^{-02} [73]	5.5×10^{-03} [183]
None	1.0	**Without In-Cabinet Detection**		
		3.6×10^{-01} [2.8]	1.8×10^{-02} [56]	8.1×10^{-03} [123]

Note: non-suppression probability estimates presented in Table 12-4 are scenario dependent and not generic. Values in "[ ]" represent the inverse of the probability of non-suppression, sometime referred to as the "reduction factor."

For this case the solution of the conventional detection suppression event tree from NUREG/CR-6850 for the terms η_1, η_2 and η_3, are identical to Case 1 and will not be repeated here.

12.1.3 Case 3: In-cabinet ASD VEWFD, power cabinet with 10 vertical sections, natural ventilation

In this example, various in-cabinet smoke detection systems are evaluated for their ability to enhance the suppression capability for a potential fire hazard located in power cabinets (motor control center with ten vertical sections). The cabinets are naturally ventilated (not well sealed). Each in-cabinet smoke detection system will be evaluated separately. It is assumed that a single zone of the ASD protects the entire cabinet bank and the spot-type detectors are addressable to a single cabinet. The following information is necessary before proceeding with the analysis.

- Based on fire modeling analysis, the estimated time to target damage is 12 minutes.
- From fire drills records, the brigade response time is 10 minutes.
- Procedures to de-energize entire cabinets or specific components within the cabinet are not available.
- When a redundant ceiling mounted conventional area-wide smoke detection system is credited, fire modeling analysis has shown that the estimated time for conventional area-wide smoke detection is 2 minutes.

Based on the above information the values presented in Table 12-5 are used in applying the in-cabinet ASD VEWFD event tree approach; each parameter estimate is provided with source information as to where the particular estimate value can be located. The results are presented in

Table 12-6 as non-suppression probability estimates.

Table 12-5. Case 3 Input Parameters: Multi-Power Cabinet, In-Cabinet

Parameter	Estimate	Source
β	3.6×10^{-03} (ASD) 5×10^{-02} (Spot)	System unavailability (Table 7-4) and unreliability (Table 7-2) in Section 7.2 of this report for ASD VEWFD systems NUREG/CR-6850 – Appendix P
α	5.0×10^{-01}	Fraction of fires that have an incipient phase Table 7-1, Power Cabinets
τ	2.7×10^{-03} : ASD CC 5.3×10^{-01} : ASD LS1 1.9×10^{-01} : ASD LS2 2.6×10^{-01} : SS 1.0×10^{-01} : ION	System ineffectiveness Table 7-5, In-cabinet, Natural Ventilation
μ	1×10^{-04}	MCR operator response Section 10.6.2.1
ξ	4.6×10^{-04} : ASD CC 4.6×10^{-02} : ASD LS 4.6×10^{-02} : SS 1.7×10^{-02} : ION	Field operator response Section 10.6.2.2 Table 10-9 – ASD VEWFD CC Table 10-10 – Ionization Table 10-11 – ASD VEWFD LS and SS
π1	2.0×10^{-02}	Same as Case 1
η1	Varies with redundant systems credited in scenario.	
η2		
η3		

Table 12-6. Case 3 Results - Probability of Non-Suppression

In-Cabinet Detection Type	In-Cabinet Detection Only	In-Cabinet Detection with		
		Redundant Auto Detection	Auto Suppression [Halon]	Auto Suppression [Wet Pipe]
LS1	2.5×10^{-01} [4.0]	2.4×10^{-01} [4.1]	1.2×10^{-02} [82]	4.9×10^{-03} [205]
LS2	2.0×10^{-01} [5.0]	2.0×10^{-01} [5.0]	9.9×10^{-03} [101]	4.0×10^{-03} [253]
CC	1.7×10^{-01} [5.9]	1.7×10^{-01} [6.0]	8.3×10^{-03} [120]	3.3×10^{-03} [300]
SS	2.5×10^{-01} [4.1]	2.2×10^{-01} [4.6]	1.1×10^{-02} [92]	4.3×10^{-03} [231]

Table 12-6. Case 3 Results – Probability of Non-Suppression (Continued)

In-Cabinet Detection Type	In-Cabinet Detection Only	Without In-Cabinet Detection		
		Redundant Auto Detection	Auto Suppression [Halon]	Auto Suppression [Wet Pipe]
ION	2.2×10^{-01} [4.5]	1.9×10^{-01} [5.2]	9.6×10^{-03} [104]	3.8×10^{-03} [260]
None	1.0	3.6×10^{-01} [2.8]	1.8×10^{-02} [56]	8.1×10^{-03} [123]

Note: non-suppression probability estimates presented in Table 12-6 are scenario dependent and not generic. Values in "[ ]" represent the inverse of the probability of non-suppression, sometime referred to as the "reduction factor."

For this case the solution of the detection suppression event tree from NUREG/CR-6850 for the terms η_1, η_2, and η_3, are identical to Case 1 and 2, and will not be repeated here.

12.1.4 Case 4: Area-wide ASD VEWFD system protecting low-voltage control cabinets

In this example, various area-wide smoke detection systems are evaluated for their ability to enhance the suppression capability for a potential fire hazard located in control cabinet. The room has an HVAC system. The following information is necessary before proceeding with the analysis.

- Based on fire modeling analysis, the estimated time to target damage is 10 minutes.
- From fire drills records, the brigade response time is 10 minutes.
- There are no redundant smoke detection systems in the fire area.
- Procedures to de-energize entire cabinets or specific components within the cabinet are not available.
- When a redundant ceiling mounted conventional area-wide smoke detection system is credited, fire modeling analysis has shown that the estimated time for conventional area-wide smoke detection is 2 minutes.

Based on the above information the values presented in Table 12-7 are to be used in applying the incipient event tree approach:

Table 12-7. Case 4 Input Parameters: Low-voltage control cabinet Type, Area-wide

Parameter	Estimate	Source
β	3.6×10^{-03} (ASD ceiling) 4.0×10^{-03} (ASD air return grill)	System unavailability (Table 7-4) and unreliability (Table 7-2) in Section 7.2 of this report for ASD VEWFD systems Note that a $4.x10^{-04}$ value for HVAC unreliability has been added to the ASD when used in an air return application. There is no basis for this value and is used for illustrative purposes only. Plant specific HVAC unreliability estimates should be used.
	5×10^{-02} (Spot)	NUREG/CR-6850 – Appendix P
α	0.28×10^{-01}	Fraction of fires that have an incipient phase Table 7-1, Bin 15 – All Cabinet Types
τ	<u>Ceiling</u> 3.2×10^{-01} : ASD CC 1.1×10^{-01} : ASD LS 5.7×10^{-01} : SS	System ineffectiveness Table 7-5, Area-wide, Ceiling
	<u>Air Return</u> 3.0×10^{-01} : ASD CC 5.2×10^{-01} : ASD LS	System ineffectiveness Table 7-5, Area-wide, Air Return Grill
μ	1×10^{-04}	MCR operator response Section 10.6.2.1
ξ	1.0	Field operator & technician response Section 10.6.5
π2	9.7×10^{-02}	See discussion below
η1	Varies by redundant systems credited in scenario.	
η2		
η3		

Table 12-8. Case 4 Results for Area-wide <u>Ceiling</u> VEWFD - Probability of Non-Suppression

In-Cabinet Detection Type	VEWFD Only	Area-wide VEW Detection with		
		Redundant Auto Detection	Auto Suppression [Halon]	Auto Suppression [Wet Pipe]
LS2	3.1×10^{-01} [3.2]	3.1×10^{-01} [3.2]	1.5×10^{-02} [65]	6.2×10^{-03} [162]
CC	3.1×10^{-01} [3.2]	3.1×10^{-01} [3.2]	1.5×10^{-02} [65]	6.2×10^{-03} [162]
SS	3.4×10^{-01} [2.9]	3.1×10^{-01} [3.2]	1.6×10^{-02} [63.8]	6.3×10^{-03} [160]
		Without Area-wide VEW Detection		
None	1.0	3.6×10^{-01} [2.8]	1.8×10^{-02} [56]	8.1×10^{-03} [123]

Table 12-9. Case 4 Results for Area-wide Air Return Grill VEWFD - Probability of Non-Suppression

In-Cabinet Detection Type	VEWFD Only	Area-wide VEW Detection with		
		Redundant Auto Detection	**Auto Suppression [Halon]**	**Auto Suppression [Wet Pipe]**
LS2	3.1×10^{-01} [3.2]	3.1×10^{-01} [3.2]	1.5×10^{-02} [65]	6.2×10^{-03} [162]
CC	3.1×10^{-01} [3.2]	3.1×10^{-01} [3.2]	1.5×10^{-02} [65]	6.2×10^{-03} [162]
None	1.0	**Without In-Cabinet Detection**		
		3.6×10^{-01} [2.8]	1.8×10^{-02} [56]	8.1×10^{-03} [123]

Note: non-suppression probability estimates presented in Table 12-9 are scenario dependent and not generic. Values in "[ ]" represent the inverse of the probability of non-suppression, sometime referred to as the "reduction factor."

Note that as a default, the field operator/technician response is set to failure (ξ = 1.0). As discussed in Section 10, unless a detailed analysis following the process outlined is followed to develop scenario specific human error probabilities for the area-wide applications is conducted, the field operator/technician response is assumed to fail (ξ = 1.0). If a value other than 1.0 can be justified, then the enhanced suppression parameter (π_2) is the probability that, given **success** of event ξ, the field operator in the area of the electrical cabinet responsible for the VEWFD system alert fails to promptly suppress the fire quickly enough to prevent damage to PRA targets outside the cabinet. This is calculated using the field operator non-suppression curve. For this case, both the time to detection of the VEWFD system and time to fire brigade response are set to 0 minutes, considering that the system has already gone into alarm and the field operator is present in the room. The 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 VEWFD 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 (π_2), once ignition has occurred, is calculated using the field operator detection curve (λ = 0.194) using a manual suppression time of 12 minutes as:

$$e^{(-\lambda_{MCB} * t)} = e^{(-0.194 * 12)} = 9.7 \times 10^{-02}$$

Figure 12-3 estimates (η_1), conventional non-suppression probability for a redundant detection systems when the area-wide VEWFD system or main control room response to an ASD VEWFD response fails. Delayed detection is assumed 1.0 for cases where no prompt or automatic detection is credited (or fails) if the estimated time for manual detection is less than the time to target damage. "η_1" is calculated through sequences F – N. Assuming a time to delayed detection of 15 minutes, the fire brigade has no time to suppress the fire before target

damage. For this case, there is no redundant detection systems credited. Accordingly, the non-suppression probability is the sum of Sequences I, M and N, which is 0.36 + 0.0+ 0.05 = 0.41.

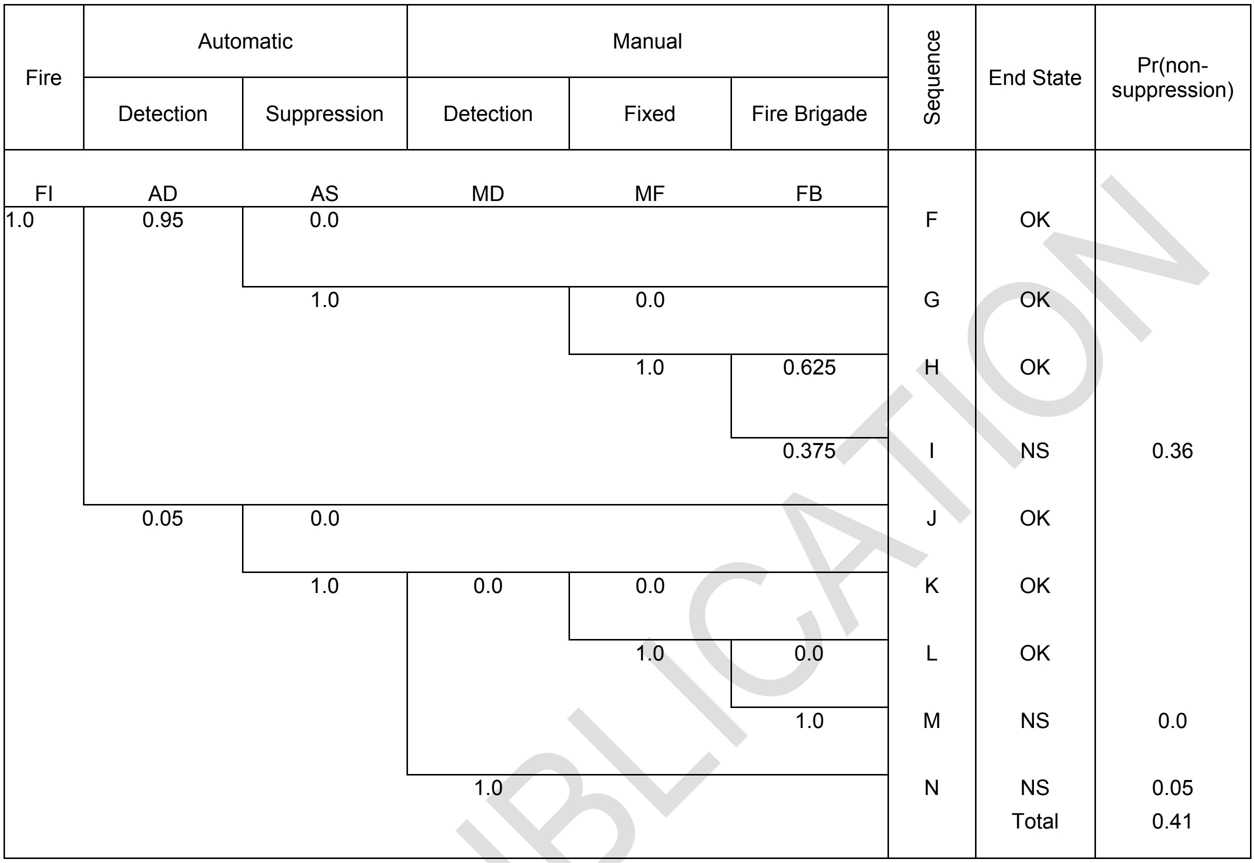

Figure 12-3. Case 4, conventional detection suppression tree for (η_1)

Figure 12-4 represents η_2, the probability that the VEWFDs system providing prompt detection for event sequences where a fast developing fire occurs or the VEWFD system is not effective in detecting the low energy fire in its incipient stage. That is, given a failure of the VEWFD system to provide sufficient advance warning, the VEWFD system will still provide prompt detection. η_2 is calculated through sequences F to I with VEWFD system represented with a failure probability of 0.0 given that detector system availability, reliability, and effectiveness is accounted for with β. The probability of failure for the fire brigade is calculated using the "electrical" suppression curve at time 12 - 0 = 12 minutes as:

$$e^{(-0.098*12)} = 0.309$$

According to Section P.1.5, the non-suppression probability is the sum of Sequences I, M and N, which is 3.1×10^{-1} + 0.0 + 0.0 = 3.1×10^{-01}.

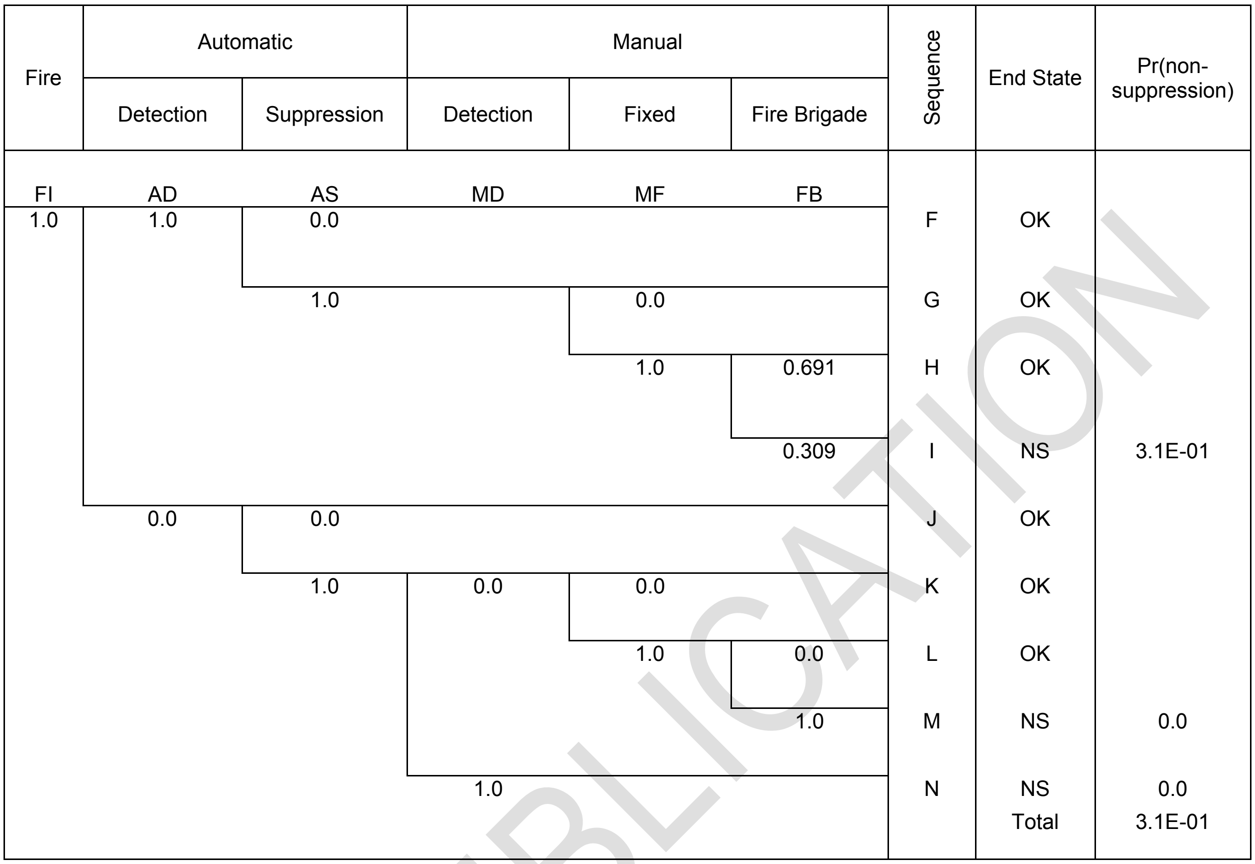

Figure 12-4. Case 4, conventional detection suppression tree for (η_2)

"η_3" represents the failure of an independent automatic fire suppression system (including automatic detection system failure, if the automatic suppression system is dependent on the automatic detection system.) See case 1 for further details.

12.2 Evaluation of the Event Tree Sensitivity

The sensitivity of the event trees are evaluated in this section. This evaluation is conducted for Case 1. The evaluation is performed by adjusting a single parameter to its bounding estimate ($5^{th}/95^{th}$ or max/min) and plotting the results on a time based probability plot. The event trees are evaluated for the "Fire Damage Outside Cabinet" damage state. For each ASD VEWFD system case, the parameters evaluated include α, β, τ, and ξ. The HEP for MCR response "μ," enhanced suppression "π_{1-2}," and conventional detection/suppression "η_{1-3}," are not evaluated here as they will have a minor effect on the end result compared to these parameters.

Figure 12-5 to Figure 12-9 present the sensitivities for case 1. As shown in these results, the "α" (fraction of fires that do not have an incipient stage) results in the largest change in the estimated probability of non-suppression. The next sensitive parameter is "τ" (system effectiveness), followed by "ξ" (human error probability), and lately "β" (system reliability/availability).

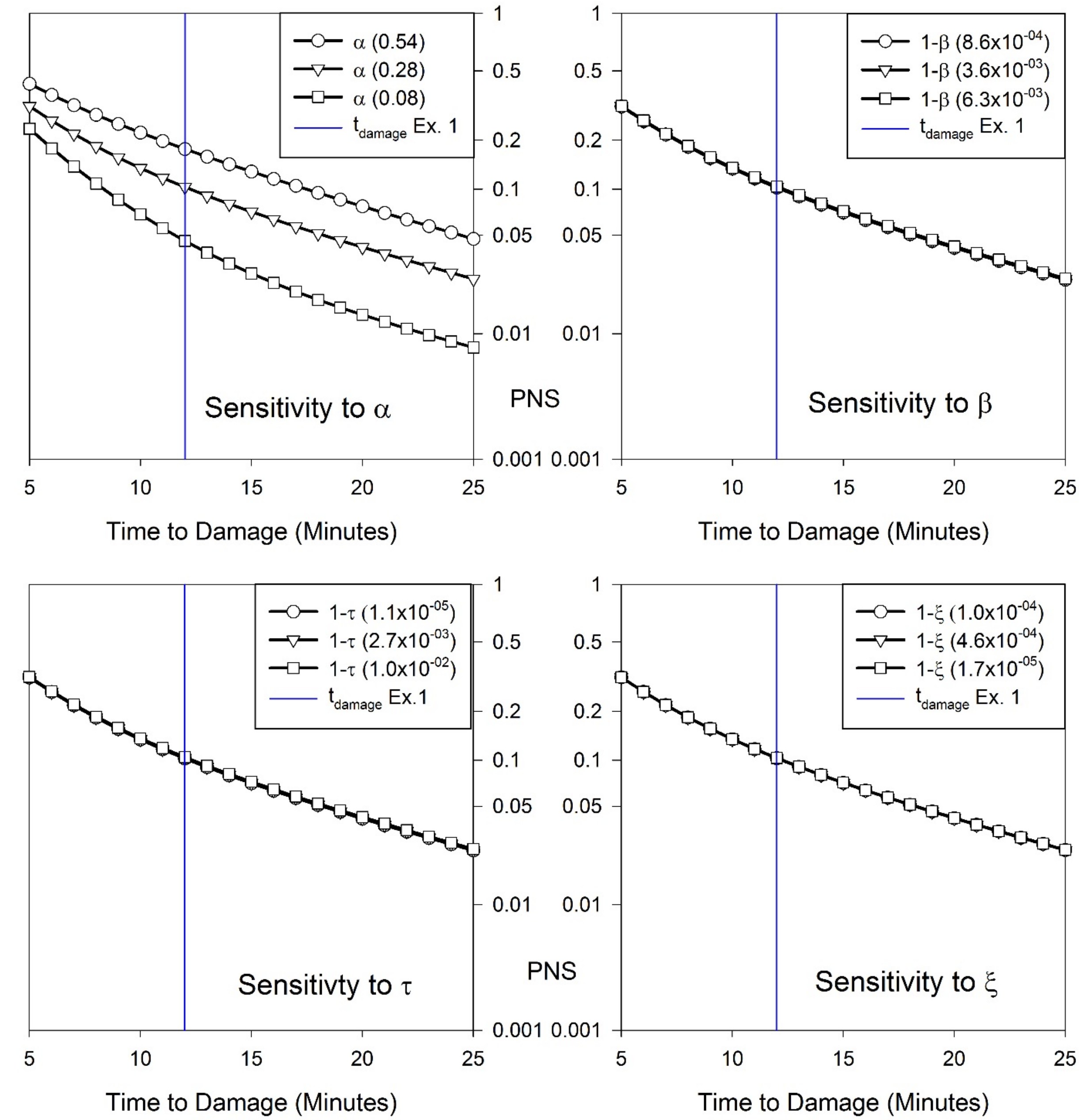

Figure 12-5. Probability plots for sensitivity of Cloud Chamber ASD VEWFD System (Case 1)

Case 1 – Cloud Chamber ASD VEWFD System

Parameter	Mean	Lower (5th)	Upper (95th)
α	0.28	0.08	0.54
β	3.6×10^{-3}	8.6×10^{-04}	6.3×10^{-03}
τ	2.7×10^{-3}	1.1×10^{-05}	1.0×10^{-02}
ξ	4.6×10^{-04}	1.7×10^{-05}	1.7×10^{-03}

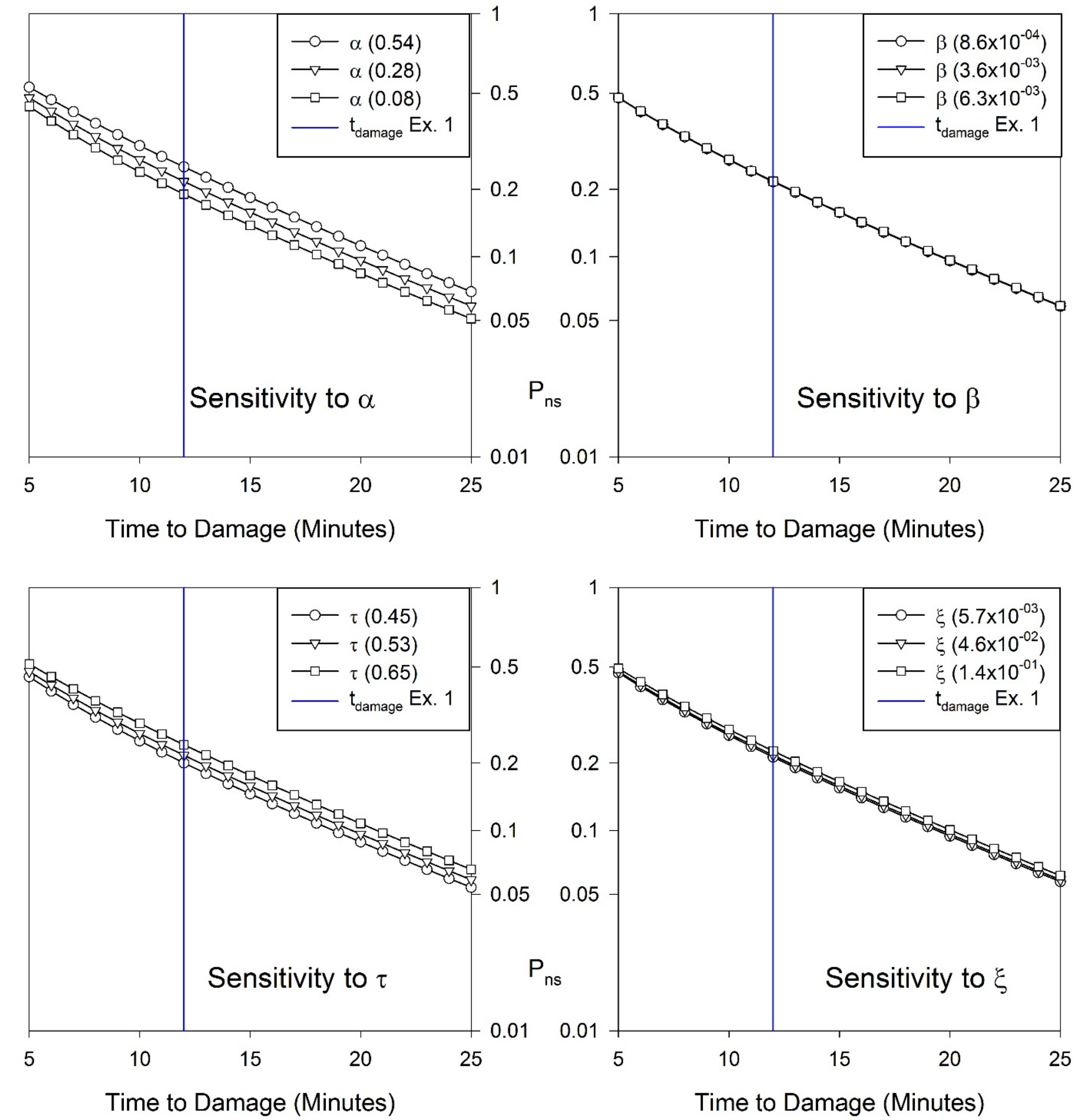

Figure 12-6. Probability plots for sensitivity of Light Scattering (LS1) ASD VEWFD System (Case 1)

Case 1 – Light Scattering 1 ASD VEWFD System

Parameter	Mean	Lower (5th)	Upper (95th)
α	0.28	0.08	0.54
β	3.6×10^{-03}	8.6×10^{-04}	6.3×10^{-03}
τ	0.53	0.45	0.65
ξ	4.6×10^{-02}	5.7×10^{-03}	1.4×10^{-01}

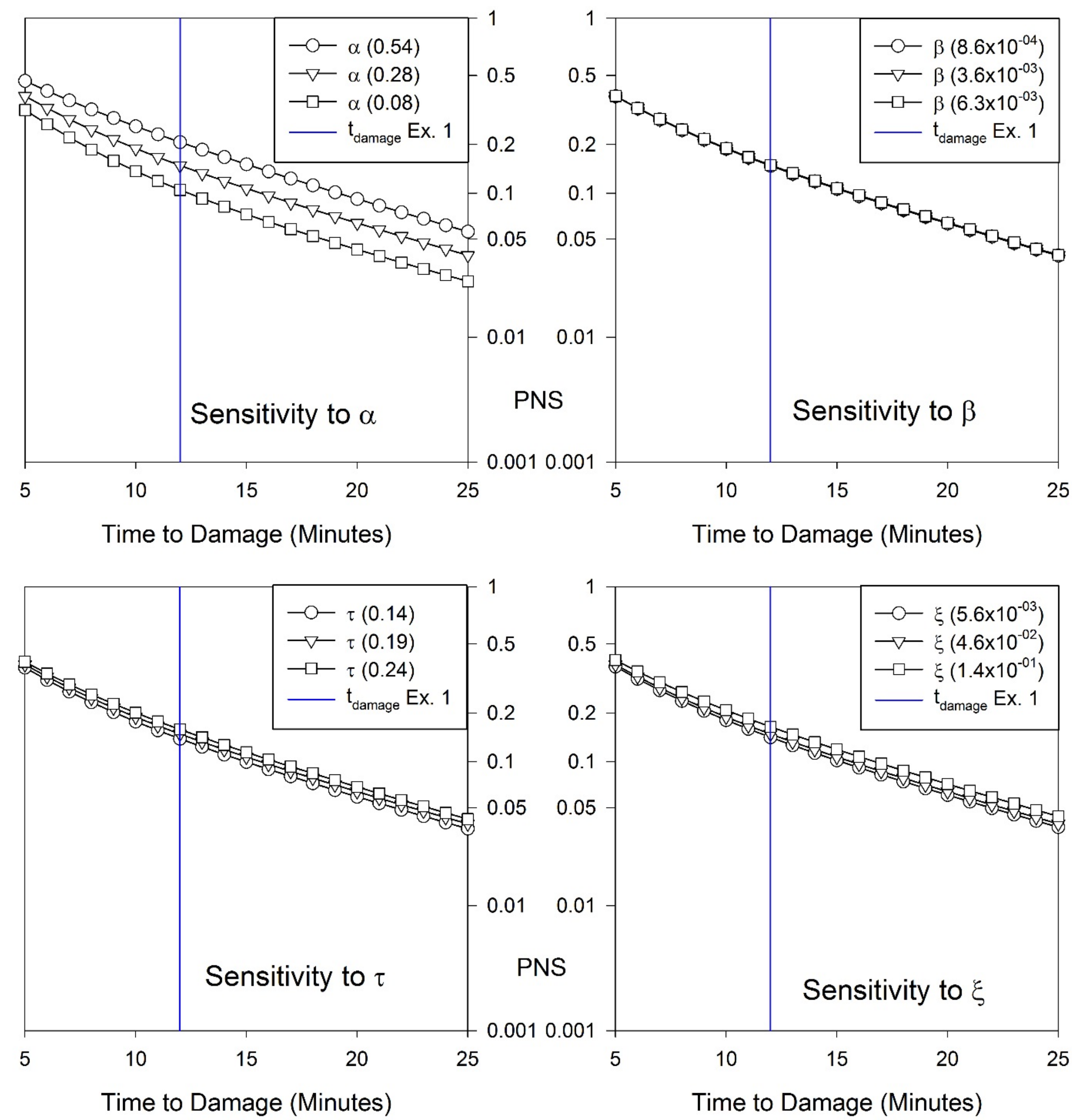

Figure 12-7. Probability plots for sensitivity of Light Scattering (LS2) ASD VEWFD System (Case 1)

Case 1 – Light Scattering 2 ASD VEWFD System

Parameter	Mean	Lower (5th)	Upper (95th)
α	0.28	0.08	0.54
β	3.6×10-03	8.6×10-04	6.3×10-03
τ	0.19	0.14	0.24
ξ	4.6×10-02	5.7×10-03	1.4×10-01

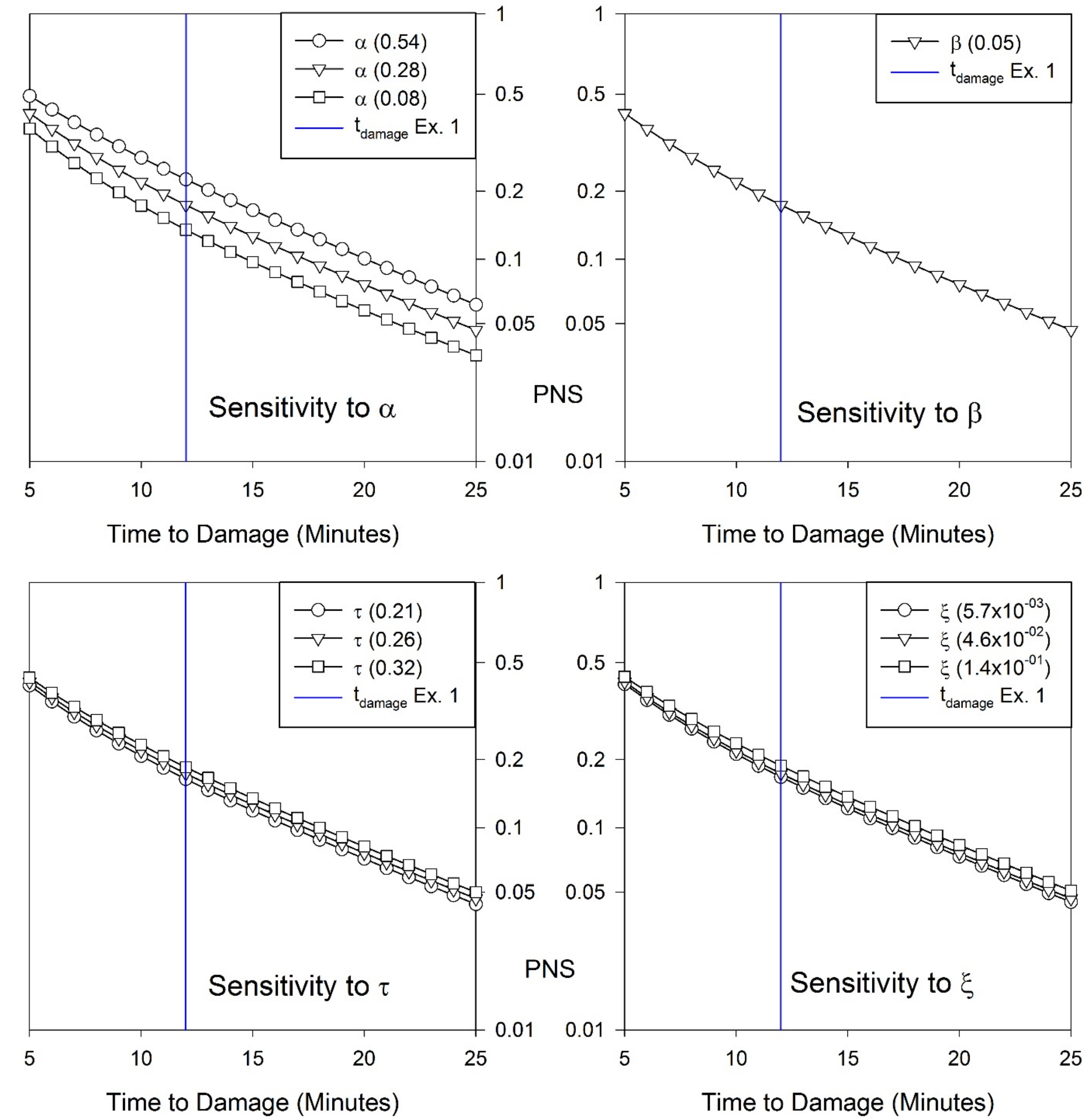

Figure 12-8. Probability plots for sensitivity of Sensitive Spot-type (SS) VEWFD System (Case 1)

Case 1 – Sensitive Spot-type (SS) VEWFD System

Parameter	Mean	Lower (5th)	Upper (95th)
α	0.28	0.08	0.54
τ	0.26	0.21	0.32
ξ	4.6×10^{-02}	5.7×10^{-03}	1.4×10^{-01}

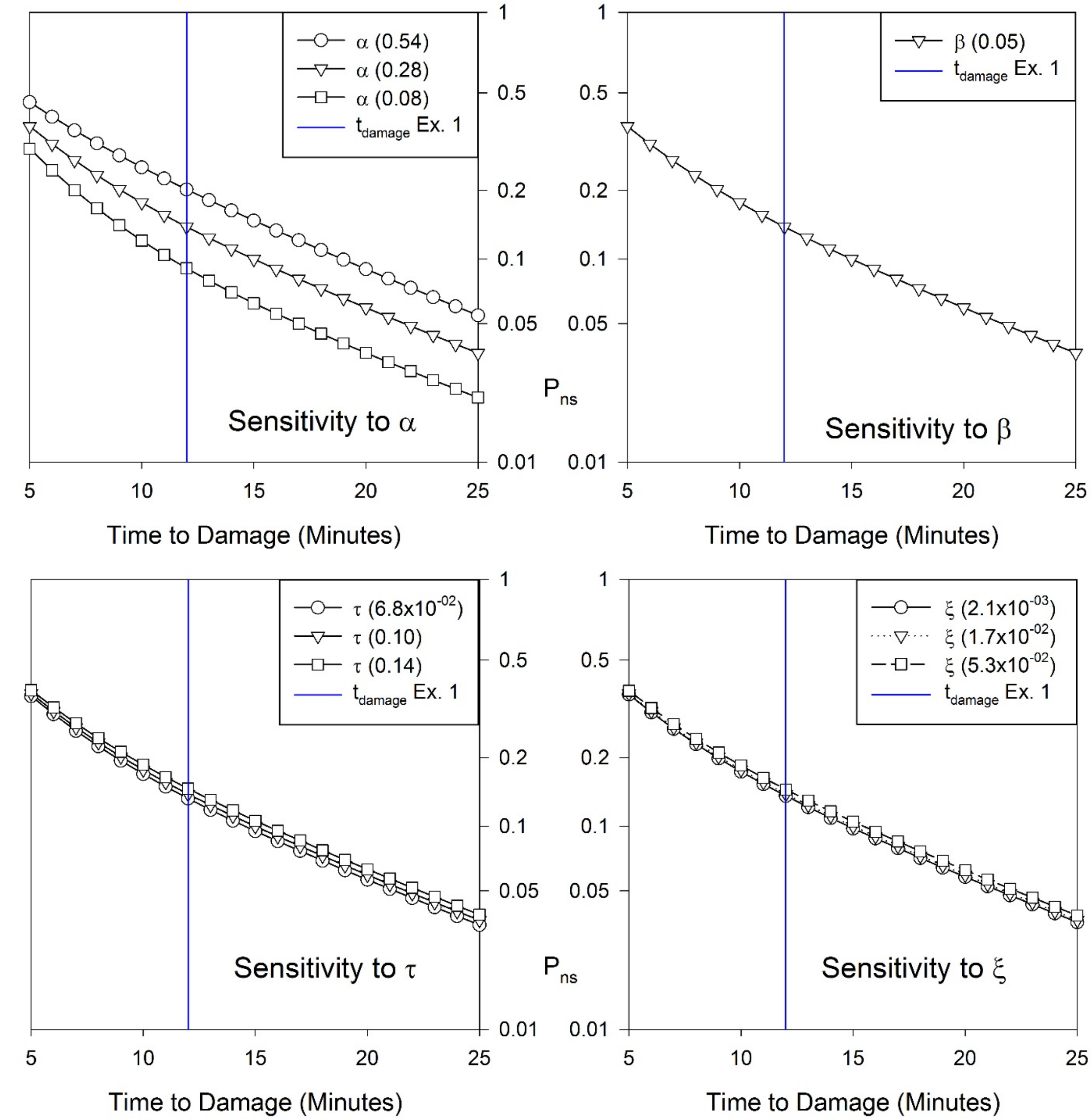

Figure 12-9. Probability plots for sensitivity of Ionization (ION) Spot-Type Addressable system (Case 1)

Case 1 – Ionization (ION) Spot-Type

Parameter	Mean	Lower (5th)	Upper (95th)
α	0.28	0.08	0.54
τ	0.10	6.8×10^{-02}	0.14
ξ	1.7×10^{-02}	2.1×10^{-03}	5.3×10^{-02}

12.3 Use of Plant Specific or Generic Data

The analyses provided in this report use a variety of data and other information sources, as well as calculated inputs. Although this analysis is not intended to represent a specific NPP, PRA conventions and the ASME/ANS PRA Standard (Ref. 60) have been followed to the extent possible. Specific NPPs that perform their own analyses will need to make different choices to satisfy, for example, the PRA Standard.

12.3.1 Use of Plant-Specific Data

Parameters used in this analysis that should be informed using plant-specific information include:

(1) Detector system availability and reliability (β) (Section 7.2)
(2) Time required for operator response (Section 10.4)
(3) MCR operator response (μ) (Section 10.6)
(4) Field operator/technician response (ξ) (Section 10.6)

In addition, the quantification tool (discussed in Section 6.4, Appendix H and provided in the companion CD to this report), fire scenario specific parameters should be included:

1. time to target damage
2. redundant automatic fire detection system parameters, if applicable
    - time to detection
    - type of system
    - failure probability
3. independent automatic fire suppression system[1] parameters, if applicable
    - type of system
    - failure probability
    - dependency on redundant automatic fire detection system
4. manual fixed fire suppression failure probability, if applicable.

12.3.2 Use of Generic Data

The PRA Standard (e.g., initiating events and data analysis Supporting Requirements in Part 2, fire ignition frequency in Part 4) identifies certain situations in which generic data is the appropriate data choice. In particular, the Standard states that generic data is appropriate when very limited data is available on an industry-wide basis, as is the case for components within electrical cabinets having an incipient phase. Also, the Standard states that the collection of plant-specific data and calculation of plant-specific parameters should be, for example:

- accomplished in a consistent manner with respect to design, operational practices, and experience
- based on a clear definition for the parameter

[1] To credit an automatic fire suppression system, an analysis should show than the suppression system is capable of suppressing the fire prior to target damage.

- have a clear basis for identifying failures (versus degraded states)

Although this report used ground rules for consistent review of operational experience, it is recommended that further work on establishing appropriate practices for identifying and using operating experience for evaluating certain parameters used in this analysis.

For the reasons outlined above, generic data should be used for the following parameters used in this analysis:

(1) Fraction of components that have an incipient phase (α) (Section 7.1)
(2) Effectiveness (τ) (Section 7.2)
(3) Time available (Sections 8 and 10.4)
(4) Non-suppression probabilities (enhanced – π, conventional – η)

Until or unless future analyses of generic data are performed, it is recommended that the generic values provided in this report be used as the generic data inputs.

13. ASSUMPTIONS AND LIMITATIONS

The risk scoping study described in Part II of this report is based on numerous assumptions and limitations. For the approach presented to provide meaningful results, the following assumptions and limitations apply:

1. System is designed and installed by trained and qualified technicians following appropriate vendor guidance. System should pass the vendor's acceptance test(s), including any extended period of commissioning prior to being placed in service. Any deviations between as-built and as-designed are evaluated for effects on system performance.

2. Systems are inspected, tested and maintained per applicable national consensus standards (e.g., NFPA 72 and 76) and vendor requirements.

3. Functionality testing via detector alarm response to smoke stimulus should be conducted following guidance in Annex B "Performance Test Procedures for Very Early Warning and Early Warning Fire Detection Systems," of NFPA 76 or vendor equivalent methods. Functionality testing supports confirmation that transport times are met and verifies air flow through each sampling port credited for protection.

   Note that the performance test method presented in Annex B of NFPA 76 or vendor equivalent methods (such as overheated polymeric material) used to test system response and transport times are not equivalent to a calibration (sensitivity) test, such as the "sensitivity test" outlined in UL 268, "Smoke Detectors for Fire Alarm Systems."

4. For in-cabinet application, the cabinet characteristics must allow for the application of aspirated VEWFD systems, such that the cabinet is <u>not tightly sealed</u>. For area-wide applications, the cabinet(s) being protected <u>must have openings</u> (vents, grates, etc.) to allow products of combustion to exit the cabinet and migrate to the VEWFD system sampling ports.

5. The parameter estimates used to support the risk scoping study assume the sensitivity settings of the VEWFD system is setup to meet or exceed (be more sensitive than) the following

   <u>Light-scattering [NFPA 76 requirements]</u>

   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.

   <u>Cloud Chamber</u>

   An *alert* is set to 1.0×10^6 particles/cm^3 at the sampling point. [Note NFPA 76 does not specify a particles/cm^3, this set point is based on the set points commonly used in the testing conducted as part of this report. This

recommended value does not imply that it is equivalent to the NFPA 76 requirements.]

Because the sensitivity directly affects the detector performance, using sensitivities other than those specified here requires justification and adjustments to several risk scoping study parameter estimates (i.e., τ, and ξ). A description of the general process to estimate these parameters, consistent with this report, is presented in Appendix B.4.

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 2.1 %/ft obscuration

7. The VEWFD system *alert* corresponds to the main control room operator, field operator, and technician response; and a VEWFD *alarm* corresponds to an expeditious fire brigade response as described in Section 10. Requirements described in Section 10 for timely response of all relevant personnel include:

   a. MCR operator response requirements (regarding procedures, training, alert/alarm design, monitoring, etc).
   b. Field operator response requirements (regarding procedures, fire watch responsibilities, available equipment, acceptable training, etc.)
   c. Technician response requirements (especially regarding the responsibility to obtain keys for locked cabinets, allowing a quicker arrival time for the field operator; also training, equipment availability, etc. to allow identification of affected cabinet and degraded component)
   d. 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.
   e. Time available for all responses is discussed in Sections 8 and 10 for the detector types addressed in this report. Time required for responses should be developed using plant specific information.

8. The approach presented is not applicable to main control room applications or other spaces that are continuously occupied. Human subject testing was not performed to assess the performance of human senses to the response of smoke detection systems tested in this project.

9. Compensatory measures are put in place whenever the VEWFD or conventional spot-type smoke detection system is unavailable.

10. Effective methods should be established for locating the source of the systems response.

a. Plant personnel responding to VEWFD or conventional spot-type systems are properly trained to respond to incipient conditions, identify the faulted cabinet, and suppress potential fires.

b. Personnel using portable equipment to locate incipient degradation must be trained in its use, including on-the-job training such that they are familiar with the equipment, procedures for its use and any limitations and/or precautions required.

c. Any portable devices used to locate the degrading component should be dedicated for use, maintained in an operable condition, available on site at all times and appropriately staged to be rapidly accessed when need.

11. The use of ASD VEWFD or conventional spot-type systems as a risk reduction measure 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 and does not eliminate the requirement to maintain defense-in-depth.

12. Area-wide HEP's are set to fail ('ξ' = 1.0). The risk scoping study does not include timing feasibility considerations for area-wide application, as discussed in Section 10.5.6. An area-wide HEP other than 1.0 could be used if a feasibility and timing study were conducted for the specific fire scenario, following the same process described in Section 10.

13. The generic unreliability and unavailability estimates presented in Section 7.2 are based on several data sets that include cloud chamber and laser based aspirated systems. If other technologies are used, the applicability of these generic estimates should be evaluated. If site (or fleet) specific unavailability or unreliability estimates are used, a basis for their use should be justified.

14. Application of the risk scoping study for 'low voltage electrical cabinets' ("alpha" term point estimate of 0.72) requires that the maximum voltage level within the cabinet be 250 volts or less. Electrical cabinets that contain any electrical components above this 250 volt threshold should be considered "power cabinets."

15. The probability of non-suppression estimates developed from the approach presented in Part II of this report is only applicable to target damage sets located outside of the electrical enclosure. That is, the VEWFD system ONLY impacts the adverse consequences related to cabinet fires resulting in fire growth outside the initiating electrical enclosure which could damage secondary combustibles and targets. For implementation guidance see Section 6.1.1.

PART III

Conclusions and Perspectives

Definitions and References

14. 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 area-wide ceiling level detection. Area-wide applications using an air return grill and those using ceiling-mounted air sampling port locations perform similarly. However, as ceiling height increases, ceiling area-wide 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 particle size for the materials tests.

In area-wide 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, for the typical NPP configuration.

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 'alert' 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 HEPs vary but combined with the suppression analysis, conclude that the trained human response is likely to succeed.

Review of operating experience, vendor supplied information, and literature has been used to estimate generic unreliability estimates of 1.6×10^{-3} per detector unit per year. This is lower than the generic estimate provided in EPRI 1016735, "Fire PRA Methods Enhancements: Additions, Clarification, and Refinements to EPRI 1019189." However, ASD system unavailability differs from that report in the EPRI document, and is estimated at 2.0×10^{-3} per detector unit per year, based on an average annual system down-time from plants where information was available. A wide variance of system downtime was observed from site visits and literature. It was noted that system unavailability improved for facilities that had these systems installed and operating for a number of years. Facilities which were using ASD systems for the first time indicated longer system downtime, likely because of the lack of understanding of the system maintenance requirements to ensure proper operation. A plant specific (or fleet specific) unavailability estimate could be used instead of this generic estimate, if sufficient data is available to support such an estimate. For area-wide air return grill applications, the unreliability/unavailability of the ventilation system should also be modeled, since the air return grill application requires forced ventilation to perform as designed.

The experimental testing program has confirmed that cabinet design, fill/obstructions and ventilation effects can influence the performance of VEWFD systems. Forced cabinet ventilation is a primary influence factor on detector response, especially with high rates of cabinet air exchange. As cabinet ventilation rates increase, so does smoke dilution. For the forced-ventilation rates used in this project's tests, the ASDs were slower to respond in force-ventilated (high air exchange rate) cabinets than naturally ventilated cabinets. In addition the ASDs were less effective in reaching an "alert" threshold in force-ventilated cabinet (high air exchange rate) tests.

For in-cabinet applications, the presence of openings or lack of partitions between adjacent cabinet sections having ASD sampling ports enhances the time to detection; this is because of the cumulative effect of drawing samples from multiple sampling ports. For this effect to be beneficial openings between cabinets would have to be sufficient in size to allow for the air space communication between cabinet vertical sections.

Smoke source location also has an effect on VEWFD response. The closer the source is to the detector or sampling point, the more rapid the response. In the full-scale small room tests where the source was elevated approximately two-thirds of the height of the cabinet off the cabinet base; the ASDs responded approximately 9 percent faster than when the sources were located on the base.

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

An evaluation of the non-suppression probability shows that the use of these systems can reduce plant risk from the consequences of electrical cabinet fires. It has been shown that a dominant contributor to the risk model is the estimation of the fraction of *potentially challenging*

or greater fires which exhibit an incipient fire stage of sufficient duration to allow for operator response. Since fire PRAs only quantify those fires that initiate and can potentially grow to a damaging state, the majority of smoking events are not modeled (included as a fire initiator). The previous methods (EPRI 1011989 and FAQ 08-0046) used to estimate this characteristic could not be confirmed based on the evaluation of the operating experience.

The risk benefit for using these systems varies by application with in-cabinet detection being the most effective approach for detecting low-energy incipient sources early enough to allow for suppressing before target damage to multiple components within or outside the electrical cabinet. Area-wide applications also provide some risk benefit; however, they are usually slower to detect low energy fires because of a number of previously discussed contributing factors.

14.1 Conclusions

This confirmatory research program has shown that the performance of smoke detection to detect low-energy pre-flaming conditions varies by detection technology, application, and aerosol characteristics (dependent on material degradation characteristics).

For in-cabinet applications, the ASD cloud chamber VEWFD and ION spot-type detection systems performed better than all light-scattering based technologies (three of the five ASD VEWFD systems, sensitive spot VEWFD and PHOTO spot-type detector). This conclusion is based on the systems response (ability to detect and mean time to detection) to the materials and methods used in testing.

In area-wide applications, the ASD systems outperformed the conventional spot-type detectors (ION, PHOTO) for detecting low energy fire sources. This program has also confirmed that the earliest and most effective method of detecting low energy fires is when the detector or sampling port is located within the NPP electrical enclosure being protected.

This research has also provided a refined approach to quantify the performance of smoke detection systems that could be used in fire PRA applications to estimate the non-suppression probability. This refined approach uses operating experience, literature, test results, human reliability methods, and the exponential suppression model to characterize the systems performance. The approach relies more heavily on timing based information to characterize the performance of the systems tested. Because of the uncertainty associated with characterizing the duration and aerosol generation of the incipient stage for equipment commonly found in nuclear power plant electrical enclosures, there are several parameters and assumptions that could enhance the overall risk characterization. Most notably, the refined approach is sensitive to the characterization of *Potentially Challenging or Greater Fires*[1] which exhibit an incipient stage with a short duration incipient stage.

All methods currently available use some form of assumptions and limitations to bound the evaluation. Validation of these assumptions and limitations could be better understood by industry support to facilitate collecting operating experience directly related to the performance of these ASD VEWFD systems in NPP applications or within other industries with similar components and equipment. Information such as nuisance alarm rate, scheduled and

1 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."

unscheduled system down time, total number of operating detectors and years of operation for each system would be useful in evaluating ASD performance. In addition, consistent and detailed reporting of instances where potential fires were caught in an incipient stage, how long it took operators from time of VEWFD system alert to de-energize the equipment, instances where flaming fires occurred and the associated time to suppress those fires that did occur would help support any future risk quantification effort. The number and frequency of nuisance alarms and the total number of detectors and ignition sources protected would also be useful. Complete and consistent reporting could be coordinated by a nuclear industry users group. General information on lessons learned from the use of these systems in NPPs could be communicated via industry forums to benefit the use of these systems such that an understanding of the performance of these systems could be achieved.

15. 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.

The human error probability (HEP) estimates were based on an estimate of time available for operator response developed from a limited number of fire events in which sufficient information was available to quantify this duration; as such, this estimate carries some 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 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. Although this process may provide additional insights and knowledge to support an alternative approach to quantifying the incipient stage duration, the outcome of such effort cannot be predicted at this time, nor would it be simple to complete. In addition, the sensitivity study presented in section 12.2 of this report indicates that the overall quantification is insensitive to this parameter based on the HRA assumptions that model current practices with regard to human response to these types of events. While the performance of such an effort could potentially provide additional insights, the impact to the quantification approach presented in this report would be minimal.

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 use of this technology and quality of records, operating experience gained over a period of 5 or 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 user group associated with the nuclear industry support a comprehensive and consistent operating experience 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. Appendix G of this report provides a list of questions that may be helpful in collecting operating experience associated with VEWFD systems performance.

The testing program was limited by the availability of electrical enclosures to test. As such, the applicability of the test results for cabinets with louvered doors and/or back panels has not been determined. Additional data on cabinet ventilation configurations and a more rigorous evaluation of the effects of varying mechanical ventilation rates, would help support an evaluation of the performance of these systems.

As mentioned in the experimental approach section, an issue was identified concerning sensitivity settings for the cloud chamber ASDs, which was not fully resolved. These ASDs do not report detector sensitivity in terms of U.S. detection industry standard engineering units of percentage of obscuration per foot, but in terms of numeric (dimensionless) settings. Although the authors are not implying that the cloud chamber technology is deficient, guidance to support the selection of set points to achieve the NFPA 76 sensitivity settings would be beneficial.

This report focused exclusively on the fire hazards associated with electrical enclosure fires. Other types of equipment found in NPPs such as pumps, motors, air handling units, transient combustibles, among others can exhibit an incipient stage and ASD VEWFD systems may provide enhanced warning and a risk reduction. An evaluation similar to what was done in this report would be beneficial. Follow-on work could catalog the types of smoke sources and materials found in NPPs that contribute to the *potentially challenging or greater fires* characterized by fire PRA.

16. 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]

Addressable Device – A fire alarm system component with discrete identification that can have its status individually identified or that is used to individually control other functions. [2]

Alarm condition – An abnormal condition that poses an immediate threat to life, property, or mission.[2]

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.[1]

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]

Enhanced fire suppression – as used in this report, refers to providing fire suppression capability earlier than typical conventional systems allow. With respect to operator response to very early warning fire detection systems, this implies arriving at the location of a potential fire threat with suppression capability before that threat transitioning to a flaming condition. This differs from prompt detection, as used in fire PRA suppression-detection analysis.

Pre-alarm condition – An abnormal condition that poses a potential threat to life, property, or mission, and time is available for investigation.[2]

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.[1]

Response time – The time between the generation of combustion aerosols at their source and the indication of their presences at the ASD. [4]

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.[5]

Sensitivity measurement – A quantitative measurement and recording of the stimulus necessary to achieve an alarm signal from an initiating device. A sensitivity measurement determines how large a stimulus is necessary to cause an alarm response. This measurement is to be compared to the value for the unit as shipped [as designed] to quantify any change in the performance one can anticipate from the unit. Thus, the sensitivity measurement is intended to assess the ability of the detector to perform its intended function when the design fire occurs. A sensitivity measurement differs from a test in that a test does not imply that the stimulus is of a similar magnitude to that obtained from the design fire.[1]

Smoke – The airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise missed into the mass.[1]

Smoke dilution – A reduction in the quantity of smoke per unit of air volume of smoke reaching the detector.[2]

Smoldering combustion – A slow, low-temperature, flameless form of combustion, sustained by the heat evolved when oxygen directly attacks the surface of a condensed-phase fuel.[6]

Spot-type smoke detector – A device whose detecting element is concentrated at a particular location.[5]

Standard fire detection systems (SFDS) – Systems that use fire detection-initiating devices to achieve certain life-safety and property protection in accordance with applicable standards.[3]

Stratification – The phenomena whereby the upward movement of smoke and gases ceases because of loss of buoyancy.[2]

Very early warning fire detection systems (VEWFD systems) – Systems that detect low-energy fires before the fire conditions threaten telecommunications service.[3]

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APPENDIX A
VIEWGRAPHS FROM MEETING WITH ASD VENDORS

A.1 Summary of Meeting

On May 16, 2013, the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research conducted a meeting between the three aspirating smoke detection (ASD) vendors whose equipment was tested. Staff from NRC, National Institute of Standards and Technology (NIST), and at least one technical representative from each ASD vendor were present. The purpose of this meeting was to inform the vendors of how their systems were being setup and tested, present how their systems may be used in fire probabilistic risk assessment applications, and to elicit feedback from the vendors on specific engineering design guidance regarding ASD systems for nuclear power plant applications. Additionally, discussion on equipment listings and approvals occurred. The morning portion of the meeting consisted of presentations given by NRC and NIST staff; these presentations are located in the NRC Agencywide Document Access and Management System (ADAMS), under Accession No. ML14356A581. The afternoon portion of the meeting consisted of open discussions among all participants.

APPENDIX B
SUPPORTING EXPERIMENTAL DATA

B.1 Alarm Times and Experimental Conditions and Sample images

A file naming convention was followed to distinguish the various experiments, data files, and image files. Table B-1 describes the naming convention.

Table B-1. File name convention

A_XLPE_5_E_2.1					
Alarm configuration	Material	Cabinet configuration	Test conditions	Heating Rate	Test repeat #
C: In-Cabinet A: Area-wide M: Multi-zone	PVC1: PVC wire (1) PVC2: PVC wire (2) Teflon: PTFE wire Silicone: Silicone wire XLPO1: XLPO wire (1) XLPO2: XLPO wire (2) XLPE: XLPE wire CSPE: CSPE wire PCB: Epoxy Printed Circuit Board PTB: Phenolic Terminal block 1XLPE : Single XLPE wire 1wire: Single wire test 2wire: Dual wire test #Resistor: # of resistors Capacitor: 2 Capacitors	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)	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	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.	

B.1.1 Raw Data File Header Descriptions

The following text describes the column header for the (raw) experimental data files for each set of experiments conducted:

Alarm Time Files—Laboratory Instrument and Large Cabinet Experiments

Time - CPU time (Hour : Minute : Seconds)
Count - Loop time increment (s)
ASD1 C Alarm - ASD 1 system C Alarm relay (0 : OFF, 1 : ON)
ASD1 Alarm - ASD 1 system Alarm relay (0 : OFF, 1 : ON)
ASD1 I2 - ASD 1 system I2 alarm relay (0 : OFF, 1 : ON)
ASD1 Alert - ASD 1 system Alert alarm relay (0 : OFF, 1 : ON)
ASD1 Pre-alert - ASD 1 system Pre-alert relay (0 : OFF, 1 : ON)
ASD1 Fault - ASD1 system Fault relay (0 : OFF, 1 : ON)
ASD2 Alarm- ASD 2 system Alarm relay (0 : OFF, 1 : ON)
ASD2 Alert- ASD 2 system Alert relay (0 : OFF, 1 : ON)
ASD2 I1- ASD 2 system I1 alarm relay (0 : OFF, 1 : ON)
ASD2 Pre-alert - ASD 2 system Pre-alert relay (0 : OFF, 1 : ON)
ASD2 Fault- ASD 2 system Fault relay (0 : OFF, 1 : ON)
ASD3 Alarm- ASD 3 system Alarm relay (0 : OFF, 1 : ON)
ASD3 Alert - ASD 3 system Alert relay (0 : OFF, 1 : ON)
ASD3 Fault/Pre-alert - ASD 3 system Fault/Pre-alert relay (0 : OFF, 1 : ON)
FACP Alarm - Fire alarm control panel Alarm relay (0 : OFF, 1 : ON)
FACP Trouble - Fire alarm control panel Trouble relay (0 : OFF, 1 : ON)
PHOTO (1) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located outside the instrument cabinet .
PHOTO (1) C Alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located outside the instrument cabinet.
PHOTO (2) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument cabinet.
PHOTO (2) C Alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument cabinet.
SS (3) Pre-alert -SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument cabinet.
SS (3) Pre-alert-SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument cabinet.
ION (4) Alarm -ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument cabinet.
ION (4) C Alarm -ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument cabinet.
Temperature at Humidity Probe (oC) – The temperature (^{o}C) at the location of the humidity probe inside the instrument cabinet.
Relative humidity (%)– Relative humidity (%) inside the instrument cabinet.
Temperature, Top cabinet (^{o}C) – Temperature (^{o}C) measurement, at the base of the Instrument cabinet.
Temperature, Bottom cabinet (^{o}C) - Temperature (^{o}C) measurement , at the ceiling of the Instrument cabinet.

Alarm Time Files – Small Room In-cabinet Experiments

Time - CPU time (Hour : Minute : Seconds)
Count - Loop time increment (s)
ASD1 C Alarm - ASD 1 system C Alarm relay (0 : OFF, 1 : ON)
ASD1 Alarm - ASD 1 system Alarm relay (0 : OFF, 1 : ON)
ASD1 I2 - ASD 1 system I2 alarm relay (0 : OFF, 1 : ON)
ASD1 Alert - ASD 1 system Alert alarm relay (0 : OFF, 1 : ON)
ASD1 Pre-alert - ASD 1 system Pre-alert relay (0 : OFF, 1 : ON)
ASD1 Fault - ASD1 system Fault relay (0 : OFF, 1 : ON)
ASD2 Alarm- ASD 2 system Alarm relay (0 : OFF, 1 : ON)
ASD2 Alert- ASD 2 system Alert relay (0 : OFF, 1 : ON)
ASD2 I1- ASD 2 system I1 alarm relay (0 : OFF, 1 : ON)
ASD2 Pre-alert - ASD 2 system Pre-alert relay (0 : OFF, 1 : ON)
ASD2 Fault- ASD 2 system Fault relay (0 : OFF, 1 : ON)
ASD3 Alarm- ASD 3 system Alarm relay (0 : OFF, 1 : ON)
ASD3 Alert - ASD 3 system Alert relay (0 : OFF, 1 : ON)
ASD3 Fault/Pre-alert - ASD 3 system Fault/Pre-alert relay (0 : OFF, 1 : ON)
FACP Alarm - Fire alarm control panel Alarm relay (0 : OFF, 1 : ON)
FACP Trouble - Fire alarm control panel Trouble relay (0 : OFF, 1 : ON)
PHOTO (1) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the single cabinet.
PHOTO (1) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the single cabinet.
ION (2) Pre-alarm - ION spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the single cabinet.
ION (2) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON)) Located inside the single cabinet.
SS (3) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the single cabinet.
SS (3) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located inside the single cabinet.
PHOTO (4) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the four- cabinet configuration.
PHOTO (4) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.
ION (5) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.
ION (5) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.
SS (6) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.
SS (6) Alarm- SS spot detector alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.
ION (7) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.
ION (7) C Alarm - ION spot detector alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.
PHOTO (8) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.
PHOTO (8) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.
SS (9) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.

SS (9) Alarm - SS spot detector alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.

ION (10) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

ION (10) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (11) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (11) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (12) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (12) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

ION (13) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

ION (13) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (14) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (14) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (15) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (15) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (16) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (16) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

ION (17) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

ION (17) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (18) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (18) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

Temperature at Humidity Probe (oC)– The temperature (^{o}C) at the location of the humidity probe inside the instrument cabinet.

Relative humidity (%) – Relative humidity (%) inside the test room.

Alarm Time Files – Small Room Area-wide Experiments

Time - CPU time (Hour : Minute : Seconds)
Count - Loop time increment (s)
ASD1 C Alarm - ASD 1 system C Alarm relay (0 : OFF, 1 : ON)
ASD1 Alarm - ASD 1 system Alarm relay (0 : OFF, 1 : ON)
ASD1 I2 - ASD 1 system I2 alarm relay (0 : OFF, 1 : ON)
ASD1 Alert - ASD 1 system Alert alarm relay (0 : OFF, 1 : ON)
ASD1 Pre-alert - ASD 1 system Pre-alert relay (0 : OFF, 1 : ON)
ASD1 Fault - ASD1 system Fault relay (0 : OFF, 1 : ON)
ASD2 Alarm- ASD 2 system Alarm relay (0 : OFF, 1 : ON)
ASD2 Alert- ASD 2 system Alert relay (0 : OFF, 1 : ON)
ASD2 I1- ASD 2 system I1 alarm relay (0 : OFF, 1 : ON)
ASD2 Pre-alert - ASD 2 system Pre-alert relay (0 : OFF, 1 : ON)
ASD2 Fault- ASD 2 system Fault relay (0 : OFF, 1 : ON)
ASD3 Alarm- ASD 3 system Alarm relay (0 : OFF, 1 : ON)
ASD3 Alert - ASD 3 system Alert relay (0 : OFF, 1 : ON)
ASD3 Fault/Pre-alert - ASD 3 system Fault/Pre-alert relay (0 : OFF, 1 : ON)
FACP Alarm - Fire alarm control panel Alarm relay (0 : OFF, 1 : ON)
FACP Trouble - Fire alarm control panel Trouble relay (0 : OFF, 1 : ON)
PHOTO (1) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
PHOTO (1) C Alarm - PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
ION (2) Alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
ION (2) C Alarm - ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
SS (3) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
SS (3) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
PHOTO (4) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
PHOTO (4) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
ION (5) Pre-alarm - ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
ION (5) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON Located on the ceiling.
SS (6) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON Located on the ceiling.
SS (6) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
ION (7) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
ION (7) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
PHOTO (8) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
PHOTO (8) C Alarm - PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
SS (9) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
SS (9) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
ION (10) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
ION (10) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
SS (11) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
SS (11) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
PHOTO (12) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (12) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
ION (13) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
ION (13) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
PHOTO (14) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
PHOTO (14) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
SS (15) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
SS (15) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
PHOTO (16) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
PHOTO (16) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
ION (17) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
ION (17) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
SS (18) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
SS (18) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
Temperature at Humidity Probe (oC)– The temperature (^{o}C) at the location of the humidity probe inside the instrument cabinet.
Relative humidity (%)– Relative humidity (%) inside the test room.

Alarm Time Files – Large Room Single-zone Experiments

Time - CPU time (Hour : Minute : Seconds)
Count - Loop time increment (s)
ASD1 C Alarm - ASD 1 system C Alarm relay (0 : OFF, 1 : ON)
ASD1 Alarm - ASD 1 system Alarm relay (0 : OFF, 1 : ON)
ASD1 I2 - ASD 1 system I2 alarm relay (0 : OFF, 1 : ON)
ASD1 Alert - ASD 1 system Alert alarm relay (0 : OFF, 1 : ON)
ASD1 Pre-alert - ASD 1 system Pre-alert relay (0 : OFF, 1 : ON)
ASD1 Fault - ASD1 system Fault relay (0 : OFF, 1 : ON)
ASD2 Alarm- ASD 2 system Alarm relay (0 : OFF, 1 : ON)
ASD2 Alert- ASD 2 system Alert relay (0 : OFF, 1 : ON)
ASD2 I1- ASD 2 system I1 alarm relay (0 : OFF, 1 : ON)
ASD2 Pre-alert - ASD 2 system Pre-alert relay (0 : OFF, 1 : ON)
ASD2 Fault- ASD 2 system Fault relay (0 : OFF, 1 : ON)
ASD3 Alarm- ASD 3 system Alarm relay (0 : OFF, 1 : ON)
ASD3 Alert - ASD 3 system Alert relay (0 : OFF, 1 : ON)
ASD3 Fault/Pre-alert - ASD 3 system Fault/Pre-alert relay (0 : OFF, 1 : ON)
FACP Alarm - Fire alarm control panel Alarm relay (0 : OFF, 1 : ON)
FACP Trouble - Fire alarm control panel Trouble relay (0 : OFF, 1 : ON)
SS (1) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
SS (1) Alarm - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
ION (2) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
ION (2) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
PHOTO (3) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
PHOTO (3) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
ION (4) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
ION (4) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
SS (5) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
SS (5) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
PHOTO (6) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
PHOTO (6) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
PHOTO (7) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
PHOTO (7) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.
ION (8) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.

ION (8) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.
SS (9) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.
SS (9) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.
ION (10) Pre-alarm - ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.
ION (10) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.
SS (11) Pre-alert- SS spot detector pre- alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.
SS (11) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.
PHOTO (12) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.
PHOTO (12) C Alarm - PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.
ION (13) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.
ION (13) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.
SS (14) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.
SS (14) Alarm- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.
ION (15) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located in the single-cabinet configuration.
ION (15) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located in the single-cabinet configuration.
SS (16) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.
SS (16) Alarm- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.
Temperature at Humidity Probe (oC) – The temperature (^{o}C) at the location of the humidity probe inside the instrument cabinet.
Relative humidity (%) – Relative humidity (%) inside the test room.
TC1 – Not used

Alarm Time Files – Large Room Multi-zone Experiments

Time - CPU time (Hour : Minute : Seconds)
Count - Loop time increment (s)
ASD4_Zone1_Alarm- ASD 4 system Alarm relay (0 : OFF, 1 : ON), located in zone 1.
ASD4_Zone1_Alert- ASD 4 system Alert relay (0 : OFF, 1 : ON) , located in zone 1.
ASD4_Zone1_I1- ASD 4 system I1 relay (0 : OFF, 1 : ON) , located in zone 1.
ASD4_Zone1_Pre-alert- ASD 4 system Pre-alert relay (0 : OFF, 1 : ON), located in zone 1.
ASD4_Zone2_Alarm- ASD 4 system Alarm relay (0 : OFF, 1 : ON), located in zone 2.
ASD4_Zone2_Alert- ASD 4 system Alarm relay (0 : OFF, 1 : ON) , located in zone 2.
ASD4_Zone2_I1- ASD 4 system I1 relay (0 : OFF, 1 : ON) , located in zone 2.
ASD4_Zone2_Pre-alert- ASD 4 system Pre-alert relay (0 : OFF, 1 : ON) , located in zone 2.

ASD4_Zone3_Alarm- ASD 4 system Fire 3 alarm relay (0 : OFF, 1 : ON), located in zone 3.
ASD4_Zone3_Alert- ASD 4 system Fire 2 alarm relay (0 : OFF, 1 : ON) , located in zone 3.

ASD4_Zone3_I1- ASD 4 system Fire 1 alarm relay (0 : OFF, 1 : ON) , located in zone 3.
ASD4_Zone3_Pre-alert- ASD 4 system Pre-alarm relay (0 : OFF, 1 : ON) , located in zone 3.

ASD4_Zone4_Alarm- Not used
ASD4_Zone4_Alert- Not used
ASD4_Zone4_I1- Not used
ASD4_Zone4_Pre-alert - Not used
ASD4_Fault - ASD 4 system Fault relay (0 : OFF, 1 : ON)
ASD5_Global_Pre-alert- ASD 5 system Alert relay (0 : OFF, 1 : ON), for all 3 zones (global.)

ASD5_Global_Alarm- ASD 5 system Fire 1 alarm relay (0 : OFF, 1 : ON), for all 3 zones (global.)
ASD5_Global_C Alarm- ASD 5 system Fire 2 alarm relay (0 : OFF, 1 : ON), for all 3 zones (global.)
ASD5_Zone2_Pre-alert- ASD 5 system Alert relay (0 : OFF, 1 : ON), located in zone 2.
ASD5_Zone2_Alert- ASD 5 system Action alarm relay (0 : OFF, 1 : ON), located in zone 2.

ASD5_Zone3_Pre-alert- ASD 5 system Alert relay (0 : OFF, 1 : ON), located in zone 3.
ASD5_Zone3_Alert- ASD 5 system Action alarm relay (0 : OFF, 1 : ON), located in zone 2.

ASD5_Zone1_Pre-alert- ASD 5 system Alert relay (0 : OFF, 1 : ON), located in zone 1.
ASD5_Zone1_Alert- ASD 5 system Action alarm relay (0 : OFF, 1 : ON), located in zone 2.

ASD5_Fault- ASD 5 system Fault relay (0 : OFF, 1 : ON)
FACP Alarm - Fire alarm control panel alarm relay (0 : OFF, 1 : ON)
FACP Trouble - Fire alarm control panel trouble relay (0 : OFF, 1 : ON)
SS (1) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
SS (1) Alarm - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
ION (2) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
ION (2) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.

PHOTO (3) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
PHOTO (3) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
ION (4) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
ION (4) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
SS (5) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
SS (5) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
PHOTO (6) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
PHOTO (6) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
PHOTO (7) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
PHOTO (7) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.
ION (8) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.
ION (8) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.
SS (9) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.
SS (9) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.
ION (10) Pre-alarm - ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.
ION (10) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.
SS (11) Pre-alert- SS spot detector pre- alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.
SS (11) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.
PHOTO (12) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.
PHOTO (12) C Alarm - PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.
ION (13) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.
ION (13) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.
SS (14) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.
SS (14) Alarm- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.
ION (15) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located in the single-cabinet configuration.

ION (15) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located in the single-cabinet configuration.
SS (16) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.
SS (16) Alarm- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.
Temperature at Humidity Probe (oC)– The temperature (°C) at the location of the humidity probe inside the instrument cabinet.
Relative humidity (%) – Relative humidity (%) inside the test room.

Bus Bar Heater File (Files ending with _T)

Column 1 - CPU time (Hour : Minute : Seconds)
Column 2 - Counter (s)
Column 3 – Set point temperature (°C)
Column 4 – Actual Bus Bar temperature (°C)

Room Temperature File (Files ending with _RT)

Time - CPU time (Hour : Minute : Seconds)
Count - Loop time increment (s)
TC 1 - Temperature (°C) in the center of the room, 2.54 cm below the ceiling.
TC 2 - Temperature (°C) in the center of the room, 5.08 cm below the ceiling.
TC 3 - Temperature (°C) in the center of the room, 7.62 cm below the ceiling.
TC 4 - Temperature (°C) in the center of the room, 0.31 m below the ceiling.
TC 5 - Temperature (°C) in the center of the room, 0.61 m below the ceiling.
TC 6 - Temperature (°C) in the center of the room, 0.914 m below the ceiling.
TC 7 - Temperature (°C) in the center of the room, 2.13 m below the ceiling.
TC 8 - Ceiling temperature (°C) in the corner of the room.
TC 9 - Ceiling temperature (°C) in the corner of the room.
TC 10 - Ceiling temperature (°C) in the corner of the room.
TC 11 - Ceiling temperature (°C) in the corner of the room.
TC 12 - Room ventilation inlet temperature (°C).
TC 13 - Room ventilation outlet temperature (°C).

Wire Thermocouples (Files ending with _WT)

Time - CPU time (Hour : Minute : Seconds)
Count - Loop time increment (s)
TC 1 (X mm)- Thermocouple #1 located X mm form the bus bar.
TC 2 (X mm)- Thermocouple #2 located X mm form the bus bar.
TC 3(X mm)- Thermocouple #3 located X mm form the bus bar.
TC 4(X mm)- Thermocouple #4 located X mm form the bus bar.

B.1.2 Sample before and after experiment images, and thermal camera image sequences

Before and after sample images use the file naming convention appended with “Before” or “After”. Table B-2 described exemplar image file names for before and after pictures of materials tested. Sequences of thermal images at fixed time intervals are given in folders labeled using the file naming convention appended with “TI”. The name of each thermal image corresponds to the time in minutes at which it was taken. The image analysis software that ships with the thermal imaging camera applies an imaging softening filter to reduce pixilation. These images do not include that filtering process.

Table B-2. 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_A_2.1_TI

		C_PTB_L_B_2.2_After	
	4 hours	N/A	C_PTB_L_B_3.1_TI
Single XLPE wire	1 hour	N/A	C_1XLPE_L_A_2.1_TI

B.1.3 Tabulated Alarm Times

Alarm times, the block temperatures at alarm, and the beginning and end of test air temperatures and in some cases humidity were extracted from the raw data files for each experiment and tabulated in Alarm Time files. The files include individual test file names, test configuration and sample mass loss. Table B-4 lists the experimental series, the report section describing the series, and the spreadsheet file name.

Table B-4. Spreadsheet file names for tabulated alarm times

Experimental Series	Spreadsheet file name
Aerosol exposure experiments - **Section B.2.1**	Instrument cabinet CMAG and Gemini exps
Instrument Cabinet aerosol measurement experiments - **Section B.2.1**	Instrument Cabinet exps - Aerosol moments
Large Cabinet experiments - Variable hold times	Large Cabinet Experiments - Variable hold times
Laboratory small cabinet experiments - **Section 5.1**	Instrument Cabinet Experiments
Laboratory large cabinet experiments - **Section 5.2**	Large Cabinet Experiments - Naturally Ventilated Large Cabinet Experiments - Force Ventilated
Small room, in-cabinet experiments - **Section 5.3**	Small Room In-Cabinet Experiments
Small room, area-wide experiments - **Section 5.6**	Small Room Area-wide Experiments
Large room, single zone, in-cabinet experiments - **Section 5.4**	Large Room Single-zone In-cabinet Experiments
Large room, multi-zone, in-cabinet experiments - **Section 5.5**	Large Room Multi-zone In-cabinet Experiments
Large room, multi-zone, area-wide experiments - **Section 5.7**	Large Room Multi-zone Area-wide Experiments

The ASD VEWFD systems tested allow for three to five setpoints (depending on vendor). The raw data files included with this report contains the data for the setpoints used and recorded in this program. The following information identifies the setpoints used for the different systems and test series. ASD 1, 3, and 5 are light scattering based technologies and the sensitivities are reported in % obscuration per foot. ASD 2 and 4 are cloud chamber based technologies and the sensitivities are reported in particles per cubic centimeter. Sensitivities for the other detectors such as the PHOTO, ION, and SS are reported in the main body of the report. The sensitivities for each of the testing configurations are presented in Tables B-5 to B-10.

Table B-5. Laboratory Scale Small Cabinet Experiments

Setpoint	ASD 1		ASD 2		ASD 3	
	Detector	Port	Detector	Port	Detector	Port
Pre-Alert	0.012	0.048	$5.1\times10^{+5}$	$2.0\times10^{+6}$	0.025	0.100
I1 Alarm	N/A		$8.5\times10^{+5}$	$3.4\times10^{+6}$	N/A	
Alert	0.050	0.200	$1.2\times10^{+6}$	$4.8\times10^{+6}$	0.050	0.200
I2 Alarm	0.100	0.400	N/A		N/A	
Alarm	0.250	1.000	$1.5\times10^{+6}$	$6.0\times10^{+6}$	0.250	1.000
C Alarm	0.500	2.000	N/A		N/A	
# of ports / zone	4		4		4	

Table B-6. Laboratory Scale Large Cabinet Experiments

Setpoint	ASD 2		ASD 3	
	Detector	Port	Detector	Port
Pre-Alert	$3.8\times10^{+4}$	$1.5\times10^{+5}$	0.025	0.100
I1 Alarm	$1.4\times10^{+5}$	$5.5\times10^{+5}$	N/A	
Alert	$1.4\times10^{+5}$	$5.5\times10^{+5}$	0.050	0.200
I2 Alarm	N/A		N/A	
Alarm	$6.4\times10^{+5}$	$2.6\times10^{+6}$	0.250	1.000
C Alarm	N/A		N/A	
# of ports / zone	4		4	

Table B-7. Full Scale Small Room In-Cabinet Experiments

Setpoint	ASD 1		ASD 2		ASD 3	
	Detector	Port	Detector	Port	Detector	Port
Pre-Alert	0.012	0.072	$5.1\times10^{+5}$	$3.1\times10^{+6}$	0.008	0.050
I1 Alarm	N/A		$8.5\times10^{+5}$	$5.1\times10^{+6}$	N/A	
Alert	0.050	0.300	$1.2\times10^{+6}$	$7.2\times10^{+6}$	0.033	0.200
I2 Alarm	0.100	0.600	N/A		N/A	
Alarm	0.250	1.500	$1.5\times10^{+6}$	$9.0\times10^{+6}$	0.167	1.000
C Alarm	0.500	3.000	N/A		N/A	
# of ports / zone	6		6		6	

Table B-8. Full Scale Large Room In-Cabinet Experiments

Setpoint	ASD 2		ASD 3		ASD 4		ASD 5	
	Detector	Port	Detector	Port	Detector	Port	Detector	Port
Pre-Alert	$3.8\times10^{+4}$	$1.5\times10^{+5}$	0.006	0.025	$1.5\times10^{+5}$	$6.0\times10^{+5}$	0.016	0.064
I1 Alarm	$1.4\times10^{+5}$	$5.5\times10^{+5}$	N/A		$2.5\times10^{+5}$	$1.0\times10^{+6}$	N/A	
Alert	$1.4\times10^{+5}$	$5.5\times10^{+5}$	0.050	0.200	$3.5\times10^{+5}$	$1.4\times10^{+6}$	0.033	0.134
Alarm	$6.4\times10^{+5}$	$2.6\times10^{+5}$	0.250	1.000	$4.5\times10^{+5}$	$1.8\times10^{+6}$	0.166	0.666
# of ports / zone	4		4		4		4	

Note that ASD 4 and ASD 5 are multi-zone detectors. For ASD 4 Zone 1 provided the in-cabinet sampling. For ASD 5 Zone 3 provided the in-cabinet sampling.

Table B-9. Full Scale Small Room Area-wide Experiments

Setpoint	ASD 1		ASD 2		ASD 3	
	Detector	Port	Detector	Port	Detector	Port
Pre-Alert	0.012	0.048	$5.1\times10^{+5}$	$2.0\times10^{+6}$	0.025	0.100
I1 Alarm	N/A		$8.5\times10^{+5}$	$3.4\times10^{+6}$	N/A	
Alert	0.050	0.200	$1.2\times10^{+6}$	$4.8\times10^{+6}$	0.050	0.200
I2 Alarm	0.100	0.400	N/A		N/A	
Alarm	0.250	1.000	$1.5\times10^{+6}$	$6.0\times10^{+6}$	0.250	1.000
C Alarm	0.500	2.000	N/A		N/A	
# of ports / zone	4		4		4	

Table B-10. Full Scale Large Room Area-wide Experiments

Setpoint	ASD 4		ASD 5	
	Detector	Port	Detector	Port
Pre-Alert	$1.5\times10^{+5}$	$9.0\times10^{+5}$	0.016	0.095
I1 Alarm	$2.5\times10^{+5}$	$1.5\times10^{+6}$	N/A	
Alert	$3.5\times10^{+5}$	$2.1\times10^{+6}$	0.033	0.200
Alarm	$4.5\times10^{+5}$	$2.7\times10^{+6}$	0.166	0.999
# of ports / zone	6		6	

Note that ASD 4 and ASD 5 are multi-zone detectors. For ASD 4 Zone 2 provided the air return sampling, while Zone 3 provided the ceiling air sampling. For ASD 5 Zone 2 provided the air return sampling, while Zone 1 provide the ceiling air sampling.

B.2 Smoke Aerosol Measurements

Instrumentation descriptions

Aerosol characterization equipment included an electrical low pressure impactor (Dekati, ELPI) to record aerosol concentration and size distribution, a condensation particle counter (CPC, TSI Model 3775) to provide the aerosol number concentration, an electrical aerosol detector (EAD, TSI Model 3007) to provide a measure of the sum of particle diameters, and a tapered element oscillating microbalance (R&P Inc. TEOM Model 1105) to record aerosol mass concentration.

The ELPI consists of a 13-stage multi-orifice, low-pressure impactor that classifies particles according to their aerodynamic size (equivalent diameter unit density sphere). A schematic diagram of the instrument is shown in Figure B1. Beginning at the first stage, particles of a narrow size range (defined by a cut-off size, $d_{50\%}$, where 50 percent of particles of a given size are collected) impact on that stage's collection plate, while smaller particles move on to the next stage. The process repeats itself until the last stage is reached. The particle concentration below 0.03 μm is not measured, thus the size distribution is truncated. This may affect concentration and average size measurements, and the instrument results are subject to this bias.

The particles are separated according to their inertial properties, thus sizes are reported in terms of the diameter of unit density spheres with the same inertial properties, termed the aerodynamic diameter. The flow through the instrument is 10 l/min. Typically, cascade impactors rely on a gravimetric determination of the amount of particles collected on any stage, thus the sampling time must be sufficient to gather a weighable amount of material on each stage. This impactor is unique in that it detects particles that impact on the different stages by measuring the charge transferred to the stage from the elemental charges carried by the particles. Aerosol particles will achieve a statistically average charge level based on particle diameter, initial charge state, and exposure to charging mechanisms.

The ELPI conditions the aerosol to such a state by a two-step process. The initial charge state is forced to an equilibrium, Boltzmann charge distribution by passing the aerosol through a charge neutralizer (external to the ELPI). Then, a high-voltage corona wire unipolar charger puts known excess charge on the aerosol particles based on their size and the residence time the aerosol remains in the charging section. Excess ions and very small, charged particles are removed by an ion trap just past the charger. Each impactor stage (excluding the first which removes particles with aerodynamic diameters larger than 10 μm) is electrically isolated and connected to an electrometer. As aerosol particles impact on the various stages, they transfer their charges and a current is measured. From the current measurement, impactor stage cut-off sizes, flow through the instrument, and the relationship between the particle size and average charge, the number of particles that impact each stage is computed and the number size distribution is characterized. The number distribution can be converted into diameter, surface area, or mass distribution, etc., and the total number, or mass (assuming spherical unit density particles) can be computed.

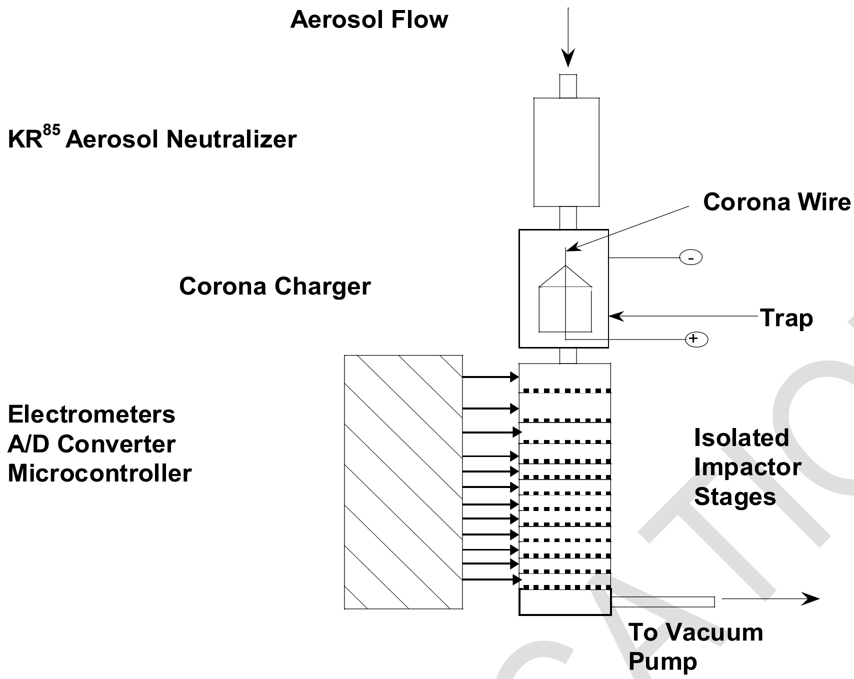


Figure B-1. Schematic diagram of the electrical low pressure impactor

Table B-11 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 B-11. ELPI Imactor Plate Cutoff and Median Diameters

Impactor Stage	Standard Impactor Plates	
	Aerodynamic $d_{50\%}$ (μm)	Aerodynamic d_i (μm)
1	0.0280	0.0395
2	0.0557	0.0727
3	0.0948	0.122
4	0.157	0.203
5	0.263	0.317
6	0.383	0.485
7	0.615	0.764
8	0.950	1.23
9	1.60	1.96
10	2.40	3.10
11	4.00	5.18
12	6.70	8.16
13	9.93	-

If density is known, then the aerodynamic diameter can be replaced with the Stokes diameter, defined as the diameter of a sphere with the same density and settling velocity of the particle. The analysis of the ELPI data takes into account known aerosol particle densities. For the unknown aerosol densities of the smokes generated from material degradation, a density of 1.00 g/cm^3 is assumed, but this adds to the uncertainty in the results for the aerosol concentrations and size distribution.

The CPC can detect and count particles 4 nm in diameter and larger up to number concentrations of 1×10^7 particles/cm^3. The CPC draws aerosols into a heated saturator where alcohol vapor and the aerosol mix, this particle/vapor mixture then flows to a condensing section where the vapor becomes superheated and condenses on the aerosol particles greater than 4 nm. The particles grow rapidly to large individual particles that are counted optically. In that respect, the detection principle of the CPC is similar to a cloud chamber ASD. The CPC combined relative uncertainty is better than ±10 percent of the reading.

The EAD measures an aerosol concentration referred to as the total aerosol length, equal to the sum of the diameter of all particles in a unit volume. This quantity is also referred to as the first moment of the size distribution (the number concentration is the zeroth moment). In the EAD, particles flow into a charging section where positive ions accumulate on particles to a net charge state proportional to the particle diameter. An aerosol electrometer measures the net charge, which is proportional to the total aerosol length. The combined relative uncertainty in the EAD measurement is typically better than ±10 percent of the reading.

The TEOM is a direct measure of the mass concentration of an aerosol. The sampled aerosol with a fixed volumetric flow is passed through a vibrating filter that accumulates the aerosol particles. The vibration frequency is proportional to the mass of the filter. The frequency is measured as a function of time, and with the volumetric flow rate, the mass concentration is computed. The TEOM combined standard uncertainty is ± 0.5 mg/m^3.

In the various laboratory test configurations, the transport time from the in-cabinet sample inlet to the various instruments was on the order of 2 seconds or less. The response time (95 percent of input change) of each instrument varied, with values for the TEOM, ELPI, CPC and EAD on the order of 5, 5, 2, and 2 seconds, respectively.

Properties of the size distribution of interest include the first moment of the number distribution with the mean size defined as the arithmetic mean diameter (AMD), given by

$$AMD = \frac{\sum(n_i \cdot d_i)}{N} \qquad \text{B-1}$$

where n_i is the number of particles of size group d_i, and N is the total number of particles. The first moment correlates with the response of the ionization chamber in smoke detectors. Another property of interest is the mass (or volume) distribution, which is a better predictor of the response of light-scattering, photoelectric alarms than the diameter distribution. The third moment of the size distribution can be represented by the total mass, M (or volume) with a mass mean diameter (d_{mm}), given by

$$d_{mm} = \frac{\sum(m_i \cdot d_i)}{M} \qquad \text{B-2}$$

where m_i is the number of particles of size group d_i, and M is the mass of all particles. Comparing these two mean diameters gives a sense of the width of the size distribution. If both AMD and d_{mm} are the same the particles are of a single size (monodisperse) while an increasing difference between the two diameters indicates ever broadening distribution. For log-normally distributed aerosols with an AMD of 0.100 µm and geometric standard deviations (σ_g) of 1.30 and 1.70, the $d_{mm}$is 0.123 µm and 0.233 µm respectively.

The diameter of average mass can be computed if the mass and number concentration are known using equation 3.

$$d_{am} = \left(\frac{6M}{\rho\pi N}\right)^{1/3} \qquad \text{B-3}$$

B.2.1 Instrument Cabinet Experiments

Experiments were conducted using a condensation mono-disperse aerosol generator (CMAG, TSI Model 3475), an instrument that can produce high concentrations of narrow size distribution aerosols from 0.1 µm up to 8 µm in diameter, and a Gemini smoke detector tester aerosol generator, which produces aerosol designed to mimic smolder smokes. The CMAG produces particles from Di-Ethyl-Hexyl-Sebacate (DEHS, density of 0.912 g/cm^3), while the smoke detector tester produces particles from mineral oil (density of 0.85 g/cm^3).

Aerosols from the CMAG or smoke detector tester were introduced into the cabinet from a tube located at the cabinet floor and pointing up. The aerosol was sampled from the ceiling of the instrument cabinet and directed to the ELPI. Experiments were conducted with 9 different settings on the CMAG, and one base setting on the smoke detector tester. Data for the experiments are located in the spreadsheet files labeled {Instrument cabinet CMAG and Gemini exps} and {Test_aerosol_ELPI}. The first file contains the ASD alarm times and the end of test number and mass concentrations, and arithmetic mean diameter and diameter of average mass, while the second file contains the number, total aerosol length, and mass concentrations, along with the arithmetic mean diameter and diameter of average mass values as functions of time. The device settings for these experiments are given in Table B-2.

Table B-12. Nominal Detector Sensitivities for Instrument Cabinet 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
VEWFDS Pre-alert	0.013 / 0.05	5.1×10^5 / 2.0×10^6	0.025 / 0.10	-	-	-
VEWFDS Intermediate (I1)	-	8.5×10^5 / 3.4×10^6	-	-	-	-
VEWFDS Alert	0.05 / 0.20	1.2×10^6 / 4.8×10^6	0.05 / 0.20	0.20	-	-
VEWFDS Intermediate (I2)	0.10 / 0.40	-	-	-	-	-
VEWFDS Alarm	0.25 / 1.00	1.5×10^6 / 6.0×10^6	0.25 / 1.00	1.00	-	-
Pre-Alarm	-	-	-	-	0.5	1.3
Conventional Alarm	0.50 / 2.00	-	-	-	1.0	2.1

The arithmetic mean particle size at the end of the test for the CMAG experiments ranged from 0.12 μm to 0.82 μm, depending on the CMAG settings, and 0.33 μm for the smoke detector tester aerosol. In only one CMAG setting did ASD2 (cloud chamber type) respond at alert or alarm settings, and in fact, only pre-alerted in one other CMAG setting. The light-scattering ASDs tended to respond at all CMAG settings. The smoke detector tester aerosol triggered all light-scattering response levels, while the cloud chamber ASD responded at the level between pre-alert and alert consistently. These results show the response to various concentrations of given particle size distributions, but by themselves do not indicate effectiveness, nor appropriateness for a given application.

An example of the ELPI data is shown below in Figures B-2 and B-3. The aerosol concentration curves are proportional to each other since the size distribution of the CMAG aerosol does not change much with time. The mean size fluctuates prior to the arrival of the CMAG aerosol at the sampling port due to the low concentration background (room) aerosol. The mean diameters show a slight growth trend in time which may be due to the aerosol generator, or aging of the aerosol at the ceiling of the cabinet.

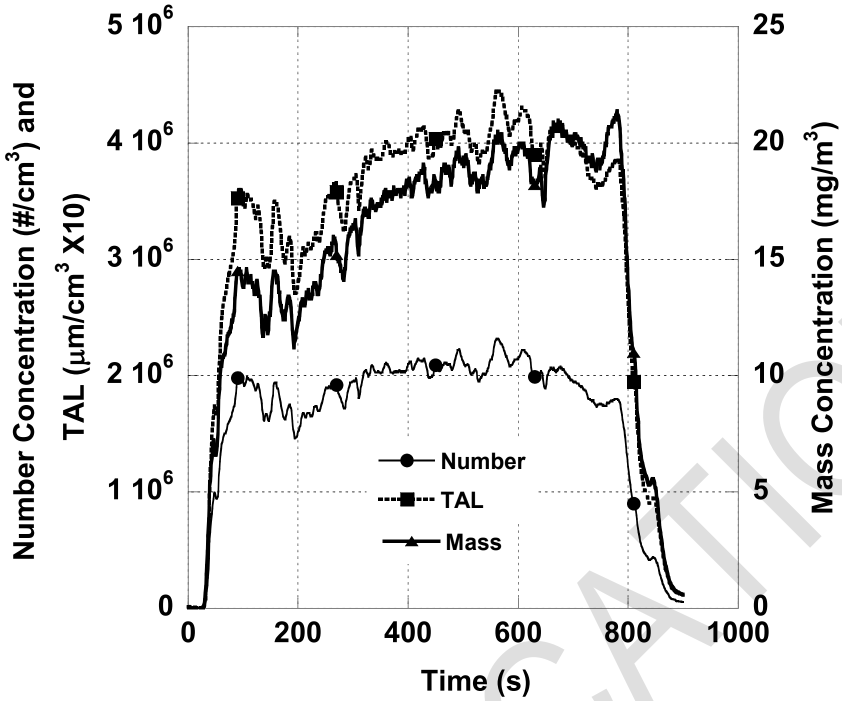


Figure B-2. ELPI aerosol concentrations for CMAG experiment 40.

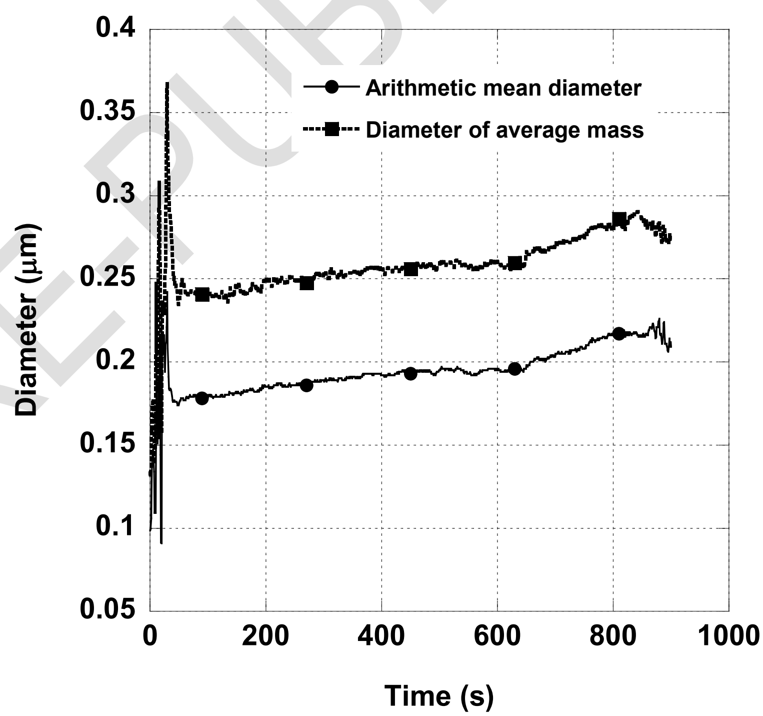


Figure B-3. ELPI aerosol diameters for CMAG experiment 40.

B.2.1.2 Degraded materials

Almost all experiments conducted in the instrument cabinet with the degrading materials were monitored with the ELPI. The spreadsheet labeled {Instrument_cabinet_ELPI} contains the ELPI results number, total aerosol length, and mass concentrations, along with the arithmetic mean diameter and diameter of average mass values as functions of time. The spreadsheet labeled {Instrument Cabinet Experiments} contains the configuration and alarm times. The device setting for these experiments are given in Table B-12. Figures B-4 – B-9 show ELPI 60.0 minute HRP results for XLPE, PVC(2), and CSPE samples.

Additional experiments were conducted in which the smoke sampled from the aerosol sampling port was directed to the CPC, EAD and TEOM as alternate direct measurements of number concentration, total aerosol length, and mass concentration. The materials examined were limited to XPLE, PVC(2) and CSPE at HRPs of 15.0 minute and 60.0 minute, and overheated resistors. The spreadsheet labeled {Instrument_cabinet_moments} contains the measurement results and the bus bar heating measurements for those experiments.

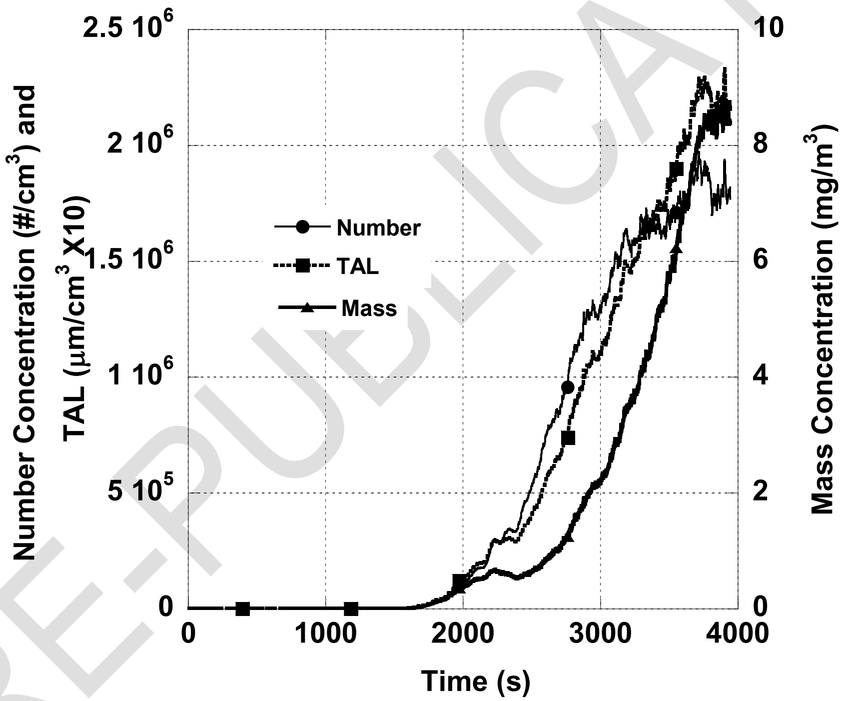


Figure B-4. ELPI aerosol concentration for XLPE and 60.0 minute HRP.

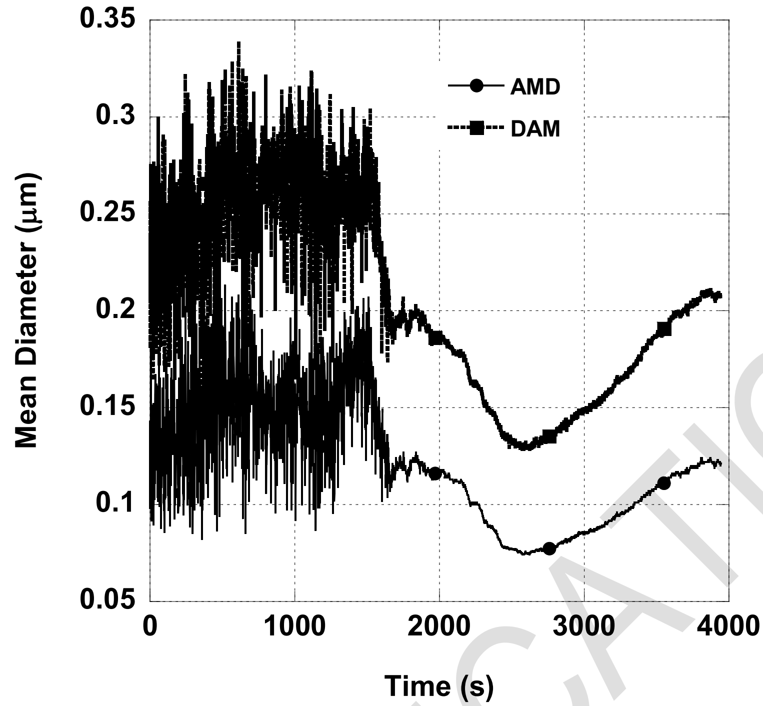


Figure B-5. ELPI mean particle diameters for XLPE and 60.0 minute HRP.

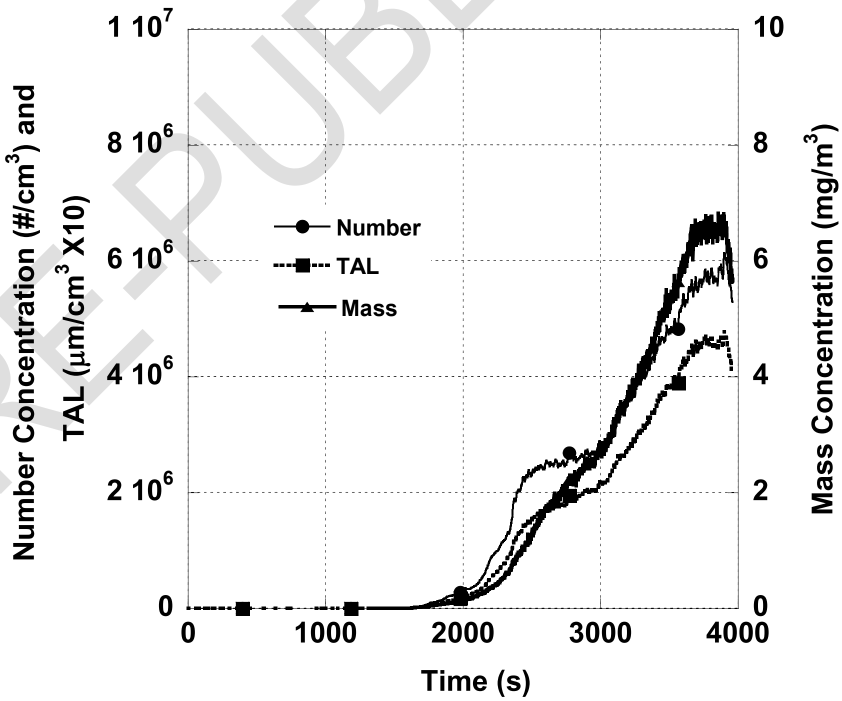


Figure B-6. ELPI aerosol concentration for PVC(2) and 60.0 minute HRP.

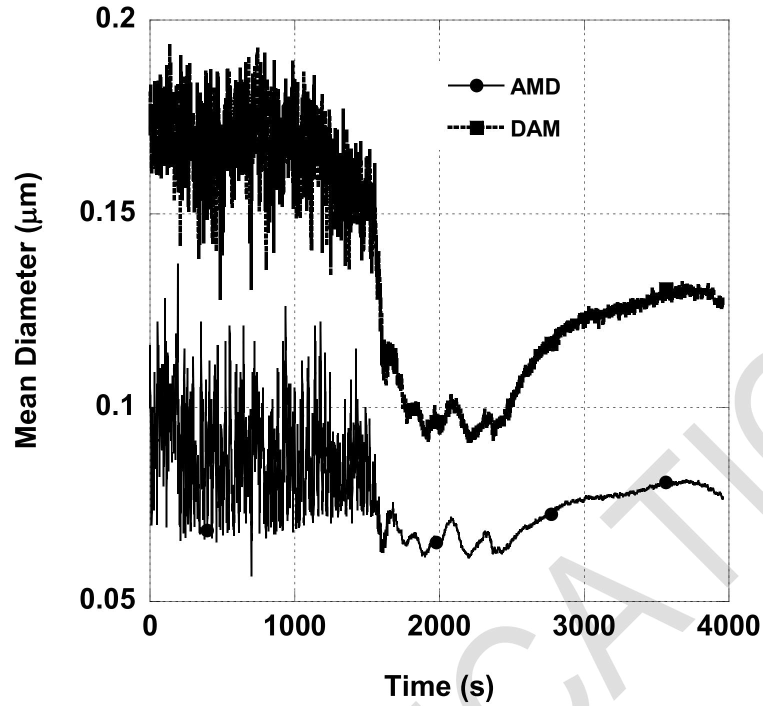


Figure B-7. ELPI mean particle diameters for PVC(2) and 60.0 minute HRP

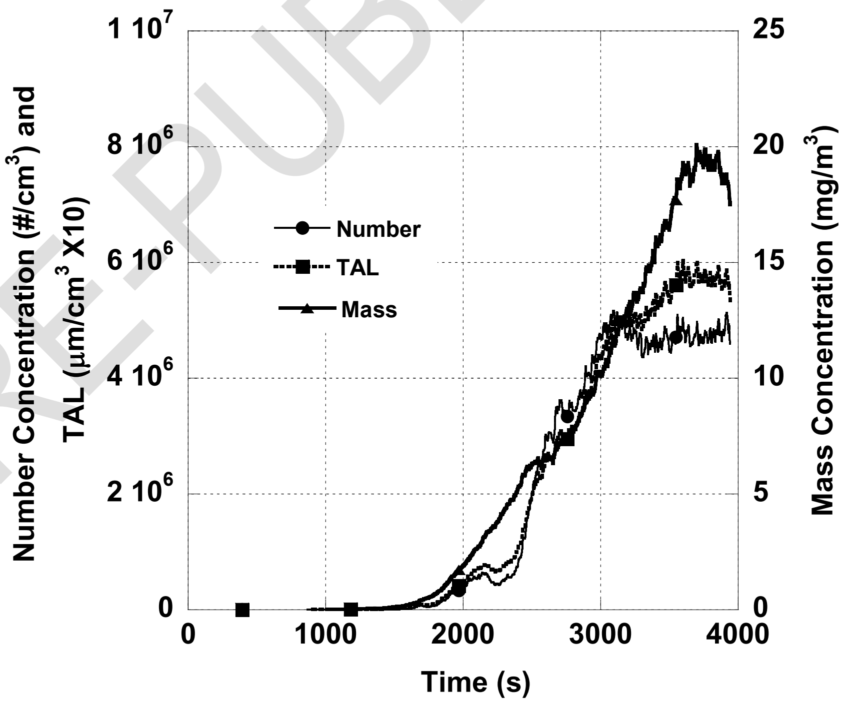


Figure B-8. ELPI aerosol concentration for CSPE and 60.0 minute HRP.

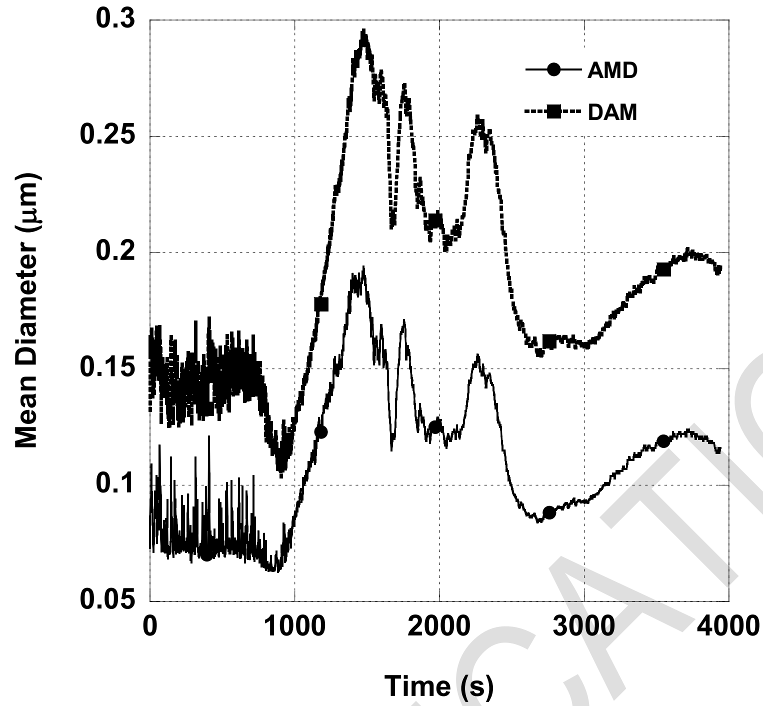


Figure B-9. ELPI mean particle diameters for PVC(2) and 60.0 minute HRP

Additional experiments were conducted where the smoke sampled from the aerosol sampling port was directed to the CPC, EAD and TEOM as alternate direct measurements of number concentration, total aerosol length, and mass concentration. The materials examined were limited to XPLE, PVC(2) and CSPE at HRPs of 15.0 minute and 60.0 minute, and overheated resistors. The spreadsheet labeled {Instrument Cabinet exps - Aerosol moments} contains the configuration and alarm times. The spreadsheet labeled {Instrument_cabinet_moments} contains the measurement results and the bus bar heating measurements for those experiments. The device settings for these experiments are given in Table B-13 for the first 15 minute and 1 hr heating ramp period experiments and Table B-14 for the next three 15 minute and 1 hr heating ramp period experiments.

Table B-13. Nominal Detector Sensitivities for Laboratory—Aerosol Moments 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
VEWFDS Pre-alert	0.013 / 0.05	1.9×10^5 / 7.7×10^6	0.0063 / 0.025	-	-	-
VEWFDS Intermediate (I1)	-	2.5×10^5 / 1.0×10^6	-	-	-	-
VEWFDS Alert	0.05 / 0.20	3.7×10^5 / 1.5×10^6	0.0125 / 0.050	0.20	-	-
VEWFDS Intermediate (I2)	0.10 / 0.40	-	-	-	-	-
VEWFDS Alarm	0.25 / 1.00	8.5×10^5 / 3.4×10^6	0.025 / 0.10	1.00	-	-
Pre-Alarm	-	-	-	-	0.5	1.3
Conventional Alarm	0.50 / 2.00	-	-	-	1.0	2.1

Table B-14. Nominal Detector Sensitivities for Laboratory—Aerosol Moments 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
VEWFDS Pre-alert	0.013 / 0.05	8.4×10^4 / 3.4×10^5	0.0063 / 0.025	-	-	-
VEWFDS Intermediate (I1)	-	1.3×10^5 / 5.2×10^5	-	-	-	-
VEWFDS Alert	0.05 / 0.20	1.9×10^5 / 7.7×10^5	0.0125 / 0.050	0.20	-	-
VEWFDS Intermediate (I2)	0.10 / 0.40	-	-	-	-	-
VEWFDS Alarm	0.25 / 1.00	8.5×10^5 / 3.4×10^6	0.025 / 0.10	1.00	-	-
Pre-Alarm	-	-	-	-	0.5	1.3
Conventional Alarm	0.50 / 2.00	-	-	-	1.0	2.1

B.2.2 Large Cabinet

During the large cabinet experiments, smoke was sampled from the top of the cabinets and directed to the ELPI. Data was collected for the 16.3 and 65.0 minute HRP experiments for XLPE, PVC(2), CSPE, and PCB materials, and for 260 minute HRP experiments for XLPE and CSPE materials. Experiments were conducted with XLPE and CSPE samples in which the HRP was reduced to achieve a lower bus bar temperature, and the hold time was increased so the EOT times, 21.3 and 70 minutes, were the same. In addition, BS 6266 1 meter wire tests were conducted. The spreadsheet labeled {Large_cabinet_ELPI} contains the ELPI results number, total aerosol length, and mass concentrations, along with the arithmetic mean diameter and diameter of average mass values as functions of time.

Figures B10 – B13 show the aerosol concentration results for naturally ventilated cabinet and XLPE and CSPE experiments, with the normal 16.3 minute HRP and shorter HRPs to set points of 325 °C and 225 °C, respectively.

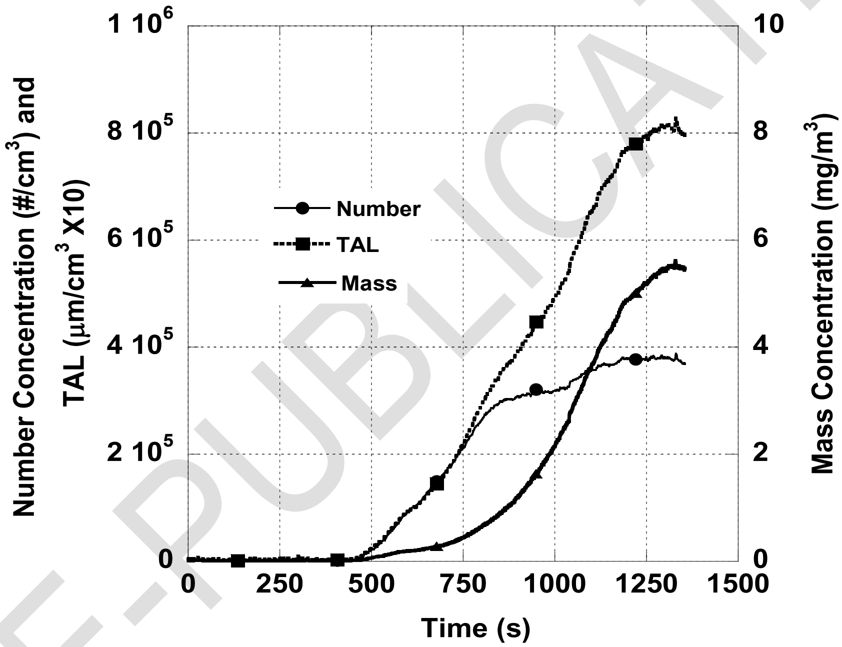


Figure B10. Large, naturally ventilated cabinet ELPI aerosol concentration for XLPE and 16.3 minute HRP.

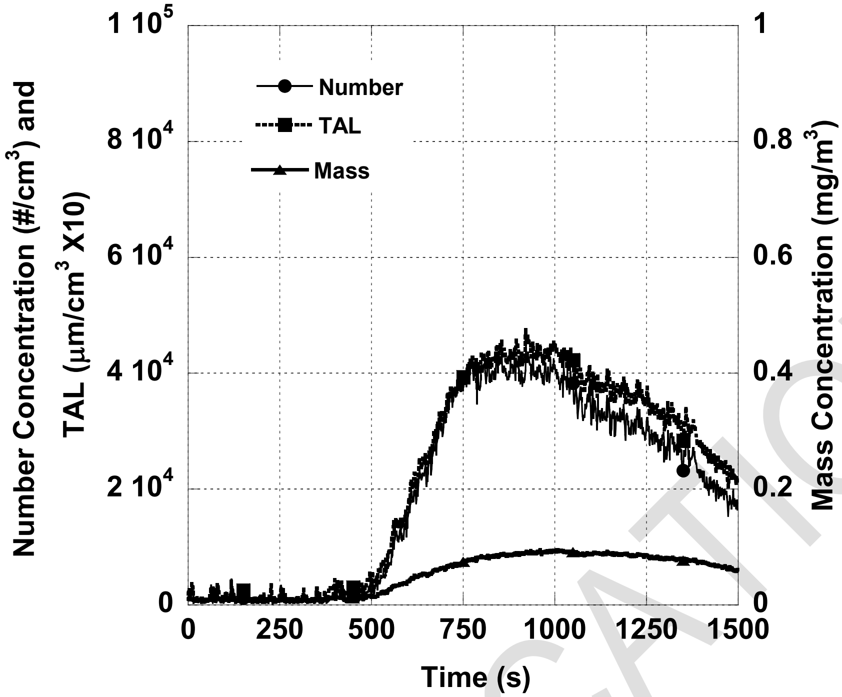


Figure B11. Large, naturally ventilated cabinet ELPI aerosol concentration for XLPE and 10.5 minute HRP to a set point of 325 ˚C and held until 21.3 min.

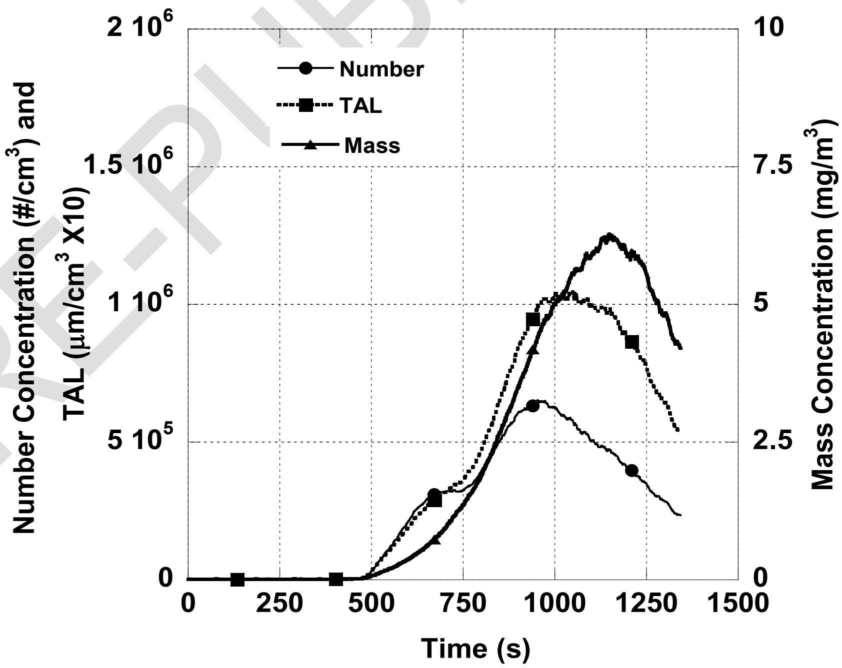


Figure B12. Large, naturally ventilated cabinet ELPI aerosol concentration for CSPE and 16.3 minute HRP.

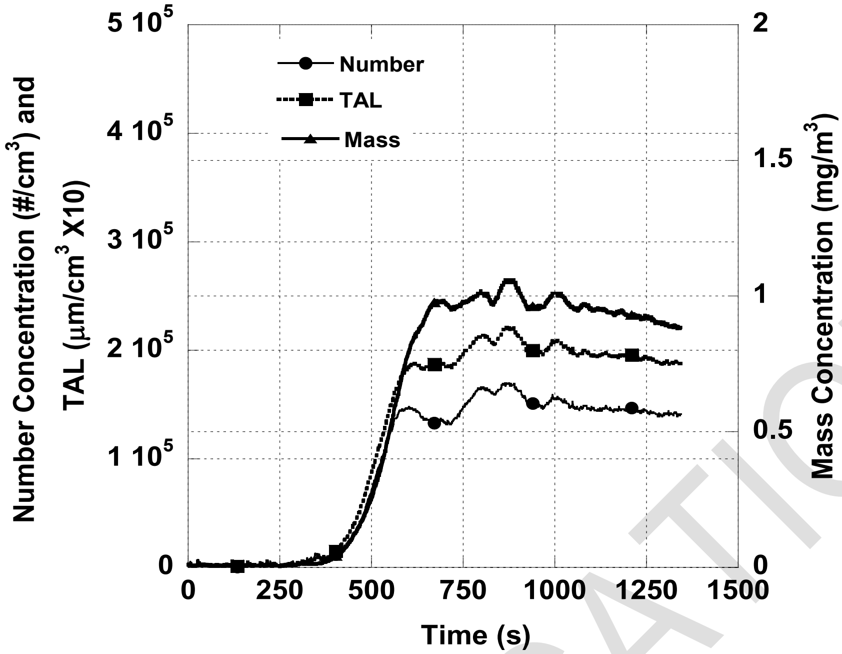


Figure B13. Large, naturally ventilated cabinet ELPI aerosol concentration for CSPE and 7.9 minute HRP to a set point of 250 ˚C and held until 21.3 min.

B.3 VEWFD System Performance versus Cloud Chamber ASD Sensitivity Setting

Experiments using the single-zone cloud chamber (ASD2) did not consistently use a fixed alert sensitivity setting, nor was a fixed estimated alert sensitivity setting used in the analysis reported in Part II of this report. The analysis in Part II used specific recorded alert times, or averaged time from two ASD2 settings, and were estimated values for sensitivity levels considered representative of what would meet the minimum sensitivity requirements of NFPA 76. It was noted that the cloud chamber sensitivity range appeared to cover a smaller sensitivity range compared to the smoke obscuration range for the overheated wire and material experiments performed, and moderate changes in sensitivity did not necessarily translate into significant alert time differences. The reason for this appears to be due to the observed exponential increase in particle number concentration throughout the cloud chamber sensitivity range during the linear heating ramp experimental test scenarios.

To assess the effects sensitivity setting on the analysis in Part II for a fixed cloud chamber ASD alert sensitivity over all experiments, estimates were made of the time to alert for a sensitivity specified by the manufacturer of the cloud chamber ASD in the multi-zone cloud chamber experiments for all experiments conducted. Note, there was no modification of the cloud chamber device sensitivity for in-cabinet nor area-wide and return air duct zones, thus effective port sensitivities will depend on the number of ports and the particle concentration sampled at each port. This followed the manufacturer's specifications for the different multi-zone ASD experiments.

Table B-15 gives conversion factors to convert between the gain setting and particle concentration. These factors were estimated from the values obtained from the instrument software. The method of calibration in unknown, so comparisons to specific particle number concentration measurements (in this report or elsewhere) should be made with caution. The conversion factors were then used to convert the specific experimental single-zone and multi-zone device and port settings to particle concentrations.

Table B-15. Estimated ASD2 and ASD4 Gain Factors

Gain	Gain Factor (particles/ cm^3)
5	17000
6	7300
7	5000
8	3850
9	2560
10	1670

The particle concentration is obtained by multiplying the gain factor for a specific gain setting by the percentage of the gain setting (i.e., the particle concentration for a setting of 50 percent of a gain setting of 5 (5/50) would be 17,000 times 50 = 8.5×10^5 particles/ cm^3. The manufacturer-specified alert sensitivity setting for the multi-zone experiments was a Gain of 7 at 30 percent (7/30), or an estimated particle concentration device sensitivity of 1.50×10^5 particles/ cm^3. It is not clear how this sensitivity setting is related to the NFPA 76 alert sensitivity of 0.2 %/ft obscuration at the sampling port or spot device location.

Table B-16 shows the specific settings for the single zone ASD2 experiments, the alert setting used for the analysis of each set of experiments and the corresponding light scattering ASD3 settings. Based on the particle concentration conversion, the large cabinet and large room in-cabinet experiment device alert sensitivity values were very close to the manufacturer-specified sensitivity, while for the other experiments the closest sensitivity setting was greater than 5 times the manufacturer-specified particle concentration sensitivity. Thus, either interpolation or extrapolation of time to reach the manufacturer-specified device setting of 7/30 will align all experiments to a single fixed alert setting.

Table B-16. Single Zone ASD2 and ASD3 Device Settings and Alert Levels

Experimental Configuration	Device Setting	ASD2 Device Sensitivity (part./cm^3)	ASD2 Port Sensitivity (part./cm^3)	Light Scattering ASD3 Device Setting (%/ft Obscuration)	Light Scattering ASD3 Port Setting (%/ft Obscuration)
Instrument Cabinet Experiments	5/30	5.1×10^5	2.0×10^6	0.025	0.10
	5/50	8.5×10^5	3.4×10^6	0.050	0.20
	5/70	1.2×10^6	4.8×10^6	0.25	1.00
	5/90	1.5×10^6	6.0×10^6		
	Alert	8.5×10^5	3.4×10^6	0.050	0.20
Large Cabinet Experiments	9/15	3.8×10^4	1.5×10^5	0.0063	0.025
	9/53	1.4×10^5	5.5×10^5	0.05	0.20
	6/19	1.4×10^5	5.5×10^5	0.25	1.00
	6/88	6.4×10^5	2.6×10^6		
	Alert	1.4×10^5	5.5×10^5	0.05	0.20

Table B-16. Single Zone ASD2 and ASD3 Device Settings and Alert Levels (Continued)

Experimental Configuration	Device Setting	ASD2 Device Sensitivity (part./cm^3)	ASD2 Port Sensitivity (part./cm^3)	Light Scattering ASD3 Device Setting (%/ft Obscuration)	Light Scattering ASD3 Port Setting (%/ft Obscuration)
Small Room In-cabinet Experiments	5/30	5.1×10^5	3.1×10^6	0.0083	0.050
	5/50	8.5×10^5	5.1×10^6	0.033	0.20
	5/70	1.2×10^6	7.2×10^6	0.167	1.00
	5/90	1.5×10^6	9.0×10^6		
	Alert	8.5×10^5	3.4×10^6	0.033	0.20
Small Room Area-wide Experiments	5/30	5.1×10^5	2.0×10^6	0.025	0.10
	5/50	8.5×10^5	3.4×10^6	0.050	0.20
	5/70	1.2×10^6	4.8×10^6	0.25	1.00
	5/90	1.5×10^6	6.0×10^6		
	Alert	8.5×10^5	3.4×10^6	0.050	0.20
Large Room In-cabinet Experiments	9/15	3.8×10^4	1.5×10^5	0.0063	0.025
	9/53	1.4×10^5	5.5×10^5	0.050	0.20
	6/19	1.4×10^5	5.5×10^5	0.25	1.00
	6/88	6.4×10^5	2.6×10^6		
	Alert	1.4×10^5	5.5×10^5	0.050	0.20

Limited experiments were conducted to ascertain the effect of a wide range of sensitivity settings on the time to alarm for ASD2. Specifically, experiments in the instrument cabinet arrangement with XLPE, CSPE and PVC(2) were conducted with the ASD2 device at settings of 8/50, 7/50, 6/50 and 5/50, and at 10/50, 9/50/ 8/50 and 5/50 with continuous air sampling directed to a condensation particle counter. The results from these experiments were used to develop a strategy for interpolation or extrapolation of ASD2 alert times given a different sensitivity setting.

The observed exponential increase in particle concentration begins soon after the time (block temperature) the particle concentration begins to rise above the ambient background level (typically less than 5×10^3 particles/cm^3 in the NIST laboratory space) during the heating ramp phase. This observation is specific to the particle evolution of the linear heating ramp exposures of the experiments conducted in this study. Thus, a plot of the activation time for each of the four device settings versus the device (or port) sensitivity settings (in particles/cm^3) would should show a logarithmic increase in activation time over a range of sensitivity settings. Examples are shown in Figures B-14, 15, and 16 where the recorded alarm times are plotted against the port sensitivity for instrument cabinet experiments. Additional alarm time settings were estimated by using a linear correlation between the recorded particle concentration and the port sensitivity at the recorded alarm times for each experiment, then interpolating or extrapolating estimated alarm times for different port sensitivities. Finally, a curve was fitted with a logarithmic function (base 10) through just the recorded alarm times.

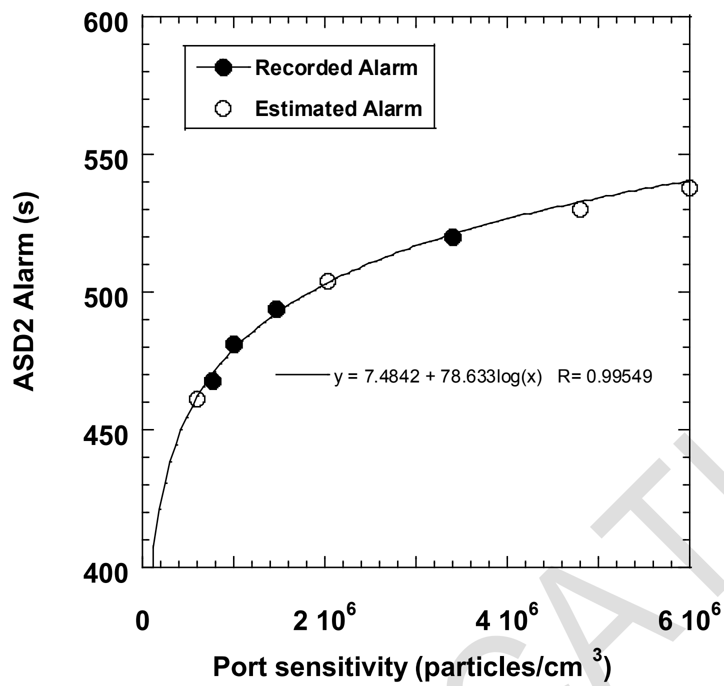


Figure B-14. Instrument cabinet experiment (filename C_CSPE_L_A_1.4) with CSPE wire and a 15 minute HRP, ASD2 device settings at 8/50, 7/50, 6/50, and 5/50, and estimated settings of 7/30, 5/30, 5/70, and 5/90

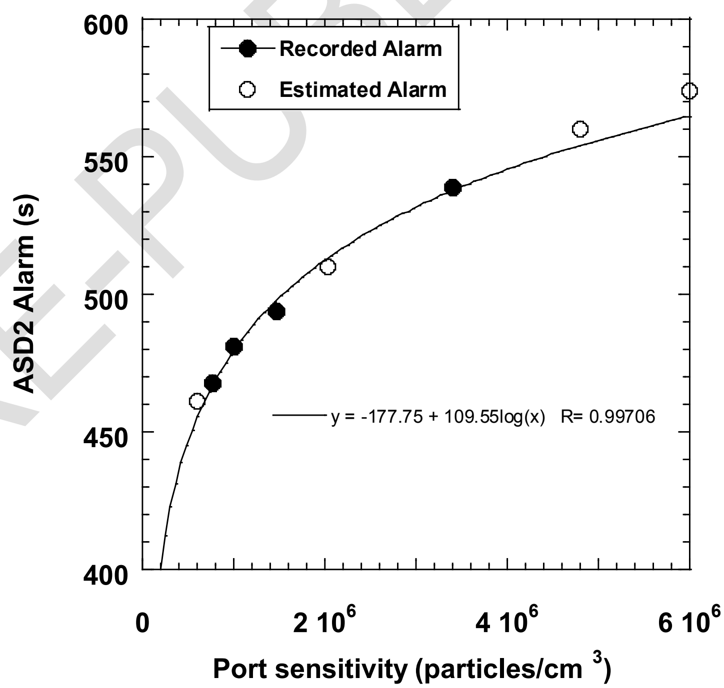


Figure B-15. Instrument cabinet experiment (filename C_XLPE_L_A_1.4) with XLPE wire and a 15 minute HRP, ASD2 device settings at 8/50, 7/50, 6/50, and 5/50, and estimated settings of 7/30, 5/30, 5/70, and 5/90

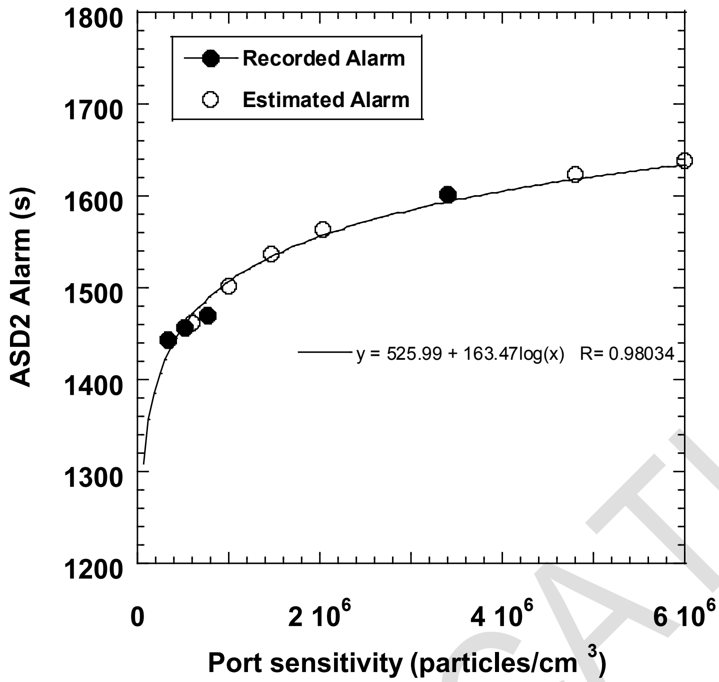


Figure B-16. Instrument cabinet experiment (filename C_PVC2_L_A_2.4) with PVC(2) wire and a 60 minute HRP, ASD2 device settings at 10/50, 9/50, 8/50, and 5/50 and estimated settings of 7/30, 7/70, 6/50, 5/30, 5/70, and 5/90

This analysis confirmed the strategy to interpolate or extrapolate activation times at other sensitivity settings by fitting the recorded alarm times (not all four, but typically two or three points closest the 7/30 setting) to a logarithmic function and estimating an alert time at a device setting of 7/30. This was done for all experiments using ASD2 and considered in the analysis of Phase II.

B.4 Supplemental Data Supporting Objective E

Figures B-17 and B-18 present the in-cabinet, naturally ventilated data for the 15 minute and 4-hour HRP, respectively. These figures show the detectors' time of response ("alert" for VEWFD systems and "alarm" for conventional spots). This data shows trends similar to the data presented in Figure 5-49.

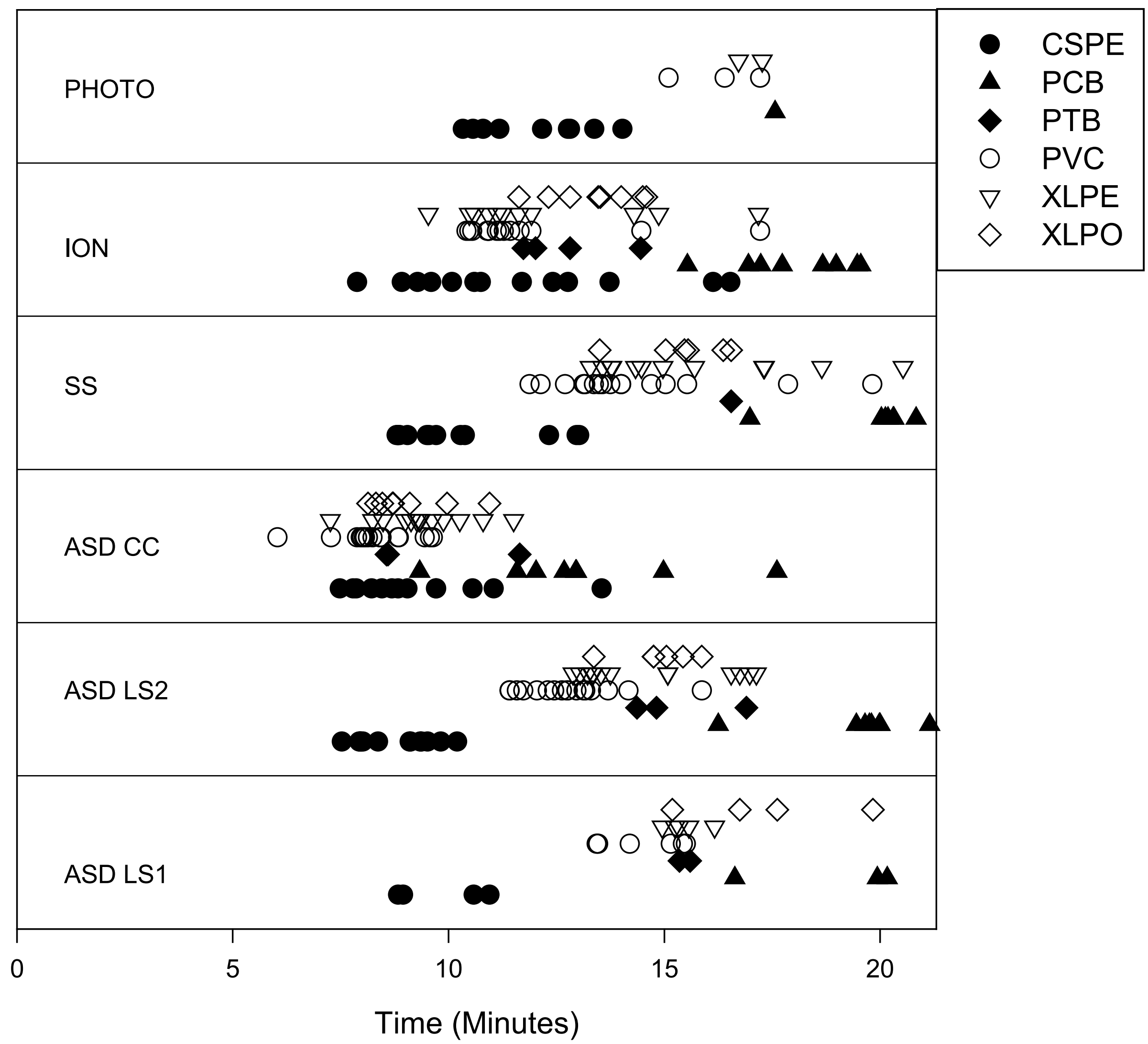


Figure B-17. Detector response to selected materials (15 minute HRP) in-cabinet, natural cabinet ventilation

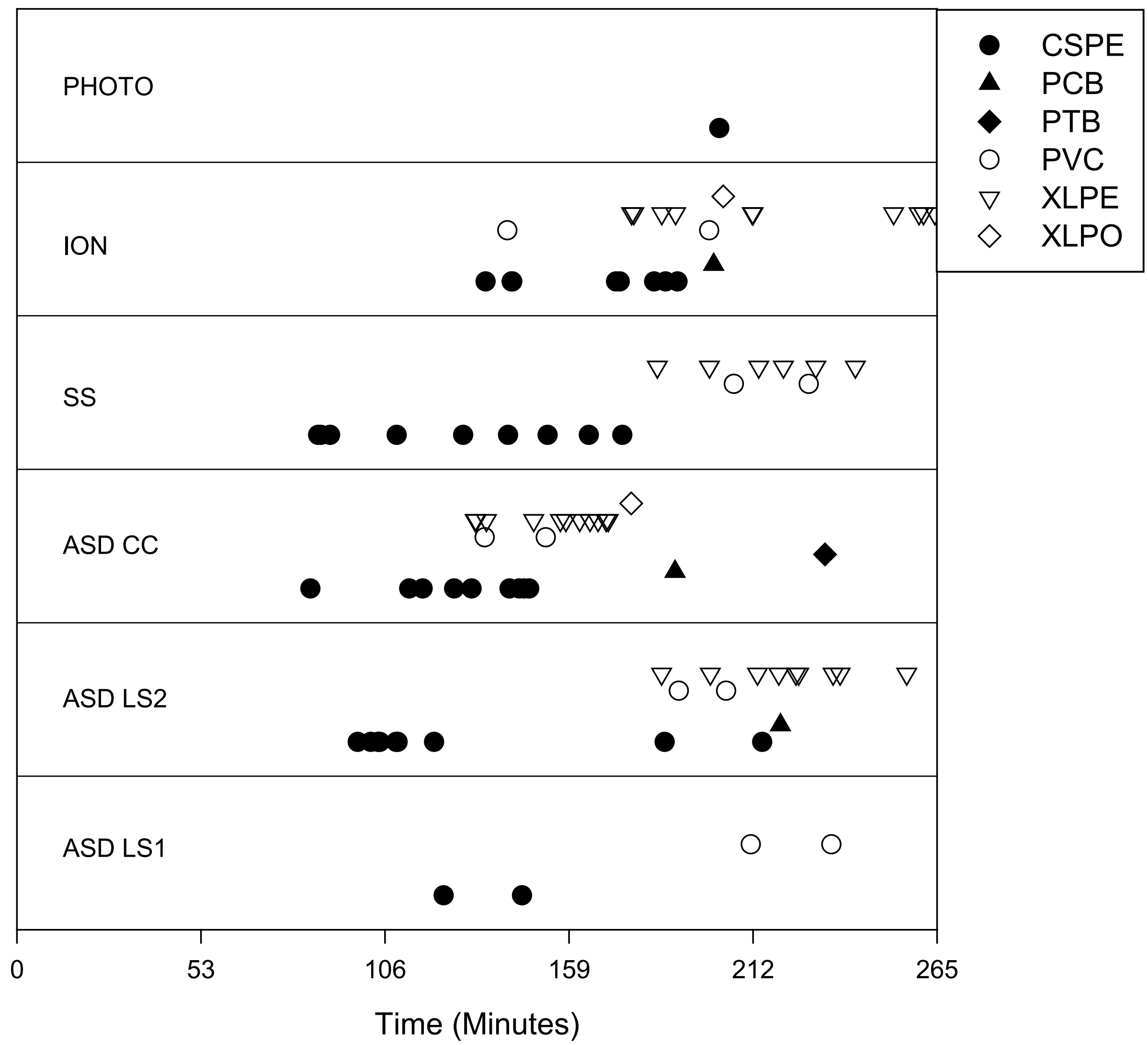


Figure B-18. Detector response to selected materials (4-hour HRP) in-cabinet, natural cabinet ventilation

The supplemental data above is based on the sensitivities reported in the body of this report. However, as discussed elsewhere, the ASD systems tested were configurable to several different sensitivities and data was logged at sensitivities other than those focused on in body of this report. Figure B-19 and B-20 present the system response at different alert set points for in-cabinet test configurations with natural or low cabinet ventilation rates. All data recorded is available on the enclosed CD. In general, as the detector port sensitivity increases (becomes more sensitive) the time to detection decreases (earlier detection). However, the data is quite disperse.

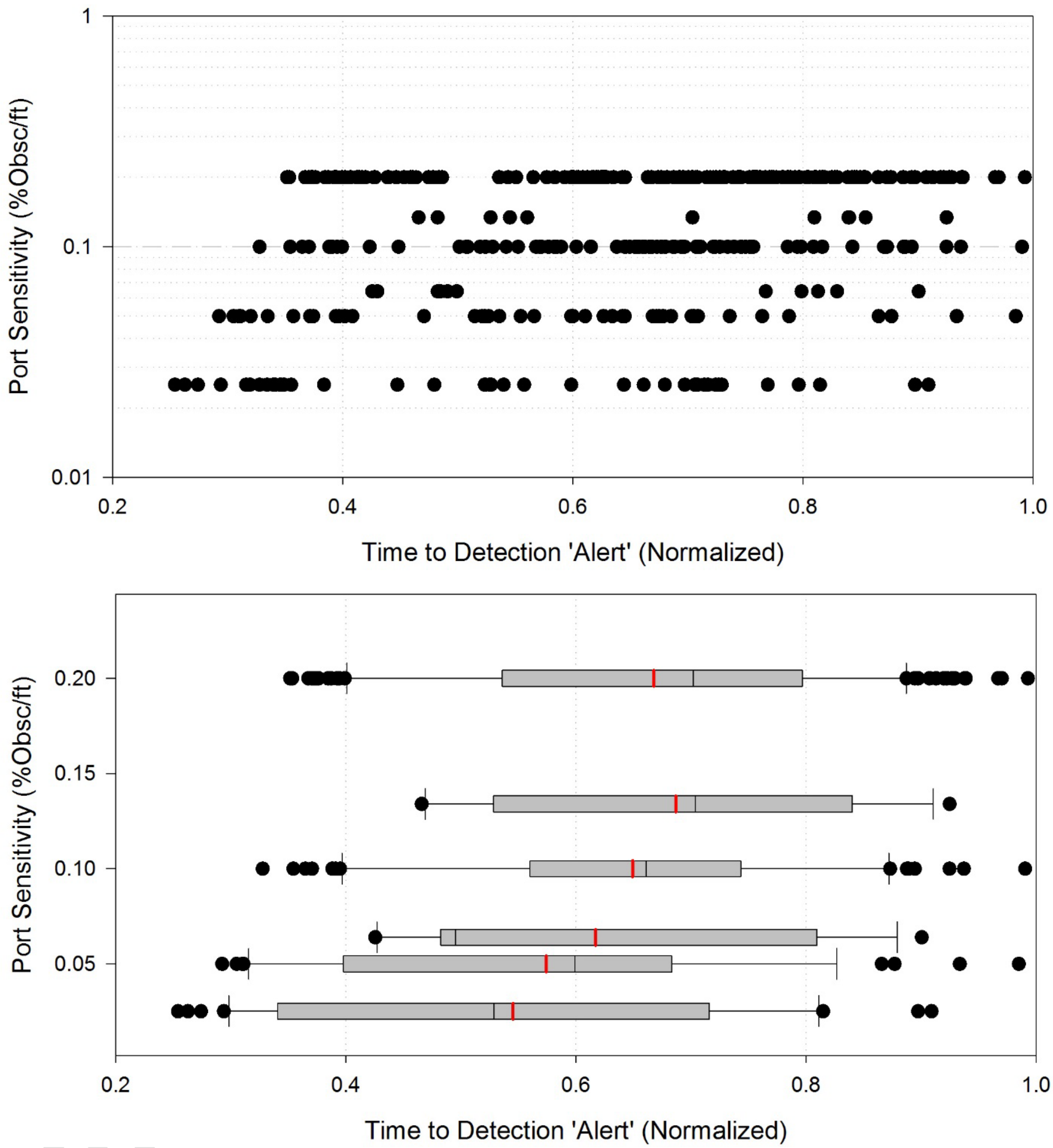


Figure B-19. Light Scattering (LS2) Alert system response at different port sensitivities. (Top – scatter plot; Bottom – Box plot with mean bolded)

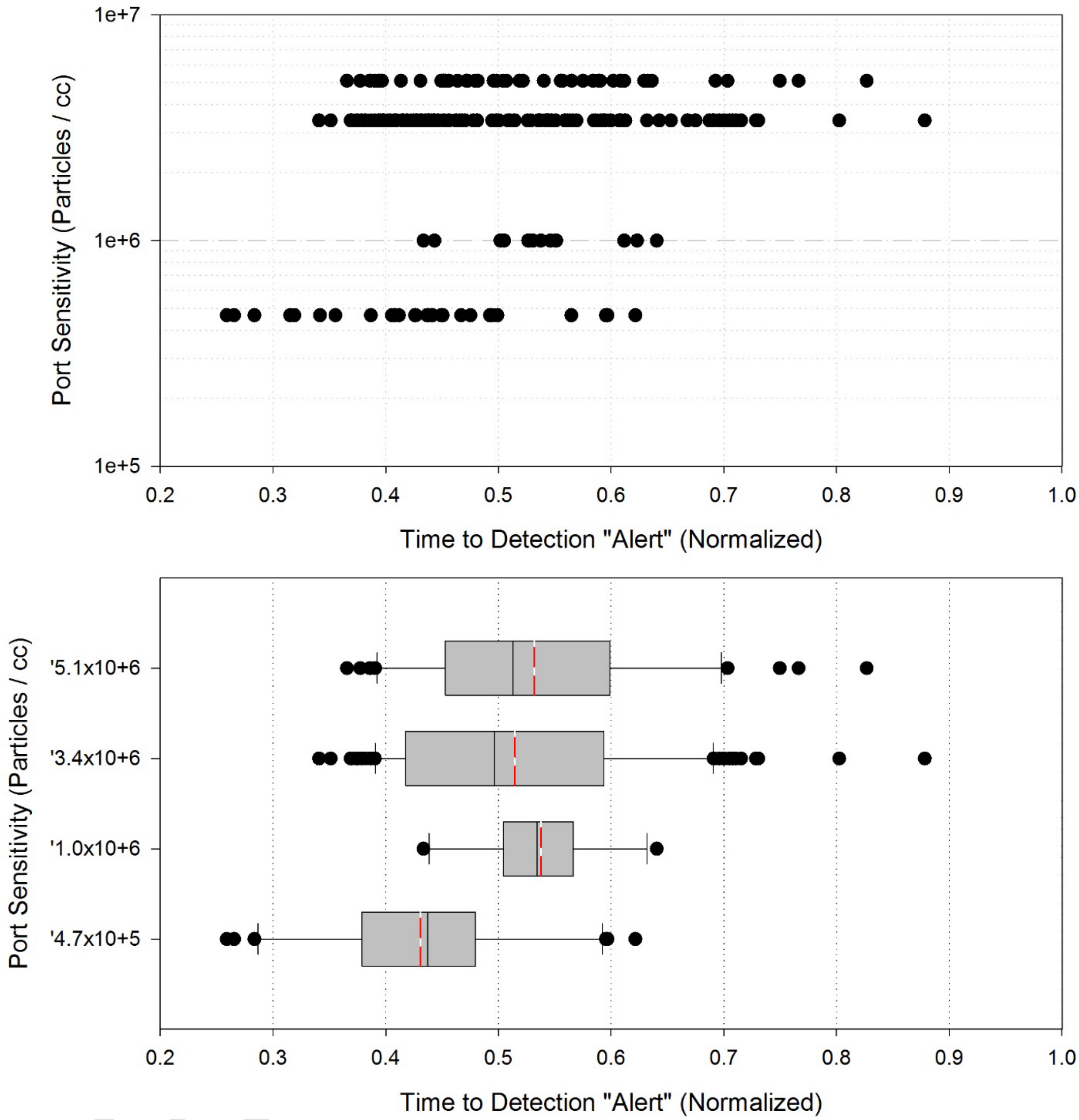


Figure B-20. Cloud Chamber (CC) Alert system response at different port sensitivities. (Top – scatter plot; Bottom – Box plot with mean bolded)

B.5 Process Used to Estimate Risk Scoping Study Parameters

Several parameters used in the risk scoping study presented in Part II of this report were estimated based on a specific set of empirical data presented in Part I. The subset of data used represented the minimum sensitivity requirements for a smoke detection system to be classified as VEWFD per NFPA 76 for detectors that reported in percent obscuration per foot or from vendor recommendations and information obtained from site visits for the cloud chamber technology. Since most ASD VEWFD systems are configurable to a range of sensitivity settings and number of sampling ports per zone, actual applications may use sensitivities other that

those used to estimate the parameters in the body of this report. Some of the VEWFD systems tested are configurable to have up to 5 different setpoints. As such the testing configured all available setpoints to cover a range of sensitivities. This data is included with this report and could be used to support parameter estimates for systems that are configured differently than the minimum sensitivity settings used in the main body of this report. The sensitivity settings of VEWFD systems will affect the system effectiveness (τ) in detecting pre-flaming (incipient) stage conditions. System sensitivity also affects the time when a system goes into 'alert' which if more sensitive should provide more advanced warning. This will have an effect on the time available curves used to support development of HEPs (ξ) for the field operator and technician response.

The purpose of the discussion presented here is to describe the process that could be followed to develop parameter estimates consistent with the approach taken in this report, but for systems that use sensitivity settings different from those use in the main body of this report.

B.5.1 Effectiveness (τ) of detecting pre-flaming (incipient) phase conditions

This term is developed based on the smoke detection system response to the incipient fire sources. As discussed in Section 7.2.3, this parameter is estimated using a "one-stage" bayes approach (Jeffery's non-informed) assuming a binomial data set (the detector either responds in the incipient stage "a success" or it does not "a failure"). The posterior distribution is a beta with parameters "α" and "β" calculated as shown below. The effectiveness estimates (τ) presented in the body of the report are based on detectors configured to setpoints as presented in Table B-17.

$$\alpha = (\#\, success) + 0.5$$
$$\beta = (\#\, trials) - (\#\, success) + 0.5$$
$$\tau_{mean} = 1 - \alpha/(\alpha + \beta)$$

Systems configured to be more sensitive than reported in Table B-17, should result in a higher effectiveness estimate. To estimate an effectiveness parameter, applicable data should be collected from the applicable available data included with this report or through testing. To be consistent with the risk scoping study presented in this report, a similar calculation method as described above is recommended.

Table B-17. Sensitivity settings used estimate effectiveness parameter as presented in Table 7-5.

Application	Cabinet/Room Ventilation	Detector Type	Sensitivity Settings at sampling port	
			% obsc/ft.	particles / cm^3
In-Cabinet	Natural and Forced <100 cabinet ACH	ION Spot	1.0	- - -
		PHOTO Spot	2.1	- - -
		SS	0.2	- - -
		ASD CC	- - -	1 x 10^{+6}
		ASD LS1	0.2	- - -
		ASD LS2	0.2	- - -
	Forced ≥100 cabinet ACH	ION Spot	1.0	- - -
		PHOTO Spot	2.1	- - -
		SS	0.2	- - -
		ASD CC	- - -	1 x 10^{+6}
		ASD LS1	0.2	- - -
		ASD LS2	0.2	- - -
Area-wide, Air Return Grill	HVAC in room	ASD CC	- - -	1 x 10^{+6}
		ASD LS2	0.2	- - -
Area-wide, Ceiling	Any	ION Spot	1.0	- - -
		PHOTO Spot	2.1	- - -
		SS	0.2	- - -
		ASD CC	- - -	1 x 10^{+6}
		ASD LS2	0.2	- - -

B.4.2 1st level field response (ξ) Technician / Field Operator

The human error probabilities (HEPs) developed in Section 10 are based in part from the time available curves presented in Section 8.2 and Appendix D. The time available curve are developed from operating experience that provides either an "incipient stage" duration or a "time available" duration for a specific technology starting at the time when a VEWFD system goes into 'alert.' Because the testing illustrated differences in response among the VEWFD systems tested, individual time available curves are developed, based on this empirical data and operating experience. The following provides a description of the process followed to develop these curves. Detector sensitivities other than those reported above (see Table B-17) will alter the performance of these systems and thus change the time available curves. To be consistent with the risk scoping study presented in this report, a similar calculation method as described below is recommended. Figure B-21 provides an illustration of the difference between the incipient stage period (duration) and the time available for operator response prior to flaming conditions, following a smoke detection system response.

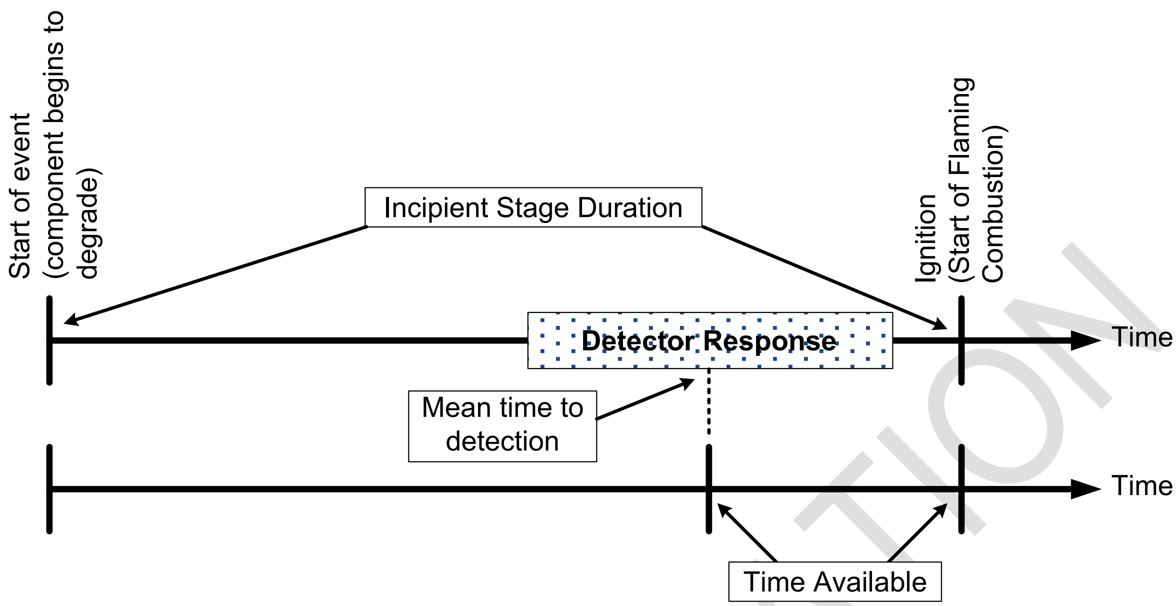


Figure B-21. Illustration of difference between incipient stage and time available[1].

Operating experience that reports an incipient stage duration, should be multiplied by the complement of the mean normalized detector 'alert' time. This results in an estimate of the time available. The mean estimate should be based on the data for the applicable sensitivities for the VEWFD system under evaluation. Table B-18 shows the mean estimates used in the main body of this report.

Table B-18. Mean Normalized Time to "Alert" for Sensitivities Reported in Table B-17

OpE Detector	Normalized Mean time to detection	Relative difference between detection technologies			
		CC	LS-SS	ION	PHOTO
CC	0.48	1.00	0.50	0.65	0.15
LS-SS	0.74	2.00	1.00	1.31	0.31
ION	0.66	1.53	0.76	1.00	0.24
PHOTO	0.92	6.50	3.25	4.25	1.00

For example, if an event indicates a 4 hour incipient phase duration, the time available is estimated as follows:

Cloud chamber :	(4 hours) x (1 - 0.48) = 2.08 hours
Light scattering / sensitive spot :	(4 hours) x (1 - 0.74) = 1.04 hours
Ionization spot type :	(4 hours) x (1 - 0.66) = 1.36 hours
Photoelectric spot type :	(4 hours) x (1 – 0.92) = 0.32 hours

[1] For illustration purposes only. In some configurations detector response may occur after ignition.

As presented in Section 5.9, the detectors response to the incipient smoke source varied over a range and did not necessarily overlap, even for detectors employing the same technology and configured to the same sensitivities. As such, the use of the mean relative difference estimates presented in Table B-18 allows for operating experience from on VEWFD detector technology type to be interpolated to another technology based on the data collected from this research project. That is, for operating experience events that are based on a specific detection technology, the relative difference estimate can be used to modify the time available from one technology to represent the time available for another technology.

For example, if an event indicates that a cloud chamber ASD VEWFD system provided 4 hours of advanced warning (time available to respond before flaming conditions), then estimates for the other technologies based on this event can be estimated as follows:

Light scattering / sensitive spot :	(4 hours for CC) x (0.50) = 2.00 hours for LS-SS
Ionization spot type :	(4 hours for CC) x (0.65) = 2.60 hours for ION
Photoelectric spot type :	(4 hours for CC) x (0.15) = 0.60 hours for PHOTO

The relative difference estimates are calculated based on the difference between the normalized mean time to detection, such as:

$$\%\,relative\ difference = 1 - \frac{(1 - OpE\ detector\ mean) - (1 - conversion\ detector\ mean)}{(1 - OpE\ detector\ mean)}$$

For the sensitivities used in the main body of this report, the relative difference estimate to convert operating experience of a cloud chamber to a light scattering data point is:

$$1 - \frac{(1 - CC_{mean}) - (1 - LS.SS_{mean})}{(1 - CC_{mean})} = 1 - \frac{LS.SS_{mean} - CC_{mean}}{1 - CC_{mean}} = 1 - \frac{0.74 - 0.48}{1 - 0.48} = 0.5$$

Once available operating experience is converted to a time available for a specific technology, the data can be fit to a distribution. This is discussed in Appendix D. The developed distribution and plant specific operator response timing can then be used to conduct the human reliability analysis to develop plant specific HEPs following the process discussed in Section 10.

Example cases for cloud chamber based ASD VEWFD system
(most vs. least sensitive setpoint tested)

To support the variations in the human error probabilities presented in Section 10.6.3, the in-effectiveness and HEP split fractions estimation process will be illustrated. The least sensitive data for the cloud chamber was collected during the laboratory large-cabinet and full-scale large-room single-zone in-cabinet experiments. In both of these cases the least sensitive of the four setpoints was configured to approximately 9,000,000 particles per cm^3 at the sampling port. The most sensitive data for the cloud chamber was collected during the full-scale small-room in-cabinet experiments. In this series of tests, the most sensitive of the four setpoints was configured to 150,000 particles per cm^3 at the sampling port. Based on these data sets, the estimation of the in-effectiveness, mean time to detection, and exponential distribution parameters are shown in Table B-19.

Table B-19. Estimation of Parameters for Cloud Chamber Variation Case.

Least Sensitive (9,000,000 particles / cm^3)	Most Sensitive (150,000 particles / cm^3)
# of tests : 44 # of responses : 44 $\alpha = (44) + 0.5$ $\beta = (44) - (44) + 0.5$ $\tau_{mean} = 1 - 44.5/(44.5 + 0.5) = 1.1x10^{-02}$ The normalized mean time to detection at the specified sensitivity: 0.60 Exponential Distribution Parameter $\lambda = \left(\frac{1}{n}\sum_{i=1}^{n} x_i\right)^{-1} = 0.674$	# of tests : 35 # responses : 35 $\alpha = (35) + 0.5$ $\beta = (35) - (35) + 0.5$ $\tau_{mean} = 1 - 35.5/(35.5 + 0.5) = 1.4x10^{-02}$ The normalized mean time to detection at the specified sensitivity: 0. Exponential Distribution Parameter $\lambda = \left(\frac{1}{n}\sum_{i=1}^{n} x_i\right)^{-1} = 0.428$

Following the process outlined in Appendix D.2, the sampling point split fractions for the CC at these sensitivities are estimated as;

For least sensitive case:

Time (Minutes)		Split Fraction
Start	End	
0	$60 \cdot \left(\frac{-1}{\lambda}\right) \cdot \ln(1-0.1) = 9$	0.10
9	30	$e^{-\lambda \cdot t_{10th}} - e^{-\lambda \cdot 0.5} = 0.19$
30	60	$e^{-\lambda \cdot 0.5} - e^{-\lambda} = 0.20$
60	∞	$e^{-\lambda} = 0.51$

For the most sensitive case:

Time (Minutes)		Split Fraction
Start	End	
0	$60 \cdot \left(\frac{-1}{\lambda}\right) \cdot \ln(1-0.1) = 15$	0.10
15	30	$e^{-\lambda \cdot t_{10th}} - e^{-\lambda \cdot 0.5} = 0.09$
30	60	$e^{-\lambda \cdot 0.5} - e^{-\lambda} = 0.16$
60	∞	$e^{-\lambda} = 0.65$

With these sample times, new HEP estimates are developed in Sections 10.6.3.2 and 10.6.3.3, following the process outlined in Section 10 of this report.

Example case for light scattering based ASD VEWFD system

Let's assume that an ASD VEWFD system using a light scattering based detection technology is configured with an "alert" port sensitivity of 0.02 % obscuration / ft. for use in an in-cabinet application. From the testing performed, one series of testing has a light scattering system configured to 0.0252 % obscuration / ft. at the sampling port. Using this tested configuration, the data is collected and summarized below to support estimating both the in-effectiveness and the mean time to detection that can be used to support the HRA.

Total number of tests : 30
Total number of system responses at specified sensitivity : 30

$$\alpha = (30) + 0.5$$
$$\beta = (30) - (30) + 0.5$$
$$\tau_{mean} = 1 - 30.5/(30.5 + 0.5) = 1.6x10^{-02}$$

The normalized mean time to detection at the specified sensitivity : 0.39

Following the process outlined in Appendix D.2, the exponential distribution parameter and sampling point split fractions for the CC at this sensitivity are estimated as;

$$\lambda = \left(\frac{1}{n}\sum_{i=1}^{n} x_i\right)^{-1} = 0.442$$

Time (Minutes)		Split Fraction
Start	End	
0	$60 \cdot \left(\frac{-1}{\lambda}\right) \cdot \ln(1 - 0.1) = 14$	0.10
14	30	$e^{-\lambda \cdot t_{10^{th}}} - e^{-\lambda \cdot 0.5} = 0.10$
30	60	$e^{-\lambda \cdot 0.5} - e^{-\lambda} = 0.16$
60	∞	$e^{-\lambda} = 0.64$

With these sample times, new HEP estimates can be developed, following the process outlined in Section 10 of this report.

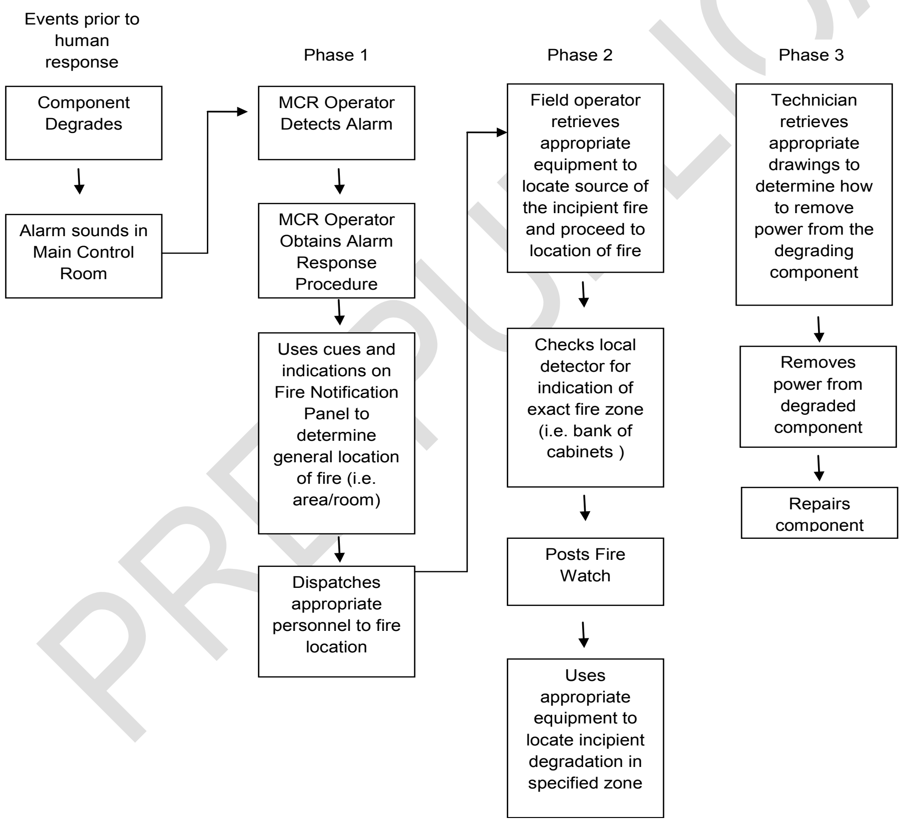
APPENDIX C
SUPPORTING INFORMATION FOR HUMAN PERFORMANCE EVALUATION

C.1 Human Factor/Human Reliability Analysis Evidence Database

This section documents questions and answers received to a written survey, with follow-up phone calls, that were collected during the project. After each entry, an application designator will appear, which are defined as follows:

IC – in-cabinet application
MCR – main control room application
AW – area-wide application

C.1.1 Response Operations: Questions and Answers[1]



[1] This set of questions was used to obtain information from 2 NPPs. One NPP provided written responses, the other through a teleconference.

The previous chart (in C.1.1.) depicts an in-cabinet very early warning fire detection system (VEWFDS) alarm response operation. It is not specific to any one plant and represents a generic case. The alarm response operations are represented here in three phases. The authors categorized the responses into three different phases because each phase is completed by different groups of personnel.

The authors recognize that there will be variations in alarm response operations. The aim is to capture examples in which operations may vary from those depicted herein. In addition, some specific questions regarding individual processes are noted below:

Operations Questions

(1) Is there immediacy associated with VEWFDS alarm response? In other words, is the alarm treated like any other fire alarm? If not, how is it different?

Plant X: Yes, if an alert comes in, an operator and instrumentation and control (I&C) tech are sent. If an alarm, the operator and tech are sent along with the fire brigade. If a system trouble annunciator comes in, an operator is sent out. Alarm does not necessarily indicate a flaming fire. The response associated with an incipient alert/alarm is the same as for spot detectors. First, the MCR dispatches an operator, not the fire brigade, as in a VEWFDS alert. If additional signs/signals of fire are detected, then the fire brigade is sent, similar to when a VEWFDS alarm comes in. Regarding immediacy, fire alarms of any kind trump other activities, so a response from operators comes within seconds. Only a reactor trip would trump a fire alarm. (IC)

Plant Y: Field operator dispatched immediately. (IC)

a. Are the VEWFDS systems set to have alerts and alarms? If so, how many of each?

Plant X: Set to have one alert and one alarm (also real-time graphic read-out of sampler) (IC)

Plant Y: Yes there is an alert and an alarm. Alerts are at 20 percent above background and alarms at 50 percent above. (IC)

b. Are alerts, alarms and system trouble differentiated on the annunciator panel?

Plant X: Yes. (IC)

Plant Y: Yes, three annunciators on front panel. (IC)

c. If both alerts and alarms are used, how does the response differ?

Plant X: If an alert comes in an operator and I&C tech are sent. If an alarm, the operator and tech are sent along with the fire brigade.

Plant Y: No difference in response, field operator will be immediately dispatched to investigate either

(2) Where is the alarm located in the control room (e.g. front panel/back panel)?

Plant X: All three annunciators are on the front panel.

Plant Y: Front panel.

(3) Where is the fire notification panel located?

Plant X: A computer screen located on shift technical advisor (STA) desk. The screen is separate from other screens and is dedicated to fire. A reactor operator (RO), senior reactor operator (SRO), or STA can look at this. Either SRO will look or he or she will assign someone to look (as STA will not be in MCR when this annunciator goes off).

Plant Y: Close to shift managers desk

(4) What personnel are dispatched by MCR operators (e.g. just field operator, field operator and digital instrumentation and controls (DI&C) technician)?

Plant X: Field operator and DI&C technician

Plant Y: Field operator only

a. Are the necessary staff available 24/7? If not, what are the contingency actions (e.g., DI&C tech called in)? How do contingency actions affect the timing of the response?

Plant X: Yes, including I&C tech. One is required at the plant at all times. Probably more than one during the day shift.

Plant Y: Field operator available 24/7.

(5) What equipment is used to locate source of incipient fire (e.g. sniffer, thermal imaging camera)?

Plant X: Portable sniffer—tested weekly.

Plant Y: Portable sniffer.

a. If a thermal imaging camera is used, are baseline heat mappings of each cabinet available to compare with current conditions? If so, is comparison done at the scene of incipient fire or is additional analysis involved (e.g., software package needed to compare conditions)?

Plant X: Thermal cameras are not used.

Plant Y: Not applicable.

b. What is the reliability and sensitivity of the sniffer technology?

Plant X: Tested weekly.

Plant Y: Not specifically known, but probably similar to fixed installation as it is the same type of equipment.

(6) How many cabinets are typically part of the same zone?

Plant X: It varies, from one to nine cabinets. There are typically sampling ports in each cabinet. The cabinets are partitioned and sealed.

Plant Y: Between 5 and 15 cabinets

(7) Is the posted fire watch a permanent or roaming fire watch? If it is roaming, how frequently is the site observed?

Plant Y: Continuous fire watch until event is concluded. Fire watch personnel are prevented from leaving the post; they cannot go through keycard door.

Plant X: Permanent fire watch following alert or alarm until situation resolved.

a. Is the dispatched field operator also considered the initial fire watch? If yes, what training is required to qualify as a fire watch (e.g., ability to use fire extinguisher, fire brigade training)?

Plant X: Yes. All (i.e., 100 percent) AO's have "fire watch incipient" training. About 95 percent of FOs are fire brigade qualified. All FOs are qualified as incipient fire watch; (this was added training, includes fire extinguisher use).

Plant Y: Yes. All operators trained in use of fire extinguishers, fire watch, and most are fire brigade members.

(8) What type of training is given to operators for using sniffers and thermal imaging cameras?

Plant X: Training—initial, continuing training cycle every 2 years, sit down instructional and practical at end, about 4-hour training. Practical training includes finding a "smoking" wire; no timing data collected on this aspect of training.

Plant Y: Training not implemented as of yet, but expect that all operators will have specific training (with qualification sign-off) in use of sniffers as part of basic operator training.

(9) Are cabinets opened when using the portable sensing equipment, or is it used with the doors closed?

Plant X: It depends on the zone to which personnel are responding. If it is a multi-cabinet zone, personnel start by sniffing the outside of cabinets to determine which specific cabinet it is. The identified cabinet is then opened to find the component. If it is a one-cabinet zone, the cabinet is opened. These actions are training-based.

Plant Y: Yes.

(10) Is the stopping point for receiving credit at the point of posting a fire watch, at the point of de-energizing the panel, or at time of repair?

Plant X: Assumption is made that 90 percent of incipient fires will be prevented and, specifically, the fire watch will prevent the incipient fire from having an affect beyond the ignition site.

Plant Y: National Fire Protection Association (NFPA) 805 Fire PRA credits incipient detection as a means of detecting fire before propagation from cabinet. No credit is taken for de-energizing or repairing affected component, or preventing loss of cabinet function.

(11) How often are VEWFDS down for service? How often are false alarms experienced?

Plant X: Annual maintenance requires system to be out-of-service for half a day. Overall, Plant X is not seeing many unplanned shutdowns.

False alarms caused by ongoing work. Personnel usually know about this work and can take detector out-of-service and post a fire watch. One detector alarms more often than others; it is not necessarily false-alarm, but rather, a bit too sensitive. The alarm often does not “lock in.” They are correcting this by changing the sensitivity settings. (IC)

Plant Y: No operating experience as yet.

Timing Questions

(12) Do you have any information regarding timing from the VEWFDS alarm sounding to a flaming fire?

Plant X: Yes, 2 hours and 42 minutes from alert to flaming fire on August 8, 2013.

Plant Y: No plant specific experience as yet.

(13) What is the average time from the alarm sounding in the MCR to the dispatch of field personnel?

Plant X: Immediately. The operator closest to location is dispatched.

Plant Y: Based on normal fire alarm response—Immediate

(14) What is the average timing between the field operator receiving the dispatch call and arriving at the fire location?

Plant X: Varies, but typically, 2 to 8 minutes. I&C tech are typically a few minutes behind auxiliary operator (AO).

Plant Y: Usually 3 to 4 minutes for field operator; 15 minutes or less for brigade response.

(15) What is the average time for the field tech to locate the degraded component using the portable equipment?

Plant X: No empirical information available. A single cabinet zone would require a few minutes to narrow down which component.

a. How does the zone size affect this timing (three cabinet zone vs. 10 cabinet zone)?

Plant Y: No experience as yet but would estimate 1 minute to sniff one cabinet. Therefore time to identify specific cabinet could be 5 to 15 minutes.

b. If thermal imaging is used, how long does comparison between baseline and current conditions take?

Plant X: Do not currently use thermal imaging.

Plant Y: Not applicable.

(16) What is the average time to de-energize a degraded component?

Plant X: Quickly once the component is identified. If whole thing is on fire, they will de-energize the entire cabinet, which takes seconds. It would take minutes for specific breaker. One breaker requires a local action whereas the whole cabinet can be done from the control room. The logic for the cabinet power is already laid out in MCR on control board. No procedures for specific equipment de-energization; this activity is directed by CR supervisor.

Plant Y: Do not anticipate de-energizing component as an immediate response unless absolutely warranted because of the impact on plant operations

(17) What is the average time to repair a component?

Plant X: Varies widely.

Plant Y: Long term.

C.1.2 Information from Trip Reports

(1) How do operators respond to the various notifications, (e.g. pre-alarm and alarm)?

Response 1: They respond in accordance with APP-044-B39. If detector indicates alarm, investigate for any indication of smoke, charring or overheating components. In addition to visual inspection, other methods such as thermography can be used to locate any overheating components. If an additional alarm on opposite train is received, activate the fire brigade. (MCR)

Response 2: In a pre-alarm condition, operation attempts to clear the pre-alarm, if no success, operation will initiate an operator alert and request ERT personnel assistance. (AW)

Response 3: Pre-alarm: control room call responding organizations, shift emergency response manager; someone checks the panel or visual size-up. Alarm: shift manager. (AW)

(2) Has the system false alarmed?

Response 1: Yes. During the initial installation of the VESDA system, multiple spurious alarms were observed. Over the years, some alarm set points have been offset to account for the environmental conditions, as a result, numbers of spurious alarms have reduced. The cause of the spurious alarm ranges from unknown reasons, to airborne charcoal dust from filters, to fumes from floor stripping, to dust bunnies. (AW)

Response 2: Yes. The most common cause is/was other work in protected areas (units not bypassed). During the summers immediately following installation, there were some issues caused by heavy smog or wildfires, causing high ambient background conditions. (AW)

Response 3: Yes, from nitrogen purging, maintenance activities. Protocol to inform CSNC, insurance company, (follow procedure for notification, SERM, duration time, same notifications if it is a real fire. (AW)

Response 4: No. (MCR)

Response 5: Yes, from burning popcorn, hot work in the battery room, and a fan failure. (AW)

(3) How would an incipient fire be located and verified (equipment used, sequence of actions taken)?

Response 1: Compensatory measures, thermal imaging (IR), only certified people can use sniffers. (AW)

Response 2: Thermal imaging cameras are used to detect incipient fires. (AW)

Response 3: Cabinet doors would be opened, visual and smell senses would be used. If necessary, a thermal imager would be used. (MCR)

Response 4: Human senses. (AW)

(4) What kind of training has been provided to the operators, technicians and fire fighters on the system?

Response 1: Control maintenance technicians were provided with a one week comprehensive training on the EST 3 and the VESDA system at Edwards. They were trained on the operation of the software and detection panel. (AW)

Response 2: Operations were provided with classroom and hands-on training for operation of the Fireworks and Cirrus-Pro software. Operators were required to show proficiency in Fireworks and Cirrus-Pro to gain qualification. Technicians were provided initial classroom training on the Cirrus-Pro detectors and the FireWorks and Cirrus Pro software which satisfied vendor qualification requirements for plant techs to work on the

Cirrus Pro detectors. A training aid that simulated the detector/fire panel/software interconnection was provided to the training department for further instruction. (IC)

Response 3: No specific training implemented, the unit is straightforward. (MCR)

(5) Are the operators trained on calibrating the system using proprietary software, if applicable?

Response 1: The control maintenance technicians are trained on the manipulation of the system and the use of the applicable software. Yes. Control Maintenance technicians have been trained by the product vendor in the use of system configuration software. This is required to enable the technicians to conduct proper maintenance, testing and troubleshooting of devices. (AW)

Response 2: Operators are trained and qualified to use Fireworks and Cirrus-Pro packages. (IC)

Response 3: No. (MCR)

(6) Where is the detector located relative to the detection zone and why?

Response 1: The detector is located outside the RGTB cabinets, but approximately 5 feet from the nearest RGTB cabinet, because of space limitations. Tech manual recommends locating the detector within the protected space. (MCR)

Response 2: Aspirating detector is located remote to the cabinets being monitored and air sample is piped from the cabinets being monitored to the detectors. Each detector has four zones. (IC)

Response 4: The detectors are typically located in the protected zone. This approach acts to minimize any adverse effects caused by pressure differentials within different areas of the station. It also serves to ensure that sampled air is discharged to the same area from which it originated, eliminating opportunities for the spread of smoke or airborne radioactive particles from one area to another (AW).

Response 5: In a different room. Both detectors are on the same wall next to each other. (AW)

(7) Are there any drawbacks specific to the VEWFDS?

Response 1: Maintenance requires quarterly and annual surveillance which is time consuming and expensive. System is somewhat complicated, requiring a significant vendor interface.

Response 2: A spare unit is recommended. MCR)

(8) What compensatory measures do you use when the system is out-of-service?

Response 1: Continuous fire watch. (AW)

Response 2: None. This detector is just one in a detection circuit made up of other spot detectors. The rest of the detector circuit remained operable. The detection circuit is located in the constantly manned control room. (MCR)

Response 3: Continuous fire watch. Also used when the fire source can't be located and alarm will not clear. (IC)

Response 4: Continuous fire watch, restricted work activities. (AW)

C.2 Shearon Harris Nuclear Power Plant Site Visit of January 13, 2016

NRC staff visited Shearon Harris Nuclear Power Plant (Harris) on January, 13, 2016 with the purpose of better understanding an operational event that occurred on August 2015, including information to support this reports' event tree analysis (Section 6), timing analysis (Section 8), the human factors analysis (Section 9), the human reliability analysis (Section 10), and non-suppression probabilities assignments (Section 11).

Pre-visit information (e.g., purpose, site visit plan, list of questions), and preliminary plant responses, are provided in Section C.2.1. The plant site visit itself consisted of three (e) major activities:

1. general, roundtable discussions between NRC and utility staff
2. plant walkdowns (including main control room and other plant areas)
3. a follow-up call on January 28, 2016 with utility staff

Notes taken during the site visit (i.e., activities #1 and #2), plus plant visit participants, are captured in Sections C.2.2, C.2.3, C.2.4, and C.2.5. Notes from the follow-up call are provided in Section C.2.6.

C.2.1 Pre-Visit Information and Preliminary Answers to Questions

This section documents preliminary information exchanged between the NRC and the utility. The NRC provided a list of questions before the plant visit. At the NRC's request, the utility provided written answers in advance of the visit.

The list of the NRC's questions and the utility's responses are the following:

Purpose: Provide RES team with additional information on event, system performance, and plant personnel performance.

Desired Outcome: Use information to support refinements to model assumptions and evaluate characterization of event and system/human performance.

Site Visit Plan: First, talk through what happened (including discussion of the timeline, operator & technician actions, etc.). Then, walkdown the relevant areas (e.g., MCR, cabinet area) with plant staff. And finally, have a follow-up discussion to clear up any remaining questions. In all cases, having the plant staff who were directly involved in the event would be the most helpful.

List of Questions:

1. Detailed timeline of event.

    a. Including timing and actions taken between MCR receipt of first VEWFD system “alert”; removal of power from control switch circuit, including resetting VEWFD system “alert”; and declaring the VEWFD system inoperable.

Response:

1. *08/01/2015 19:52 - Received ALB 30/4-1 IFD System Alert for the ACP area. Dispatched Operator and I&C, they reported no unusual conditions. WR# 20002776 CR#1938438.*
2. *08/01/2015 20:05 - ALB 30/4-1 IFD System Alert annunciator is clear.*
3. *08/01/2015 23:08 - Received ALB 30/4-1 IFD System Alert for the ACP area. Dispatched Operator and I&C, they reported no unusual conditions.*
4. *08/01/2015 23:30 - ALB 30/4-1 IFD System Alert annunciator is clear.*
5. *08/01/2015 23:34 - The Incipient detection was declared inoperable and a continuous Incipient Detection fire watch established. (Fire OOSL –15-5338)*
6. *08/03/2015 – Work order 20008305 given to FIN Team*
7. *08/03/2015 – following initial troubleshooting, with no results FIN Team requests Thermography.*
8. *08/03/2015 14:10 PM – Thermography performed (time stamp on picture)– see Thermography picture.*
9. *08/04/15 13:14 Opened PP-1A312-SA-8, MS LINE ‘C’ PORV (1MS-62) SERVO AMP-ALTERNATE*
10. *08/04/15 13:51 - Hung PSC-1-15-3020-CSGPORVALT-0092 for C SG PORV alt power.*
11. *08/04/15 14:24 - ALB-030/4-1, IFD SYSTEM ALERT, is clear. 1SFD-E087 for the ACP has been reset.*
12. *08/04/15 14:58 - Completed FPT-3220A INCIPIENT FIRE DETECTION ALARM NOTIFICATION FUNCTIONAL TEST - MONTHLY INTERVAL, Satisfactory*
13. *08/05/2015 – 07:30 The detector declared functional and returned to service following removal of power from CS-1256.2 (C SG PORV) and the Alarm clearing. (Fire Watch secured)*
14. *08/05/2015 – 14:45 Work on repair begins*
15. *08/06/2015 – 15:00 Work complete*

2. Operator/technician response
    a. Description of actions taken.

Response:

Operator and I&C dispatched Pre APP-ALB-030. See below

    b. Procedural requirements for operator, technician and fire brigade.

Response:

See APP-ALB-030 and/or APP-ALB-030 incipient detection info only (attached)

    c. Handheld ASDs
        i. How much time was used with handhelds and what/how survey was conducted?

Response:

1. The Shift I&C technician sniffed with the portable incipient fire detector for at least 30 minutes during the first alarm.
2. The second alarm no abnormal indications reported from field.
3. 1SFD-E087 declared Non-Functional and established a continuous fire watch (within one hour).

        ii. Were doors opened, vents surveyed, etc.
        [May be useful to conduct a walkthrough of procedure.]

Response (on shift SRO):

*Yes, I spoke with the I&C technician about sniffing the ACP panel and sniffing/surveying behind door. An AO was present while I&C tech monitored behind all the door panels. I&C techs get special IFD training and are qualified to respond to IFD alarms (**ICC0016H-N**).*

    d. Description of fire watch (actions, responsibilities, procedure).

Response:

This is a continuous Fire Watch performed by personnel qualified as a fire watch that are also trained to use a fire extinguisher.

From AR 405845:

The plan for incipient fire watch is as follows:

1. *A new qualification group FH32 will be created called Fire Watch/Incipient Detection*

2. *The qualification will require qual group FPQ0001G which will require a fire extinguisher practical.*

3. *NLOs will be scheduled to undergo training for FPQ0001G.*

4. *The procedure for requiring a fire watch for incipient fire detection equipment failure,*

FPP-005 will require any individual performing a fire watch for out of service or failed incipient fire detection equipment, to hold the qual FH32.

3. Thermal imaging camera

   a. What process were you in when you used the Thermal Imaging Camera (part of fire response, troubleshooting nuisance VEWFD system alarms, part of repair/planning, etc.)

   Response by Engineer that used the Thermal imaging Camera:

   Part of repair/planning

   b. What did you do and were procedures followed/available for this?

   Response by Engineer that used the Thermal imaging Camera:

   There are no procedures for thermography

   c. Were baseline images available?

   Response by Engineer that used the Thermal imaging Camera:

   No. This component is does not have a thermography route and had not ever been scanned prior to my knowledge

   d. Did investigation stop after control switch was located?

   Response by Engineer that used the Thermal imaging Camera:

No. The entire Auxiliary Control Panel was scanned.

4. Switch Repair

   a. Were actions taken to de-power component (cabinet) prior to replacement?

   Response (FIN Team supervisor) :

   Yes, see plant status control tag # PSC-1-15-3020-CSGPORVALT-0092 for timeline of deenergizing CS-1256.2SA from PP-1A312-SA-8.

   b. When was power removed from the switch?

   Response:

   08/04/15 13:14

   c. Component switch cut sheet/bill of material information
      i. thermal rating

   Response:

   WO 20008305 was used to replace CS-1256.2SA with part number 9220143121 PQL1.

   Thermal rating 120 hours at 80 degrees C (176 degrees F), 50 degrees Rise.

      ii. qualification, if applicable

   Response:

   See ESC-STD-1000 Rev 6. Which is EC 62343
   Attachment C. Electroswitch Series 20, Part Number 38050M-132/Type M1S1L Rev.A (Drawing No. G51, Sheet 1 dated 03-24-06), shall be Nuclear Safety Related in accordance with the requirements of ESC-STD-1000 Rev.6 and Technical Publication MIN-1 Dated April1, 1991. See ESC-STD-1000, rev 6 attached.

5. VEWFD system reports
   a. List of "alerts," "alarms," nuisance alarms

   Response:

   Not available

b. Outcomes of system annunciation (nuisance, fire, smoke, etc.)

Response:

All items to date with the exception of four alarms were no fire products found.
Those four items were:

1. *Hot resistor found in Main Termination Cabinet. This was around 180°F, and was due to inadequate spacing around the resistors. The proper gap was established by bending the resistor*
2. *Ground in Transformer 1E2 (ground alarm received). This was outside the cabinets being sampled, but the sniffer started at the cabinet and was able to follow the combustion particles across the room to the ground resistor which was at about 250 °F.*
3. *Ground in Transformer 1D2 (ground alarm received) This was outside the cabinets being sampled, but the sniffer started at the cabinet and was able to follow the combustion particles across the room to the ground resistor.*
4. *The 8/1/15 ACP event*

c. Time spent investigating

Response:

About 30 minutes

6. Data to update Availability, Reliability estimates.

No response

7. System set points.

a. What are the system set points for each of the VEWFD systems installed at Harris (Gain, % of gain, # ports per zone)?

Response:

Sensitivity of 7. Alert is 30% of range and Alarm is 50% of range, There is one port serving Three Zones for 1SFD-E087 (for ACP.

b. Any change to set points following event?

Response:

No – would require an Engineering Change.

C.2.2 Shearon Harris Plant Site Visit - Participants

Harris plant staff who supported the site visit included:
- Fleet Fire Protection Program Manager
- Site Appendix R / safe shutdown engineer
- Site Fire Protection engineer
- Site Licensing
- Site I&C Technician
- Site Thermal Imaging engineer
- Site Detection System engineer
- Site Operations

NRC staff who participated in this plant site visit were:
- Office of Nuclear Reactor Regulation (NRR) - Harold Barrett (fire protection)
- Office of Nuclear Regulatory Research (RES):
  - Gabe Taylor (fire protection)
  - Susan E. Cooper (HRA)
  - Nick Melly (fire PRA, fire protection)
  - Amy D'Agostino (HF)

C.2.3 Human Factors/Human Reliability Analysis Notes

Plant site visit notes taken by NRC HF and HRA analysts are combined in the text immediately below.

C.2.3.1 Expected Sequence

Sequence of activities for incipient detector "alert" response was discussed.

- Alert comes into main control room (MCR)
- Board operator retrieves and follows alarm response procedure (ARP)
  - Exact field location of alert is determined via "fireworks" computer program on Shift Technical Advisor (STA) desk
  - Board operator directs STA to handle communications, communications flow through the STA (Harris STAs are operators and some are Senior Reactor Operators [SROs])
  - AO is called (can be called via PA, cell phone, radio or to the AO corral)
  - AO is dispatched to the alert location to investigate
    - the estimated travel time to the field location is 3 minutes
  - STA dispatches the Instrumentation and Control (I&C) tech

  NOTE: If the alert clears before the I&C tech arrives, the AO can leave
  - I&C tech secures his current work first, then:
    - goes to shop area behind the MCR to retrieve portable sniffer
    - Stops at MCR to verify location and get keys for any locked cabinets
    - Goes to location:
      - Puts detector on floor to get background reading (assess initial condition outside of cabinets) (takes a few minutes)
      - I&C opens each cabinet

- Inserts sniffer hose (a part constructed by utility; not provided by vendor) inside cabinet & partially closes door to sample air inside cabinet
- Uses sniffer:
    - -Starts at most sensitive range

inserts the sniffer hose (the hose it a part constructed by the utility, not provided by the vendor) and partially closes the cabinet to sample the air
- I&C says this can take 5-8 minutes (or 2-10 minutes?)[2] per cabinet

C.2.3.2 *August 2015 Event Notes:*

General timeline for event that occurred in August 2015 was discussed.

-An alert was received twice and cleared both times on its own

-In both cases the AO reported "no unusual conditions" meaning no flaming fire or signs of fire (smoke, etc.)

-After the second alert and clear, the system was declared inoperable

-This declaration was made to allow a continuous fire watch to be posted, however, the incipient system was still in operation

C.2.3.3 *Thermography*

Plant personnel trained to use thermography equipment discussed use of this equipment.

-Personnel are required to complete a qual card to use the thermographic camera

-includes 1 week of offsite training and over 100 hours of working with the camera

-Personnel claim that the hotspot is typically immediately apparent

-Occasionally they need to look at comparison data or look at trends of the temperature of a component over time

- In this case, it took thermography about 1 hour to find the hotspot

-Once the hotspot was identified, the cabinet was de-energized in order to fix the component

-A thermographer is not always on shift but can be called in

C.2.3.4 *Equipment Notes*

General discussion on incipient detector equipment included some specifics on plant-specific detector installations.

-Portable sniffer has 10 sensitivity settings

-Incipient detectors are set to a setting of 7 or 8, except one that was causing problems and is now set to 5

-Computer/notification "panel" on STAs desk in MCR

C.2.3.5 *Personnel/Training Notes*

-There is one I&C tech on every shift

-Personnel receive IFD response training that is run in-house

[2] Conflicting information in notes; likely from different sources (e.g., group meeting versus walkdown group).

-More detailed training is given to maintenance staff that will be working on the system
-STA - mostly licensed RO-SRO (plus engineer or tech ed)

C.2.3.6 Opinion/Insights/Operating Experience from plant personnel

-I&C tech is confident that the system will pick something up if there is something to be found
-Example instances showing how sensitive detector is:
a) vacuum used to clean out cabinets set off detector in same room
b) microwave cooking kitchen adjacent to MCR set off MCR detectors
c) in transformer event, overhead ion detector went off ~4 hours after incipient detector (with incipient detector 20 feet away)
-Thus far there have been no “flaming fires” in rooms with incipient detection
-Personnel estimate that there are 1 to 2 events per month that require the I&C tech to go out with the portable sniffer
-Personnel noted that cabinets are always opened in order to inspect using the portable sniffer
-Personnel noted that the often see “spikes” on the system. In other words, the particles being counted quickly go up and right back down. This indicator was down for 8/2015 event.

C.2.4 Probabilistic Risk Assessment Notes

During the site visit the question arose as to what the risk drivers were for many of the installed systems. This line of questioning led to specific changes to section 6.1.1.1 “Application of VEWFDS Probability of Non-Suppression; Pns”. This section describes the applicability of suppression system use and highlights the inherent use of these systems to mitigate damage to targets outside the enclosure of origin.

For suppression credit to be applied to targets within an enclosure a more detailed evaluation of de-energization strategies, including adequate and appropriate justification in the form of a detailed human reliability analysis must be performed. One way a licensee could achieve significant fire prevention credit would be to “pre-locate” the isolation devices for all ignition sources within each cabinet in an effort to speed up the process. If such an effort was taken, additional credit for preventing fires could be allowed. This would need to include predetermining the isolation devices, conveniently displaying that information for use in response to VEWFD system alerts, training responders so that they could rapidly locate and operate the isolation device(s), and conducting drills to periodically demonstrate this ability.

C.2.5 Notes from follow-up call with utility

The NRC team that made the site visit had some follow-up questions that were addressed in a conference call.

Those who attended the call included:

- NRC:
  - NRR – Harry Barrett
  - RES – Gabe Taylor, Susan E. Cooper, Nick Melly

- Utility:
  - o Fire protection
  - o I&C technician
  - o Operations

Questions:

1. A key was needed for the remote shutdown panel cabinet when we did the walkdown. Regarding keys and locked cabinets:
   a. Do all cabinets with incipient detectors have keys?
   b. Is it typical for the technician to get the keys from the MCR?
   c. Is there somewhere else (or another way) to get a key to technician at "alert" location?
   d. Is there a scenario where the field operator would get the keys?
   e. Once the technician confirms the location of the degraded component in a cabinet, does he close & lock the cabinet?
   f. Does the technician return the key to the MCR? Or, does he give it to field operator?
   g. If technician returns key to MCR, what is process for field operator if fire suppression is needed, e.g.,
      i. Does field operator have a key with him?
      ii. Is there a key in the room with the affected cabinet?
      iii. If there is no key available, what does field operator do if fire suppression is needed?

2. If possible, I'd like to have a general talkthrough with a field operator to what he/she does when called out for an incipient detector alert

3. Specific questions for field operator, e.g.,
   a. When does the field operator stay (versus leave room with "alert")?
   b. Especially what he/she is trained to do per incipient fire detector training IF technician does confirm with hand-held detector that there is a degrading component, e.g.,
      i. An overall talkthrough would be great - for cases where the "alert" signal DOES NOT CLEAR
      ii. With the "alert" signal confirmed, what is the status of the detector panel (i.e., is the signal cleared or does it stay "locked in")?
      iii. Where is he/she positioned with respect to the degraded component & affected cabinet (after its identified)?
         1. How near affected cabinet?
         2. Can he/she see the affected cabinet at all times?
         3. If not, what is he/she monitoring, etc.?
         4. Would the field operator open the cabinet if the incipient detector signals changed (e.g., local panel shows elevated readings and/or incipient detector changes from "alert" to "alarm")?
            5. What role, if any, do the local panels for the incipient fire detector play (e.g., are they monitored?)
      iv. When or under what conditions would the field operator move (per training, etc.)?

Answers:

- Operations:
  - o Need key for some local panels, etc.
  - o All keys are kept in MCR

    - There's a key log (for signing in & signing out keys)
    - Typically, the I&C tech logs out the key
    - MCR operators in touch with stationed fire watch with updates for STA desk computer
    - ARP-   -30 has note on "alert" locked in[3]
    - All ROs, SROs, STAs have qualification cards on use of detector on STA desk, including continuous monitoring of detector
    - Usually, STA is in the MCR
    - MCR operators will put high on "radar screen" to validate "alert" conditions
- Other:
    - Key not issued to continuous fire watch
    - Various and diverse indications of fire effects, e.g.,
        - Plant-installed incipient detector
        - Trend information on computer
        - Hand-held "sniffer"
        - Fire brigade thermal-imaging
        - Noses & eyes
        - Etc.
- Fire protection:
    - Extinguisher would be used
    - Cabinets are vented
    - Do not need key (to open cabinet) in order to extinguish fire
    - Are situations where detector goes straight to "alarm" (with no "alert")
    - When detector reaches "alarm," MCR operators dispatch: a) field operator, b) I&C tech w/ keys to open cabinet door (if needed), c) fire brigade (w/ thermal imaging camera)
    - Will de-power, if possible

[3] Later review of plant procedures identified these steps in the relevant procedure:

- **DISPATCH** an operator to the Incipient Detector Zone causing the alarm to investigate the source of the initiating signal.
- **DISPATCH** the on-shift I&C technician to the Incipient Detector Zone causing the alarm with the portable incipient detector to investigate the source of the initiating signal.
- **MONITOR** the initiating detector response on the CirrusPro screen during the field investigation.

APPENDIX D
EVALUATION OF OPERATING EXPERIENCE DATA

D.1 Evaluation of Fraction of Fire That Have Detectable Incipient Stages

This appendix documents the review of *potentially challenging or greater fires* from the fire events database. The results are summarized in Table D-1, which contains several fields described below.

Fire ID	Record number from EPRI Fire Events database
Fire Cause	Identifies apparent cause of event
Detected by	Identifies how the event was detected
Cabinet Type	Identifies the type of cabinet where the event occurred
Ignition Component	Identifies the component which ignited
Description	Provides summary of event
Incipient stage	Identifies if the event involved an incipient failure mode. Possible classifications are Yes, No, and Undetermined. Definitions are provided below.

Table D-1. Evaluation and Description of Bin 15 Events							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 instrumen-tation / annunciator	MCC	MCCB	Failure on demand. Following start of the main turbine turning gear motor a fire occurred in the 480V Engineered Safety Features (ESF) Motor Control Center (MCC) 2B64. Cause is attributed to design of breaker cubicle allowed misalignment when installing the breaker without providing a method of verifying proper breaker position.	PC	N	N
38	Run Contactor Short damaged CPT	Control Room instrumen-tation / annunciator	MG set Breaker	CPT	Failure During Test. During a bus undervoltage and ECSS integrated functional test for Units 2/3 Diesel Generator, a short in the run contactor coil to the 3A RPS MG Set Drive Motor Breaker caused excessive current flow through the control power transformer, which caught fire. This resulted in a loss of power on 3B RPS bus (because of the Reserve RPS Power Supply being out of service for a modification), a half scram and an unplanned Engineered Safety Feature (ESF) actuation.	CH	N	N

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	**Fire Cause**	**Detected by**	**Cabinet Type**	**Ignition Component**	**Description**	**Severity Class**	**Reviewer 1**	**Reviewer 2**
41	Stab misalignment	Fire Alarm	MCC	Breaker	Failure on demand. Immediately following start of the 'D' River Water Supply (RSW) pump, a fire alarm was received. Investigation identified fit between breaker primary disconnects and the associated breaker cubicle stabs was inadequate. Poor fit resulted in arcing in the breaker cubicle and subsequent fire. Breaker had been recently replaced as part of a design modification package and insufficient inhouse review of the breaker interface design specification is the apparent root cause.	PC	N	N
45	Undetermined	Control Room Instrumen-tation / Annunciator	MCC	MCC	Electrical fire in intake structure affecting 2 MCCs. Unite 1 Circ. Water MOVs and Lube Oil Cooling Water Pumps affected, and Unit 2 Circ. Water Pump Motor Bearings affected. Insufficient information to determine cause of failure or component that failed.	PC	U	U
69	Overheating wire	Control Room Instrumen-tation / Annunciator	Control Cabinet	Electrical cable insulation	Breaker self-closing caused by breakdown of insulation in breaker control cabinet. Breakdown caused by insulation contact with protruding tap of a wire wound power resistor, associated heat from resistor and deterioration caused by water intrusion (cabinet located in switchyard). Failure is a result of accumulated effects of 25 years of deterioration.	U (NC-PC)	Y	Y

Table D-1. Evaluation and Description of Bin 15 Events							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 did not 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	Undeter-mined	7.2kV Switchgear	Undetermined	Fire in the non-safety 7.2kV switchgear room.	CH	U	U
187	Undetermined	Plant Personnel	Control Cabinet	Undetermined	Smoke from Unit 3 condensate demineralizer control panel. Power supply in the panel was unplugged to extinguish the fire.	PC	U	U
188	Lightning Strike	Plant Personnel	Power Control Cabinet	Undetermined	Lightning strike caused a fire in a power control center. De-energizing bus supplying power extinguished the in the power control center.	PC	N	N
203	Undetermined	Plant Personnel	MCC	Undetermined	Two MCCs burned	CH	U	U

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	**Fire Cause**	**Detected by**	**Cabinet Type**	**Ignition Component**	**Description**	**Severity Class**	**Reviewer 1**	**Reviewer 2**
206	Missing Component	Plant Personnel	Breaker	Breaker	Fire in recirculation motor generator field breaker caused by missing extension piece for the center phase shorting bus. This allowed the field to be continuously shorted during operation.	PC	U	U
211	Undetermined	Plant Personnel	MCC	CPT	Control Power Transformer failure in MCC	U (NC-PC)	Y	Y
219	Undetermined	Roving Fire Watch	MCC	CPT	Control Power Transformer failure in MCC	PC	Y	Y
224	Human Error	Plant Personnel	MCC	Undetermined	Electrical fault in 480V MCC cubicle caused by human error during maintenance/cleaning	U (NC-PC)	N	N
253	Breaker Failure	Plant Personnel	Switchgear	Trip Coil	Breaker failed to open causing excessive current in trip coil.	U (NC-PC)	N	N
254	Undetermined	Plant Personnel	MCC	Undetermined	MCC electrical overload	U (NC-PC)	U	U
303	High Resistance	Plant Personnel	Control Cabinet	Fuse Disconnect	Plant heater boiler control cabinet on fire caused by high resistance connection in the 60 amp fuse disconnect. Cabinet doors were found open with flames coming out of the cabinet and paint burning off of the top.	PC	Y	Y
320	Breaker Failure	Plant Personnel	MCC	Breaker	Feeder breaker tripped when operator attempted to start 'B' main chill water pump. Local breaker was observed to be on fire and had not tripped.	PC	N	N
381	Breaker cooling fan failure	Control room Instrumentation / annunciator	MCC	Cooling fan	Aux cooling equipment fan motor shorted out with fan motor assembly on fire.	PC	U	U
411	Water intrusion	Plant personnel	Breaker box	Breaker	Breaker box failure caused by water intrusion	U (PC-CH)	N	N

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	**Fire Cause**	**Detected by**	**Cabinet Type**	**Ignition Component**	**Description**	**Severity Class**	**Reviewer 1**	**Reviewer 2**
517	Transformer fault	Control room annunciator & Smoke Alarm	UPS	Transformer	Fire in ERFDADS computer uninterruptable power supply. Apparent cause was a turn to turn fault in the top winding. Vibration, temperature, and age are contributing factors to this failure.	CH	Y	Y
520	Inverter fault	Control room annunciator & Smoke Alarm	UPS	Unknown	Fire in ERFDADS Inverter	PC	U	U
588	Ground fault	Control room annunciator & smoke alarm	Switchge ar	Unknown	Ground fault on 480V SWGR	CH	U	U
10338	Breaker fault	Plant Personnel	MCC	Breaker	Failure on Demand. During start of pump, breaker flashed and resulted in small fire in cubicle with door forced open.	PC	U	Y
20264	MCC Coil fault	Plant personnel	MCC	Coil	Smoke observed coming out of MCC. Hold in coil overheated.	U (NC-PC)	U	U
20267	Breaker fault	Plant Personnel	MCC	Undetermined	Breaker malfunction	U (NC-PC)	U	U
20268	Overheated component	Plant Personnel	MCC	CPT	Control Power Transformer overheated	U (NC-PC)	Y	Y
20269	Undetermined	Plant Personnel	Electrical Lighting Panel	Undetermined	Electrical Lighting Panel Failure	U (NC-PC)	U	U
20270	Transformer Failure	Fire Watch	MCC	Transformer	MCC Breaker Transformer failure	U (NC-PC)	Y	Y
20272	Relay failure	Plant Personnel	Electrical Panel	Relay	Electrical Panel Relay	U (NC-PC)	U	U

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	**Fire Cause**	**Detected by**	**Cabinet Type**	**Ignition Component**	**Description**	**Severity Class**	**Reviewer 1**	**Reviewer 2**
20273	Trip coil failure	Plant Personnel	Switch-gear	Breaker trip coil	Heavy smoke was observed in the Train ‘A’ switchgear room caused by a faulted trip coil.	U (NC-PC)	N	N
20275	Overheat	Plant Personnel	MCC	CPT	Control power transformer burned up causing the diesel generator lube oil heater MCC to smoke.	U (NC-PC)	Y	Y
20276	Breaker	Plant Personnel	Switch-gear	Undetermined	RCP breaker cubicle	U (PC-CH)	U	U
20282	Overheat	Plant Personnel	MCC	CPT	Operator saw smoke coming from an MCC for the MISV hydraulic pump; transformer fault.	U (NC-PC)	Y	Y
20287	Overheat	Roving Fire Watch	MCC	CPT	Control power transformer overheat	U (NC-PC)	Y	Y
20295	Overheat	Plant Personnel	MCC	CPT	Control power transformer overheat	U (NC-PC)	Y	Y
20302	Ground fault	Plant Personnel	MCC	Undetermined	Ground fault on main and/or reserve feed breakers cause fire	U (NC-PC)	U	U
20312	Switch	Smoke alarm	Switch-gear	Switch	EDG roto test switch damaged and failed causing a fire	U (NC-PC)	U	U
20325	Chemical Spill	Plant Personnel	Heat trace wiring	Heat trace wiring	Acid spill on heat trace wiring	U (NC-PC)	Y	Y
20328	Undetermined	Smoke alarm	Electrical Distri-bution	Undetermined	Sudden electrical distribution panel failure with smoke.	U (NC-PC)	U	U
20329	Relay fault	Plant personnel	Switch-gear	Relay	Relay stuck in intermediate position	U (NC-PC)	U	Y
20334	Breaker	Plant Personnel	MCC	Breaker	MCC Breaker	U (NC-PC)	U	U
20346	Breaker	Plant Personnel	MCC	Breaker	Breaker in 4kV room	CH	U	U
20356	Internal Short	Plant Personnel	MCC	Light bulb	Short in light bulb	U (NC-PC)	U	U

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	**Fire Cause**	**Detected by**	**Cabinet Type**	**Ignition Component**	**Description**	**Severity Class**	**Reviewer 1**	**Reviewer 2**
20357	Human Interaction, Improper Maintenance	Plant Personnel	MCC	MCC internals fell on power phase	Ground fault inside a nonsafety-related MCC caused by improperly equipment restored to service. Internal plane cover not properly secured and fell during investigations and caused ground fault.	U (PC-CH)	N	N
20362	High Resistance	Other Equipment Failure	MCC	Insulation / fuse block	Insulation burned off of one lead to motor starter contactor and fuse block severely melted. Termination screw loose on starting input terminals.	U (NC-PC)	Y	Y
20382	Undetermined	Plant Personnel	Switch-gear	Undetermined	Switchgear failure	U (NC-PC)	U	U
30276	PCB fault	Plant Personnel	Emer-gency Lighting	Power transformer	Emergency Lighting Battery Box Failed during annual inspections. Power transformer inside the box was observed to have sparked and caused a fire. Failure caused by bad charging board and one bad cell.	PC	N	N
30281	Procedure Error	Plant Personnel	Control Panel	Insulation	During testing of synch switches for Main Xfmr, Emergency Aux Xfmrs and Main generator, insulation failed because of excessive applied voltage (230,000volts applied to a 120V synch bus).	CH	N	N
30338	Inadequate PM	Control Room Instru-mentation / Annun-ciation	Control Panel	Panel Blower	Panel blower (fan) failure. Blower found to be full of dust and dirt.	PC	Y	Y
30478	Relay failure	Plant Personnel	Control	Relay	Condensate demin panel fire and smoke from affected relays (3).	PC	U	U

Table D-1. Evaluation and Description of Bin 15 Events

Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Incipient stage (Y/N/U)	
							Reviewer 1	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 Instrumen-tation / Annunciator	Control Cabinet	HFX relay	Received numerous alarms in control room related to FP filter low-flow alarm. Found FP pump tripped and pressure drop. Smoke observed in room. Investigation found HFX relay burning. Extinguished with portable.	PC	U	U

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	**Fire Cause**	**Detected by**	**Cabinet Type**	**Ignition Component**	**Description**	**Severity Class**	**Reviewer 1**	**Reviewer 2**
50874	Breaker failure	Plant personnel	Switchgear	Trip Coil	During shutdown of Recirc MG set the field breaker failed to open. Trip coil smoking and on fire. Fire extinguished and fuses pulled.	PC	N	N

D.2 Quantification of the Time Available for Operator Response

As shown in Figure 2-2, the fire growth profile is made up of several stages. Of importance is the early stage of the fire referred to as the "Incipient" stage. Although many fires exhibit this incipient stage, it is not typically modeled in performance-based design, primarily because of the variability of its duration. This variability is caused by several reasons; including deviations in material properties, ignition source, and configuration, just to name a few. Additionally, for fires which do display an incipient stage, testing has shown that aspirating smoke detecting systems configured to provide very early warning fire detection (VEWFD) do not detect the component degradation at its onset, but sometime after the first quartile of the incipient stage duration. 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 minutes.[1]

It should be noted that prior to the effort undertaken by this project, the state of knowledge related to understanding the duration of component degradation and associated fire signature from such degradation, was 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). Even when such actions are successful in identifying degrading components and removing/repairing them, there is not tracking system to document a representative incipient stage duration.

[1] The 30-minute minimum was chosen based on a factor of 2 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.

Numerous efforts were made to obtain relevant operating experience to support quantification of the incipient stage duration. The process involved identifying detailed timing information from all available sources, including: fire events database, industry provided operating experience, and national laboratory fire experience. This evaluation is based on operating experience, test results, and in one case the application of engineering judgement.

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 (480 or 600V), 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 last source sought for insights was 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, 2013, 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 way notifies an alert condition. Two hours and forty-two minutes later an explosion occurs involving the Aux Bus 1E2. Therefore, the IFD provided 2.7 hours of advanced warning before ignition; in this case ignition is considered to be the occurrence of the explosion. Information from this event was taken from the following source, Beasley, K., 08-08-2012 HNP Fire Event on 1E2 Bus. Retrieved July 29, 2014 from Fire Protection Information Forum Archives: http://www.nei.org/Conferences/Conference-Archives/Fire-Protection-Information-Forum-Archives.

2014 event: The event occurred because of an internal fault in the 480V load center station service transformer 1D2. The event started at 07:51, with the MCR receiving electrical equipment trouble alarms associated with 1D2. At 08:32, it was confirmed that grounds were present on both sides of the transformer. At 09:00 a single zone of the IFD notified an alert condition, and at 09:02, the same IFD zone indicated an alarm condition. At 09:29, the resistor associated with the ground relay was glowing red, and at 09:31 it was determined to de-energize 1D2. At 10:07, local plant personnel identified smoke emanating from the 1D2 transformer cubicle and a determination was made to trip the reactor, which was at 75 percent power. At 10:24, a confirmation was made that no more smoke was emanating from the 1D2 transformer. Report never identified if flaming conditions occurred.

Regardless of the severity classification of this event, it provided timing information associated with the time between ASD response and fire, if it is assumed that when the plant was shut

down a fire was eminent. Because of the limited amount of data, it was decided to keep this event data. So, given the IFD notified the MCR of an alert condition at 09:00, if we assume that ignition occurred at 10:07, there was approximately 1.12 hours of advanced warning before assumed flaming conditions.

During the public comment period for the draft version of this report, an event occurred involving an ASD VEWFD system. Summary information of the event was provided as part of the comments received and a follow-up site visit was performed by several NRC staff.

<u>2015 event</u>: A description of this event was presented at the NEI Fire Protection Information Forum and transmitted to the NRC during the public comment period for the draft report. This event began at 19:52 on August 1, 2015 when the first of two alerts was received from a VEWFD system installed within an electrical cabinet. Operator and technician responded and reported no unusual conditions. Thirteen minutes after the alert, the annunciator was cleared. At 23:08 the same day the same system issued a second alert. Again no unusual conditions were found and the system alert annunciator was cleared for the second time 22 minutes after the second alert. At 23:34 the VEWFD system was declared non-functional because of multiple alerts and no local abnormal conditions detected using a portable VEWFD system. A continuous fire watch was established and a work request to investigate further was initiated. [Ref. 2015 NEI Fire Protection Information Forum Slides titled, "Harris Incipient Detection Success," Bob Rhodes] Subsequently, an overheated control switch was found within the protected cabinet using a thermal imaging camera. The control switch was associated with the control power to the "C" steam generator power operated relief valve. The maximum temperature reading of 65 °C (149 °F) was observed with the thermal imaging camera. On August 3rd at 7:28am a work order was completed and on August 6th, the control switch was replaced.

Based on the description of the event, the in-cabinet VEWFD system provided approximately 35 hours of advanced warning from the first alert until the overheated control switch was found and over 95 hours until the control switch was replaced. In comparison to the previous event descriptions, this event was significantly longer, but did not lead to any adverse conditions (fire, smoke, reactor trip). An important question to answer regarding the applicability of this event relates to its severity classification. Because this event did not lead to a fire, the question of assigning a severity classification is purely speculative. That is, if actions were not taken to eliminate the abnormal condition, the component may have developed into a fire that would be characterized as potentially challenging or greater and would contribute to fire PRA ignition frequency; alternatively, it may have never resulted in a fire (via self-mitigation or other means) and would not be considered a challenging fire of importance to the fire PRA quantification.

The event appears to meet all the criteria for one of the standard override criteria developed to support the updated fire events database, "Individual Sub-Component Failures Not Resulting in Flaming Combustion" (Ref. "The Updated Fire Events Database: Description of Content and Fire Event Classification Guidance," EPRI 1025284, Palo Alto, 2013.). Events meeting this classification were categorized as "Not Challenging" (NC) because they did not indicate the potential for development of a spreading fire. Typical examples of conditions meeting this override include overheating of; motor windings, terminal blocks, single printed circuit cards, light or light sockets, indicators, control switches, relays, motor contactors, etc. These types of NC fires were prevalent within the database prompting the creation of a generic override criteria. Fires that do not indicate the potential for development of a spreading fire are not be considered to be of importance to fire PRA quantification and

therefore are screened out of frequency. The point being made is that current methods to quantify fire risk only consider events that have the potential to challenge plant safety.

This event description also identified that the plant personnel were not successful in locating the source of the system alert using the handheld VEWFD system (sometimes referred to as a “sniffer”). These insights question the assumptions and estimates of the human error probabilities presented in the body of this report. Other insights from this event include a discussion of how close this component was to an ignition threshold. Most materials/components found in an NPP have ignition temperatures above 200 °C (392 °F). Thus, 65°C (149°F) is well below the ignition temperature cited here.

Regardless of the unknowns from this event, the authors of this report determined that this event should be considered in the time available estimates. However, the large difference between the other event durations (mean of 1.4 hours) and this event (90 hours) would result in a distribution that is influenced more by this long event (due to the use of a single parameter distribution). As such, a surrogate value was used to characterize this event, and is suggested to be used for any subsequent events that an ASD VEWFD system and operator response prevent a fire. The surrogate value represents the mean of an exponential distribution that has a 10th percentile (first sampling point from Section 10) that is feasible. The time used for this feasibility is equal to the cumulative time from “alert” for a successful identification of cabinet for the 10 cabinet case, i.e., 30 minutes. Based on this approach a time available estimate of 4.75 hours is used. For any future updates to the time available curves, this value is recommended to be used as a surrogate incipient stage duration for instances where transition to flaming conditions does not occur (unable to determine severity classification) and the time between the VEWFD system alert and end of event is more than 4.75 hours. For events that do not transition to flaming and are less than 4.75 hours, the actual time duration should be used. This approach is recommended until such time that sufficient operating experience data is collected and can be analyzed to better understand these systems performance to challenging type fires per the fire PRA characterization.

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 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 discussed above and adjusted using the data from the NIST testing. The resulting exponential distribution fit to the “Time Available” data is shown in Figure D-1 and Table D-3. Software packages were used to fit the data and evaluate the goodness of fit. An exponential distribution provided the best fit and made seemed reasonable for the small sample of data available. The single parameter “lambda” of the exponential is estimated by the inverse of the arithmetic mean of the data.

$$\lambda = \left(\frac{1}{n}\sum_{i=1}^{n} x_i\right)^{-1}$$

where x_i represents an individual data point of the data set $x_1, \ldots, x_n$ and n represents the total number of samples. The cumulative distribution function for an exponential is,

$$1 - e^{-\lambda t}$$

where t is time in hours.

If sufficient additional data becomes available in the future, any update to this analysis should evaluate the reasonableness of this distribution and the continuity with those fires that are fast developing and not included in the data set.

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
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
2015 Event		Ŧ 4.75	*2.38	*3.11	*0.73
Lambda		*0.518*	*1.036*	*0.793*	*3.382*

* estimate based on operating experience adjusted with experimental results (mean time to detection) and assumption of linear component degradation

Ŧ basis for estimate discussed in Appendix D

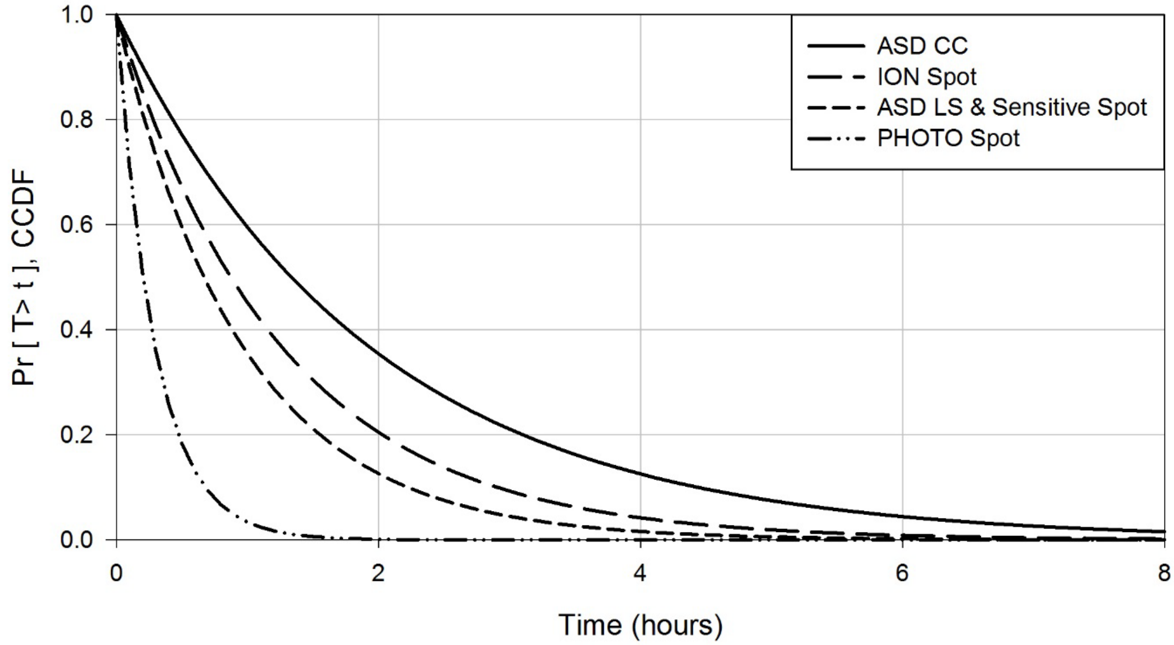


Figure D-1. Exponential distributions fit to data for the time available for operator response following an ASD alert for different detection technologies tested

The distributions presented in Figure D-1 and Table D-3 are based on the system response at the sensitivities discussed in Appendix B.4. This information is used in Section 10 to develop split fractions to support human error probability estimation for specific time periods. If NPP systems use other port sensitivities, applicable data could be used to develop new distributions for those settings. The following provides equations to estimate the sampling points.

Table D-3. Exponential Distribution Values for Time Available for Operator Response by Smoke Detection Systems

Time (Minutes)	Complementary Cumulative Distribution Function			
	ASD CC	ASD LS and SS	ION Spot	PHOTO Spot
0	1	1	1	1
1	0.99	0.98	0.99	0.95
2	0.98	0.97	0.97	**0.89**
3	0.97	0.95	0.96	0.84
4	0.97	0.93	0.95	0.80
5	0.96	0.92	0.94	0.75
6	0.95	**0.90**	0.92	0.71
7	0.94	0.89	0.91	0.67
8	0.93	0.87	**0.90**	0.64
9	0.93	0.86	0.89	0.60
10	0.92	0.84	0.88	0.57
11	0.91	0.83	0.86	0.54
12	**0.90**	0.81	0.85	0.51
. . .	. . .	. . .	. . .	. . .
30	0.77	0.60	0.67	0.18
. . .	. . .	. . .	. . .	. . .
60	0.60	0.36	0.45	0.03
Lambda	0.5185	1.0355	0.7928	3.3818

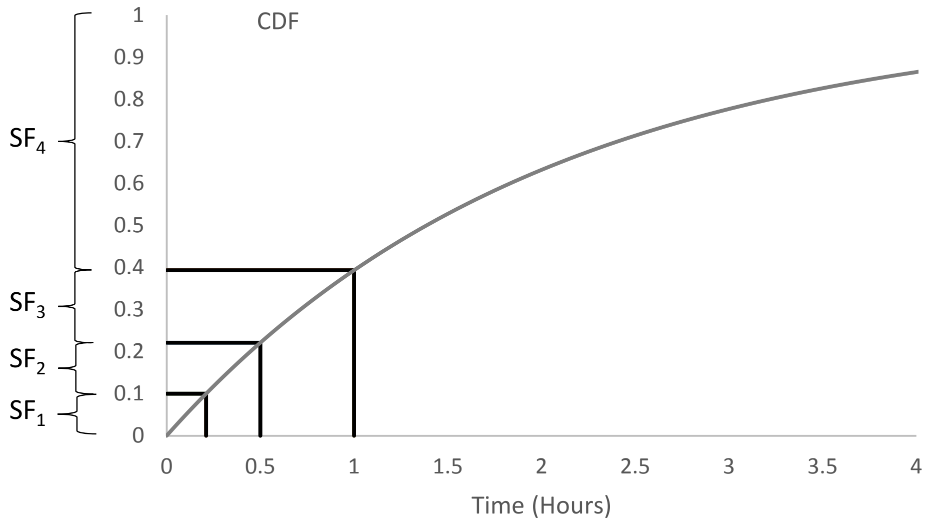


Figure D-2. Illustration of sample point to split fraction relation of cumulative distribution function curve for time available.

First split fraction (SF_1) is fixed at 0.10. The corresponding time is calculated as;

$$t_{10^{th}} = \left(\frac{-1}{\lambda}\right) \cdot \ln(1 - 0.1)$$

The second split fraction (SF_2) corresponds to the portion of the CDF between t_{10th} and 30 minutes (0.5 hours), and is calculated as;

$$SF_2 = e^{-\lambda \cdot t_{10^{th}}} - e^{-\lambda \cdot 0.5}$$

The third split fraction (SF_3) corresponds to the portion of the CDF between 30 and 60 minutes (0.5 and 1 hour), and is calculated as;

$$SF_3 = e^{-\lambda \cdot 0.5} - e^{-\lambda}$$

The last split fraction (SF_4) corresponds to the portion of the CDF beyond 60 minutes (1 hour) and is calculated as;

$$SF_4 = e^{-\lambda}$$

D.3 Evaluation of Enhanced Fire Suppression Fire Events

This section documents the review of fire events from the fire events database where an operator was present in the room of origin when a flaming condition began. These results were used to develop a new suppression curve. The results are summarized in Table D-3, which contains several fields described below.

Fire ID	Record number from EPRI Fire Events database
Fire Cause	Identifies apparent cause of event
Detected by	Identifies how the event was detected
Cabinet Type	Identifies the type of cabinet where the event occurred
Description	Provides summary of event

Table D-3. Evaluation of Enhanced Fire Suppression Fire Events

Fire ID	Fire Cause	Detected by	Cabinet Type	Description	Suppression Time (min)
83.1	Ground Fault	Plant Personnel	Power	Smoke was discovered in the back boards area of the control room by a security officer performing an hourly fire watch tour. Smoke was emanating from the Emergency Lighting Uninterruptible Power Supply and the Essential Lighting Distribution Panel. Cause was short circuit current in plant ground system because of inadequate grounding procedures. Fire was self-extinguished by removal of power by opening AC breaker in ELDP.	9
161	Undetermined	Plant Personnel	MCC	'D' control rod drive mechanism (CRDM) fan (1-HV-F-37D) tripped. Approximately 30 minutes later operations locally opened the breaker after identifying a strong odor and that the breaker associated with CRDM fan was smoldering. Upon opening the cabinet a "6-inch flame" was observed. At the time of fire discovery the Operations fire brigade members were in the area. When the source was found the fire was immediately extinguished and reflash watch set	5

Table D-3. Evaluation of Enhanced Fire Suppression Fire Events

Fire ID	Fire Cause	Detected by	Cabinet Type	Description	Suppression Time (min)
253	Breaker Failure	Plant Personnel	Switchgear	Breaker failed to open causing excessive current in trip coil. Operations crew were present within room during failure.	10
20270	Transformer Failure	Fire Watch	MCC	MCC Breaker Transformer failure detected by fire watch	1
20272	Relay failure	Plant Personnel	Electrical Panel	Electrical panel relay fire. Detected by security guards within the fire area.	4
30276	PCB fault	Plant Personnel	Emergency Lighting	Emergency Lighting Battery Box Failed during annual inspections. Power transformer inside the box was observed to have sparked and caused a fire. Failure caused by bad charging board and one bad cell. An indication existed of the smell of smoke in the Control Room. Upon investigation found Emergency Lighting Battery Box # E7-12 on the East Wall of the Control Room, behind 1C614, with smoke coming out.	2

APPENDIX E
LITERATURE REVIEW

This appendix provides a summary of literature reviewed in support of this project. All summaries are from publically available documents. The literature is from a variety of sources, including the National Fire Protection Research Foundation, academia, vendors, conference proceedings, and journal articles. The summaries are provided in chronological order. At the end of this section, additional reading material that was reviewed is identified, but not summarized below.

E.1 Custer, R.L.P., Bright, R.G., "Fire Detection: The State-of-the-Art," U.S. Department of Commerce, National Bureau of Standards, June 1974.

This report, although dated, provides a substantial amount of information related to fire detection technologies with consideration of fire signatures, detection modes, test methods, performance requirements, and code requirements. For those with limited-to-no knowledge of fire detection systems operations, review of the report is strongly recommended.

Important concepts gathered from this report, applicable to the current study include a description of submicrometer particle counting detectors; ambient condition effects on detector response; and an emphasis on the importance of detector maintenance. Relevant information is communicated in the main body of this report.

E.2 Meacham, B.J., "Factors Affecting the Early Detection of Fire in Electronic Equipment and Cable Installations," May 1992.

This article provides an overview of the factors that influence fire detection, such as fuel characteristics; compartment configuration; environmental configurations; and maximum allowable fire size at time of detection; and guidance on selecting appropriate devices. The focus is on telecommunication facilities. The first factor discussed is the fuel and fire characteristics, which consist of circuit, component, or interconnecting wiring, which can produce considerable combustion products, but have a relatively low-energy output, and may never transition to a flaming fire. Loss history has shown that small, low-energy fires are a serious problem and make early detection difficult because of weak plume strength. Weak plumes and low ambient temperatures can cause insufficient smoke transport to the uppermost level of a ceiling-height enclosure.

E.3 Gottuk, D.T., McKenna, L.A., "Response Time Comparison of Spot vs. Aspirated Laser Smoke Detection," September 1999.

Hughes Associates, Inc. performed 56 full-scale tests for Pittway Systems Technology Group, comparing the response time of laser-based Notifier VIEW spot detection systems to Vision Systems laser aspirating smoke detectors (ASDs), which were exposed to a variety of smoke sources and ventilation conditions within a telecommunications facility.

An operating Bell Canada switch center was selected as the test site (100 ft. wide, 180 ft. long [18,000 sq.ft.], 15.5 ft. high. Five smoke sources were evaluated, including BSI 6266 wire; Bell Canada wire; BSI 6266 chemical smoke test; internal printed wire board; and conductive heating of EPDM cable insulation. The sources were evaluated at ten different locations with variable source heights and two different ventilation conditions. Normal ventilation conditions consisted of three recirculation air conditioning units, operating at a combined 25844 cubic feet per minute (cfm), serving the DMS switching center, and a general HVAC unit serving the larger toll/frame area at 12,618 cfm. Reduction ventilation conditions consisted of shutting down two of the three recirculation air conditioning units. Several variations of detector configuration were also used to evaluate any performance differences. The VIEW spot detectors were arranged in two redundant loops. One loop used detector spacing at 200 ft^2 while the other loop spaced the detectors at 400 ft^2. VIEW detectors were also placed on the return air grills, and detector-mounting angles were varied among tests to evaluate the effect on system response. Two laser ASDs were installed in the ceiling area-wide configuration, and one laser ASD was installed on the return air grills of the recirculation system.

Several key insights were identified from this testing, namely the following:

- Comparable performance between the laser ASD and 200 ft^2 VIEW systems was demonstrated, while the 400 ft^2 VIEW system showed decreased performance compared to either the 200 ft^2 VIEW or laser ASD systems.

- Return air grill detection showed no clear difference between the laser ASD and the spot VIEW detectors. For the VIEW system, the return air grill configuration responded to fewer sources than the 200 ft2 system and was slower to respond; however, the returns did detect 3 additional fires not detected by the area-wide 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 area-wide 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 did not 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 does not correlate to sampling hole blockage for the particular ASD system tested.

E.4 Geiman, J., Gottuk, D., "Alarm Thresholds for Smoke Detector Modeling," Fire Safety Science Proceedings of the Seventh International Symposium, 2002.

This paper illustrates an evaluation of the use of smoke optical densities outside a detector as a criterion for predicting smoke detector response. The Temperature Rise Method was not evaluated because of the highly questionable accuracy. The study applied three full-scale experimental data sets that used optical density meters located in close proximity to some of the detectors (ion and photo). This paper concludes that determining the precise alarm times is not currently possible with the large number of variables that not only exist, but influence smoke detector response. Using nominal detector sensitivities as an alarm threshold, leads to only about 20 percent of the alarm predictions corresponding to actual detector alarms. In most cases, the use of the nominal sensitivity will result in predicting alarms before they actually occur. One exception is ionization detector response to flaming fire conditions, which corresponded with predicted alarm conditions 50 percent of the time. Using an alarm threshold of 0.14OD/m (9.4 %/ft obscuration) provides a relatively high level of confidence in predicting detector alarms, but will typically predict alarm response times that are potentially longer than would actually occur.

E.5 Nicholson, J., "Looking Up: NFPA 805, Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants," NFPA Journal, May/June 2003.

This article provides a high-level overview of how performance-based fire protection application of NFPA standards have improved safety at Canadian nuclear power plants (NPPs). The use of performance-based, over prescriptive requirements, facilitates the use of (their) equivalencies in making more realistic analyses of Bruce Power Plants safe shutdown capability. The Bruce implementation of performance-based initiatives was deemed to be equivalent to the Canadian Standards Association N-293. As part of the plant upgrades, Vesda Air Aspiration Systems were installed.

E.6 Tieppo, Eddie, "Very Early Warning Aspirated Smoke Detection in Nuclear Power Facilities," October 2003.

This paper provides a high-level overview of design and benefits of VEWFD systems over conventional spot-type detectors. Maintenance considerations for ASD systems are also presented with discussion of detector unit, filter, and pipe network maintenance concerns. This paper concludes with a discussion of several applications used in Canadian NPPs in areas such as the main control room, equipment rooms, cable tunnels, and generators halls.

E.7 Vision Systems, "White Paper: Using Air Sampling Smoke Detection to Protect Mission-Critical Facilities from Fire," 2004.

This paper provides a high-level overview of the importance of protecting mission-critical facilities, such as essential financial installations, from the effects of smoke damage on their electronic computer systems. More and more, the risks associated with data center fires are caused by increased energy consumption from modern computers, and the need to use high-ventilation, flow rate air conditioning to cool the computer electronics. Consequently, such high air flow environments, using conventional spot-type detectors becomes ineffective. However, it is not only

potential fire damage from which the data centers need to be protected. Smoke contamination of electronic equipment, even as small as 16 micrograms per square centimeter, can cause corrosion and long term effects and 30 microgram per square centimeter can result in short-term effects.

The paper also provides an overview of how ASD systems work; common application in typical data center environments; ASD system design characteristics that are important to consider in ensuring the EW or VEW detection; coverage area; and sensitivities. The paper also establishes that in-cabinet and integrated-equipment detection enable an excellent VEWFD solution for the following reasons:

1. Sampling is performed closest to the source.

2. Addressability is enhanced as compared to ceiling or air return type detection.

3. Likelihood of smoke/fire damage to other equipment is minimized.

4. Background noise (dust/smoke) within enclosures is relatively consistent.

5. Numerous detector set points made a staged response replicable/possible.

E.8 Vision Fire & Security, "Development of Performance Equivalency Methodology for Detection and Suppression System Integration," 2006.

Vision Fire & Security Pty Ltd. developed a detection equivalency method, which resulted in development of an "application tool" to allow ASD systems to be specified as an alternative to the conventional spot-type detection design for applications in which detection is used for suppression system actuation. The study focused on the use of ASD systems in challenging environments, such as areas with high airflow, very low or non-thermal energy fire hazards, and dense equipment layout as a solution for risk management and business continuity. The Fire Dynamics Simulator (FDS), a fire modeling computational fluid dynamic tool developed by NIST, was used to determine the appropriate ASD alarm level to establish an equivalent or better level of performance as compared to the benchmark for conventional spot-detection.

This work identified that, for an equivalent performance, ASD requires higher sensitivity settings in rooms where (1) the airflow is higher, (2) the room size is increased, and (3) the ceiling height is increased. For the application using an ASD system to supplement or replace conventional spot-type detectors, the report concludes that with proper alarm settings (based on airflow characteristics and room physical dimensions), detection performance can be enhanced, and more consistent fire size at time of suppression can be achieved. The report does not appear to take into consideration the uncertainness associated with the FDS modeling, nor does it explicitly describe the basis equivalency calculation method.

E.9 Fabin, T.Z., Gandhi, P.D., "Smoke Characterization Project," April 2007.

The Fire Protection Research Foundation, along with the Underwriters Laboratories, undertook a smoke characterization study to more fully characterize the products of flaming and non-flaming combustion for materials found in common residential settings. Small-scale cone calorimeter, intermediate scale calorimeter and UL 217/268-type fire room tests were conducted to evaluate smoke characteristics for natural, synthetic, and multi-component materials in both flaming and non-flaming combustion modes. Quantities such as mass-loss rates; heat and smoke release rates; smoke particle size and count distribution; effluent gas composition; combustion mode effects; smoke alarm response; and smoke stratification were characterized. Although the report provides a thorough evaluation for the combustion modes and materials tested, most of the materials are not commonly found in NPP applications, making the application of these results uncertain.

E.10 Collier, P.C.R, Whiting, P.N., “Timeline for Incipient Fire Development: Study Report No. 194,” 2008.

The Building Research Levy funded work to evaluate incipient fire development of furniture fires with regard to the modeling of the incipient stage in performance-based design fires. Using test data, and literature and statistical evaluations, the researcher noted that the incipient fire development period is variable and its duration was dependent on intensity and location of the ignition source. Because of the variability in the incipient stage, the report recommends no allowance for incipient fire development in performance-based applications. Although furniture fires are not realistic surrogates for electrical cabinet fires, the variability of the duration of the incipient stage is a characteristic likely applicable to electrical cabinet fires.

E.11 Milke, J.A., et al., “Validation of a Smoke Detection Performance Prediction Methodology,” Volumes 1-4, October 2008.

The Fire Protection Research Foundation sponsored a research project to evaluate the current capabilities of the computational fluid dynamic (CFD) code FDS to predict smoke detector activation in response to relatively low energy incipient fire sources. This work was performed by the University of Maryland and Underwriter Laboratories, and is documented in a four-volume report titled, “Validation of a Smoke Detection Performance Prediction Methodology(Milke, Mowrer, Brookman, & Gandhi, 2008).” Volume 1 documents the characterization of the heat and smoke release of eight incipient fire sources that were selected for the project; Volume 2 provides a detailed description of the large-scale room fire tests. Volume 3 evaluates the smoke detector response, and Volume 4 compares the experimental results with the predictions of FDS simulations.

Modeling of smoke detector response typically uses one of three methods, namely, temperature rise, critical velocity, or optical density. However, these methods do not address the operational principles of the detectors resulting in uncertainty in the detector response modeling approximations. Eight smoke sources were characterized by performing small-scale tests using the IMO intermediate scale calorimeter at UL in Northbrook, IL. The smoke sources used include: shredded office paper, polyurethane (PU) foam with micro-fiber fabric, printed circuit board, and an ABS plastic computer case, which was used to create flaming smoke sources, while PU foam with micro-fiber fabric, ponderosa pine sticks, cotton lined fabric, and polyvinyl chloride (PVC)-insulated wire were used for smoldering smoke

sources. The primary smoke signature of interest was the obscuration of visible light, but particle count density, mean particle diameter, CO and CO2 production data were also collected.

The interesting results from this small-scale testing, as it relates to NPP smoke sources, are the characterization of the PVC-insulated wire test. The PVC test followed the procedure outlined in Annex B, “Performance Test Procedure for Very Early Warning and Early Warning Fire Detection Systems” of NFPA 76, using the North American Wire Test outlined in Table B.2.1 of that standard. However, the UL test deviated from the Annex procedure in that the test duration lasted 60 seconds, instead of the standard specified 30 second duration. The results indicated that the average maximum smoke release rate of 0.10 m^2/s occurred just after 60 seconds; the maximum mean particle diameter of 0.135 micron occurred just before 120 seconds; and the average maximum particle count density of 200,000/cc occurred at approximately the same time.

The large-scale testing included unventilated and ventilated conditions. The 24 unventilated tests were conducted in the UL 217/268 room, measuring 10.8 m by 6.6 m and 3.0 m tall. The rooms were instrumented with photocell/lamp assemblies; measurement ionization chamber units; spot-type smoke detectors (both ionization and photoelectric types); thermocouples; thermocouple trees and velocity probes. The 64 ventilated large-scale tests were conducted in different room measuring 7.2 m wide, 7.2 m long (51.8 m^2) by 9.0 m high. This enclosure was equipped with an injection-type mechanical ventilation system, with two ceiling air injector diffusers, and four transfer grills providing air exhaust to the plenum space above the ventilated test room. The ventilated room experiments consisted of testing three ventilation rates, namely 0, 6, or 12 air changes per hour (ACH). The ventilated room tests included the same instrumentation as the unventilated tests, with the addition of three ASD single-zone systems, having three sampling ports per zone (two sampling ports within the test room, one port sampling from outside the test room). The intent of including the ASD systems was to collect information to evaluate the prediction capabilities of FDS. Unfortunately, the data files associated with the ASD system could not be synchronized with the other data files.

Evaluation of the data/feedback indicates that the point type “smoke detector response(s) appear to be strongly dependent on the specific characteristics of the smoke and, in some cases, on the detector technology.” The researchers then evaluated the detector response based on the 80th percentile values of obscuration and suggested nominal guidelines for detector response, depending upon the ventilation conditions, fire characteristics, (flaming vs. smoldering) and in some cases, detector technology.

Table E1. 80th Percentile Obscuration Level at Detector Response

Smoke Source	Ventilation	Detector Type	
		Photoelectric	Ionization
Flaming	With	5%/ft	8%/ft
	Without	8%/ft	
Non-Flaming	With	1 – 2.5%/ft	
	Without	10%/ft	12%/ft

The report classified the smoke sources as “incipient fire sources,” considering that half the sources used produced their smoke signatures during flaming combustion; the basis for classifying these smoke sources as “incipient fire sources,” is questionable given that all were identified as either smoldering or flaming. In addition, no clear distinction was made as to the portion of the overall smoke release rate profile that corresponds to the incipient stage. Although these tests provided useful data for characterizing the effluent from the various fire sources and for evaluating the smoke prediction capabilities of FDS, because the results were not reported for the ASD system tested, little can be drawn from these results regarding the response of an ASD VEWFD system.

E.12 Xtralis, “IT/Server Room Fire Test Demonstrations – VESDA & photoelectric conventional point detectors, Technical Report,” October 2008.

Xtralis provides a case study from demonstration tests conducted at their Test Facility IT/Server room. Smoke tests were conducted in various locations within the room to demonstrate an ASD smoke detector’s early warning (EW) and very early warning fire detection (VEWFD) capability. The ASD applications tested included ceiling, return air grill, air duct, and cabinet configurations. The ASD system results were compared to conventional spot-type detectors that were included in the tests.

The test facility measured 11.0 m wide x 6.5 m deep x 3.0 m high for a total floor surface area of 71.5 m^2. The room ventilation conditions were representative of those found in telecommunication facilities, namely, clean, cool air is introduced through the floor, and exhaust via the air return grill located on a wall.

Individual Xtralis VLC detectors were used for cabinet, ceiling, air return grill and duct detection with conventional photoelectric spot-type detectors set to 1.4 %/m obscuration (Mode 1) located adjacent to the ASD sampling points, except for the cabinet applications. An alarm control panel was used to log all detectors’ alarm times. Fire/smoke tests included overheated PVC wire, overheated resistor, and smoldering smoke pellet tests were also conducted. The duration of the overheated cases did not exceed 10 seconds. Seven different locations throughout the facility were used to locate the fire/smoke generation specimens.

Results indicated that for the short-duration fire/smoke sources tested and the locations of the EW and VEWFD systems, performed better than the conventional spot-type detectors. These tests did not provide any information on system performance for slowly degrading electrical components or timing information for operator response to such incipient stages.

E.13 Xtralis, “Warehouse Fire Detection Test Results - ASD vs Point (spot-type) vs Beam Detectors, Case Study,” April 2008.

Case study presents results from a series of demonstration tests conducted in Victoria University’s Warehouse. Three small fire tests were conducted to illustrate the benefits of EW and VEW detection capabilities. Comparisons were drawn between ASD EW and ASD VEW, as well as conventional spot-type and beam detectors.

The warehouse was 43 m long, 12 m wide for a gross floor area of 516 m^2, and had a ceiling height of 8.5 m at the central pitch. A single ASD pipe was installed along the ceiling ventilated ridge and contained six sampling holes spaced 7.2 meters apart. Several alarm thresholds were used for the ASD system, however only the Alert (~0.1 %/ft obscuration [0.3 percent per meter obscuration]) and Fire 1 (~0.37 %/ft obscuration [1.2 percent per meter obscuration]) alarm times were reported. Thus the Alert threshold was twice as sensitive and the Fire 1 threshold was almost ½ as sensitive as the minimum sensitivity for an alert per NFPA 76. Six optical spot-type detectors were also placed along the ceiling ridge vent adjacent to each ASD sampling point. The spot-type detectors had a sensitivity of 1.4 %/m obscuration. Smoke sources included liquid heptanes (100 ml), timber, and smoke pellets and were all located in the same area under the center line of the sloped ceiling, between the farthest two sampling points of the ASD system, and directly below the projected beam detector line of sight; positioning of the warehouse rollup door(s) also varied.

The results indicated that the ASD system performed better than the conventional and projected beam. For tests in which conventional spot-type detectors responded, the ASD system responded on average 52.2 seconds before the spot-type detector. Of the 21 tests conducted, the ASD systems responded with an alert 19 times, while the spot-type responded only 4 times, and the beam detector only responded in one test. The report concludes that the ASD system performed better than the other systems compared and supports the use of ASD systems in challenging warehouse type environments that promote smoke dilution because of high ceiling heights, stratification and natural ventilation conditions. However, it should be noted that, unless the report contains a typographical error, the 4.6 %/ft obscuration [1.4 %/ft obscuration] sensitivity of the spot-type detector is outside the bounds of UL 268 (0.5-4.0 %/ft obscuration) and would not be cited on the listing.

E.14 Milke, J., et al., "Guidelines for Estimating Smoke Detector Response," Suppression and Detection Research and Applications Symposium (SUPDET 2009), Orlando, FL

This paper summarizes the work completed in Volume 3 of the "Validation of a Smoke Detection Performance Prediction Methodology," sponsored by The Fire Protection Research Foundation. See Section E.11 for a full description of this work.

E.15 Miller, J., "Analyzing Photo-electric smoke detector response based on aspirated smoke detector obscuration," Masters of Science Thesis, University of Maryland 2010.

Following the completion of the fire protection research foundation work, the data was analyzed by a student at the University of Maryland to improve the obscuration-level response accuracy of spot-type photoelectric smoke detectors. This work is documented in a Master of Science thesis titled, "Analyzing Photo-Electric Smoke Detector Response Based on Aspirated Smoke Detector Obscuration" (Miller, 2010). In this work, the ASD data files were analyzed against the other light obscuration measurements made during the testing, such that the data files could be synchronized. Then, the spot-type detector response was compared to the obscuration measurements made by the ASD system. The results concur with the conclusions made in the original test program, with the exception of non-flaming fires without ventilation; in this case, the student's analysis indicated that the photoelectric detector performed better (responded at lower obscuration values) than the original report suggested (range of 0.4 to 5 %/ft obscuration).

Although the results compare well with the conclusions from the original report, uncertainties associated with averaging the ASD system response, unknown system offset time, filter effects, and smoke transport lag, were not explicitly quantified, and complicated the analysis. Even so, the results of this work parallel the conclusions from the original report suggesting a relatively large deviation in the expected obscuration level of 2.5 percent at photoelectric detector response. Unfortunately, because the ASD system was used as a measurement device, rather than setup as a detector, little can be drawn from this work regarding its performance. However, the underlying conclusion re-enforces the basic fire detection principles that are applicable to ASD detectors, which state that smoke characteristics, smoke transport, and detector characteristics directly impact the performance of a detectors response compared to its listing.

E.16 Zaworski, J., Laramee, S., O'Conner, D.J., "Comparative Testing of Various Detection Technologies," Schirmer Engineering Corporation, 2010.

Schirmer Engineering witnessed and reported the results of a series of fire tests conducted in a warehouse environment for axonX. The work was commissioned by axonX to evaluate the relative performance of their video image fire and smoke detection (VID) against numerous flame and smoke detection technologies. The test series consisted of 21 different fire scenarios which were repeated three times each for a total of 63 tests using five technologies (ASDs, projected beam smoke detection, spot-type ionization and photoelectric, and VID).

An ASD sampling pipe was located near the ceiling (~18ft) and ran the length of the room with three sampling ports spaced approximately 20ft from each other. The default ASD detector sensitivities were used with the "Fire 1" and "Fire 2" set points used for comparison (~0.18 %/ft obscuration and 1.2 %/ft obscuration, respectively, at each sampling point). Seven different fire sources ranging from smoldering to flaming fires, were used. Of interest to the NRC/NIST project was the overheated smoldering wire source, which consisted of a bundle of Type NM-B 14/3 cables wrapped around a heating element energized for 20 minutes per test. The fire sources were placed in three different locations within the room.

Results from this test series indicated that, in general, for warehouse type applications, the VID response fastest form most fire sources typically followed by the ASD and Ion spot detectors. For the low-energy overheated wire and smoldering wood tests, the VID responded in the 298 – 455 second range, while the ASD, beam, and Ion detectors responded in the 805 – 1016 second range. Given the sensitivity settings for the ASD systems, physical arrangement, and fire source characteristics, these results are reasonable.

E.17 Gottuk, D., et al., "Validation of Modeling Tools for Detection Design in High Air Flow Environments, Final Phase I Report," The Fire Protection Research Foundation, August 2012.

The Fire Protection Research Foundation sponsored an effort to examine the applicability of using computer modeling tools for modeling smoke detection system designs in high airflow rate environments. This report documents the identification of modeling requirements, potential computer models, gaps in knowledge, and

development of a research program to address these gaps. Seventeen model requirements and eight models were identified. The gap analysis identified the following four gaps:

1) Specification of the fire and smoke input
   Specification of the rate of smoke production for incipient fires and the smoke production and heat release for flaming fires is considered a modeling gap. Two aspects for this gap include existence of applicable measured data, and the methodology for specifying the inputs. The capability to predict the ignition and growth of fires of real world objects remains the subject of academic research.

2) Smoke transport
   Soot deposition upon walls and equipment is a known challenge related to smoke detection system design and modeling. Deposition of soot reduces the concentration of soot in the air, and acts to delay detection response. Soot deposition is primarily caused by thermophoresis (thermal gradients), electrophoresis (electric fields), and impactation (sharp turns in air streams near obstructions). This all suggests deposition is more significant inside electrical equipment than outside.

3) Smoke detection performance
   The ability to correlate conditions predicted by a model at a smoke detector/ASD sampling port to an alarm condition within the detector is a significant gap. There are no established correlations for predicting alarm response for ASD systems at either low or high air flow environments. ASD test data indicates that correlations will be highly dependent upon the specific detector model.

4) Large-scale integral test data set
   Limited data exists for HVAC flows and cooling effectiveness of IT/telecom facilities. An IT/telecom facility-specific set of large-scale tests would serve as a validation benchmark for determining the suitability of a specific model.

In the development of a test plan to address these gaps in knowledge, the authors identified the following issues, which are applicable to NPP fire scenarios in electrical equipment enclosures:

- The duration and amount of smoke released from electrical equipment will be dependent upon the size of the heat source, the orientation of the material with respect to the heat source, and the amount of material exposed.

- Significant fire development occurs when pyrolysis/smoldering combustion transitions to flaming. Although it is generally a goal to detect fires before flaming conditions, there are practical issues that can prevent successful intervention at the early stage. These include smoke levels not visible to site personnel, resulting in a source being difficult to find, and fires that occur because of energetic events, and result in relatively fast fire growth.

- Smoke production from an incipient circuit board fire may impact several other circuit boards and pieces of electrical equipment, before being enveloped into the primary air flow. In this scenario, soot deposition on the impacted equipment may reduce the overall smoke concentration that is transported to a detection site, compared to the same source in the open.

- Given the range of cabinet and ventilation configurations, it may be necessary to evaluate several potential configurations with sources at different locations within a cabinet. Total soot deposition may be significantly different for source in the bottom of a cabinet that has continuous vertical ventilation openings exposed to external ventilation conditions (smoke flows out of the cabinet), compared to a source at the bottom of the cabinet with exhaust openings at the top of the cabinet (smoke must flow up through the cabinet.

- Several detection devices used complex algorithms that continuously monitor ambient conditions and adjust detection levels accordingly.
  An understanding of the operation of such software, the optional and default settings, and the manufacturers recommendations are needed to ensure that the device meets performance goals.

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iv. Ludewig, F.A., "Application of Cloud Chamber Techniques to Fire Detection," Environment One Corporation, Schenectady, NY.

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xvii. Floyd, J., Overholt, K., Ezekoye, O., “Soot Deposition and Gravitational Settling Modeling and the Impact of Particle Size and Agglomeration,” Proceedings of the Eleventh International Symposium, Fire Safety Science, 2014.

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xxii. Brookman, M.J., “Smoke Characterization of Incipient Fire Sources for FDS Modeling,” Master of Science Thesis, University of Maryland, College Park, MD 2008.

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APPENDIX F
QUICK REFERENCE FOR PARAMETERS USED IN RISK SCOPING STUDY

The purpose of this appendix is to provide a quick reference to the parameter estimates developed and presented in Part II of this report. This appendix was developed based on comments received on the draft version of this report. These comments related to the effort required to quickly and efficiently locate parameters estimate that are dispersed in different sections of the report. Tables F-1 to F-6 repeat the information found in the body of this report.

Table F-1. Fraction of Fires that Have an Incipient Stage - Parameter 'α'

Category	Incipient Stage Detectable by VEWFD System			Total # Events	Fraction (alpha) Mean [lower/upper]
	Yes	No	Undetermined		
Power Cabinets#	16.5	16	22.5	55	**0.50** [0.36 / 0.64]
Low Voltage Control Cabinets	6	2	5	13	**0.28** [0.08 / 0.54]

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

Table F-2. Unreliability and Unavailability – Parameter "β"

Parameter	Mean (per device-year)	5th / 95th percentile
ASD Unreliability	1.6×10^{-3}	9.7×10^{-4} / 2.3×10^{-3}
ASD Unavailability	2.0×10^{-3}	3.0×10^{-4} / 3.7×10^{-3}
Total Unreliability & Unavailability (β)	$\mathbf{3.6\times10^{-3}}$	8.6×10^{-4} / 6.3×10^{-3}

Table F-3. ASD VEWFD System In-Effectiveness – Parameter "τ"

Application	Cabinet/Room Ventilation	Detector Type	Mean (τ) [5th/95th percentile]
In-Cabinet	Natural and Forced <100 cabinet ACH	ION Spot	**1.0×10^{-1}** [6.8×10^{-2} / 1.4×10^{-1}]
		PHOTO Spot	**7.7×10^{-1}** [7.1×10^{-1} / 8.3×10^{-1}]
		SS	**2.6×10^{-1}** [2.1×10^{-1} / 3.2×10^{-1}]
		ASD CC	**2.7×10^{-3}** [1.1×10^{-5} / 1.0×10^{-2}]
		ASD LS1	**5.3×10^{-1}** [4.5×10^{-1} / 6.5×10^{-1}]
		ASD LS2	**1.9×10^{-1}** [1.4×10^{-1} / 2.4×10^{-1}]
	Forced ≥100 cabinet ACH	ION Spot	**7.9×10^{-1}** [6.5×10^{-1} / 9.0×10^{-1}]
		PHOTO Spot	No Data
		SS	No Data
		ASD CC	**1.9×10^{-2}** [7.8×10^{-5} / 7.3×10^{-2}]
		ASD LS1	No Data
		ASD LS2	**3.7×10^{-1}** [2.2×10^{-1} / 5.2×10^{-1}]
Area-wide, Air Return Grill	HVAC in room	ASD CC	**3.0×10^{-1}** [1.7×10^{-1} / 4.5×10^{-1}]
		ASD LS2	**5.2×10^{-1}** [3.6×10^{-1} / 6.7×10^{-1}]
Area-wide, Ceiling	Any	ION Spot	**8.1×10^{-1}** [7.3×10^{-1} / 8.9×10^{-1}]
		PHOTO Spot	**8.7×10^{-1}** [8.0×10^{-1} / 9.3×10^{-1}]
		SS	**5.7×10^{-1}** [4.7×10^{-1} / 6.7×10^{-1}]
		ASD CC	**3.2×10^{-1}** [2.3×10^{-1} / 4.2×10^{-1}]
		ASD LS2	**1.1×10^{-1}** [4.6×10^{-2} / 1.8×10^{-1}]

Table F-4. Human Error Probability (HEP) for ASD VEWFD Cloud Chamber Detectors – Parameters "μ" and "ξ"

<table>
<tr><th rowspan="3">Detector Type</th><th colspan="3">Total Human Error Probability Estimates</th></tr>
<tr><th rowspan="2">MCR (μ)</th><th colspan="2">Field Operator (ξ)</th></tr>
<tr><th>In-Cabinet</th><th>Area-Wide</th></tr>
<tr><td>ASD VEWFD Cloud Chamber (CC)</td><td rowspan="3">1×10^{-04}</td><td>4.6×10^{-04}</td><td rowspan="3">1.0◊</td></tr>
<tr><td>Ionization spot (ION)</td><td>1.7×10^{-02}</td></tr>
<tr><td>ASD VEWFD Light Scattering (LS) and VEWFD Light Scattering Sensitive Spot (SS)</td><td>4.6×10^{-02}</td></tr>
</table>

◊ the variability of area-wide applications does not permit the development of a generic field operator HEP. As such, an HEP of 1.0 is assumed. If a scenario specific analysis were conducted following the process outlined in Section 10, the result of such an analysis may support using a value other than 1.0.

Table F-5. Enhanced suppression parameters

Parameter	Estimate	Suppression Rate Parameter (λ)	Guidance
π_1	Scenario Dependent#	0.324	Use main control room suppression rate for manual suppression from EPRI 3002002936 / NUREG-2169 and the scenario dependent time to damage value to calculate enhanced suppression parameter.
π_2	Scenario Dependent#	0.194	Use occupied room suppression rate developed in this report for manual suppression and the scenario dependent time to damage value to calculate enhanced suppression parameter.

the estimate mean is dependent on the time to damage calculation. This parameter will vary per scenario based on fire modeling inputs used

Table F-6. Conventional Suppression Parameters

Parameter	Applicability	Guidance
η_1	In-cabinet & Area-wide	Used to credit redundant detection and suppression (automatic and manual) system response. Solve conventional detection and suppression event tree (See Figure F-1) and sequences F-N in Table F-7.
η_2	In-cabinet & Area-wide	Used to credit VEWFD system prompt response (time to detection = 0 minutes). Solve conventional detection and suppression event tree (Figure F-1) and sequences F-I (Table F-7).
η_3	In-cabinet & Area-wide	Used to credit automatic detection and suppression system response only. Parameter is estimated from automatic detection and suppression system unreliability estimate, including any dependencies.

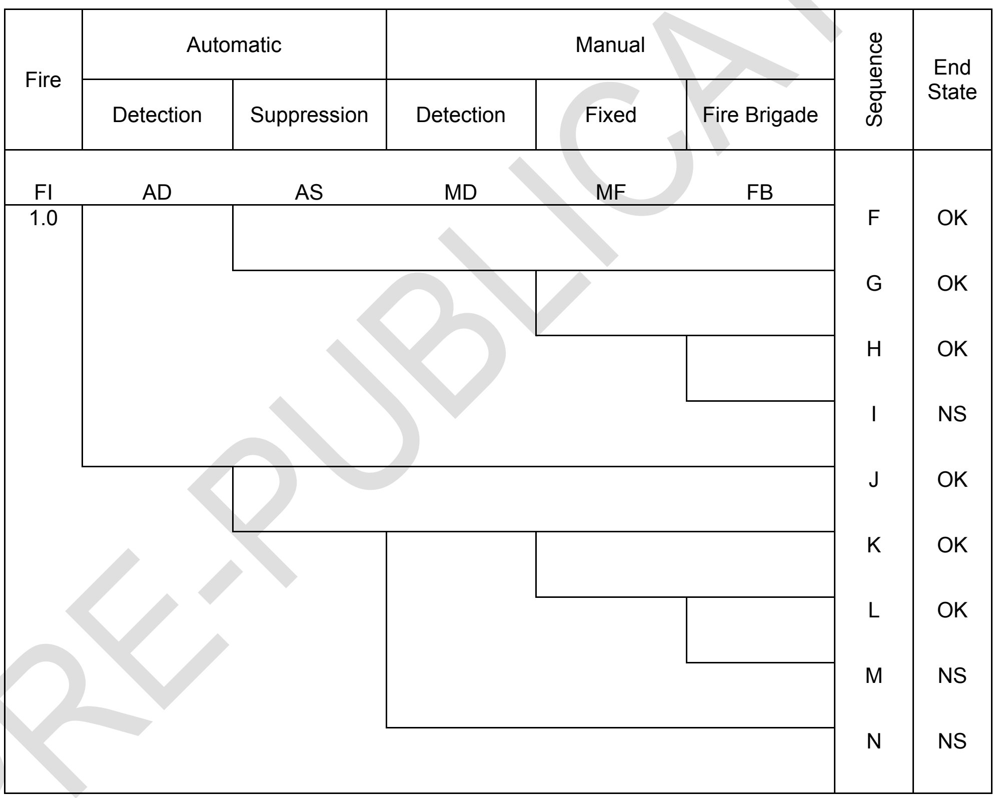


Figure F-1. Conventional detection suppression event tree

Table F-7. Conventional Detection Suppression Event Tree Outputs

Sequence	Detection	Suppression
F	Automatic detection by • Heat detectors • Smoke detectors	Fire suppression by an automatically actuated fixed system
G		Fire suppression by a manually actuated fixed system
H		Fire suppression by the fire brigade
I		Fire damage to target items
J	Delayed detection by • Roving fire watch • Control room verification	Fire suppression by an automatically actuated fixed system
K		Fire suppression by a manually actuated fixed system
L		Fire suppression by the fire brigade
M		Fire damage to target items
N	Fire damage to target items	

APPENDIX G
VEWFD SYSTEM DATA COLLECTION

This report concluded (see Sections 14.1 and 15) that consistent reporting criteria and collection of data on VEWFD system performance could support a better understanding of their risk benefit. This appendix identifies (see boxes and Table G-1) the types of information that could be collected to support this objective.

System unavailability, unreliability and nuisance alarm rate data could be reported every 5 or 10 years. This would provide a snapshot of system performance across the industry. Section 7.2 discusses how the unavailability and unreliability estimates are calculated, as used in this report.

VEWFD system Unavailability

_____ Total system downtime during surveillance interval

_____ Surveillance interval

VEWFD system Unreliability

_____ Number of observed failure

_____ Total operating period in hours

Nuisance “Alert” Rate

_____ Number of Nuisance Alarms

_____ Total operating period in hours

The nuisance “Alert” rate does not have a direct use in the risk scoping study presented in this report. However, the frequency of “Nuisance Alerts” could be useful for end users that may be considering the installation of these systems. It could also allow for a comparison across detectors at a site or across the industry to identify trends and outliers. This could identify the need to evaluate the acceptability of the system set points to the background noise (baseline). Tracking the system response to these nuisance alerts may provide insights as to what is the root cause of the nuisance alerts.

Specific VEWFD incident information

For each event where a VEWFD system "alert" occurred before a fire, explosion, or pre-flaming condition, provide the following;

Type of Detection : ______ In-Cabinet
______ Area-wide (Ceiling)
______ Area-wide (Air Return Grill)
______ Other (please specify) ________________

Detection Technology : ______ ASD VEWFD Cloud Chamber
______ ASD VEWFD Light Scattering
______ ASD VEWFD Other (please specify) _____________

Port Sensitivity : ____________ % obsc. / ft.
____________ % obsc. / m.
____________ particles / cc

If port sensitivity is not known, detector sensitivity along with the number of sampling ports on the zone could be reported.

Detector Sensitivity : ____________ % obsc. / ft.
____________ % obsc. / m.
____________ particles / cc

# of sampling ports on "alert" zone : ____________

Time between initial "alert" and identification of degrading component

_______:________(Hours:Minutes)

Time between initial "alert" and de-energization of degrading component / cabinet

_______:________(Hours : Minutes)

Table G-1 identifies event timing information that, if consistently collected, could support advancements to the evaluation of ASD VEWFD system performance. The first column identifies the timing input, followed by the parameter identification to represent the timing input, followed by a brief description. The far right column identifies existing versus new information reporting based off of what is currently collected in the INPO ICES Fire Event Reporting system.

Table G-1. VEWFD timing information collection

Timing Input	Parameter	Description	Reporting
Time of initial detection	t_{alert}	Time when first ASD VEWFD system “alert” received in MCR.	Existing
Time of arrival at location	$t_{arrival}$	Time when first responding plant personnel arrives at location of ASD VEWFD system “alert”	New
Time fire confirmed	t_{fire}	Time when fire was confirmed	Existing
Time component identified	$t_{identify}$	Time when overheating component identified	New
Time component de-energized	$t_{power\_removed}$	Time when the power is removed from the component responsible for the ASD VEWFD system “alert”	New
Time of manual suppression actuation	$t_{man\text{-}supp}$	Time when the manual fire suppression begins	Existing
Time fire was under control	$t_{control}$	Time when the fire was controlled by suppression	Existing
Time of fire brigade dispatched	$t_{fb\_dispatch}$	Time when the fire brigade was dispatched	Existing

The information identified in Table G-1 and outlined with boxes above serve to support a quantitative assessment of operating experience. However, a narrative of the event could also help the reviewers of this information better understand the event. As such it is recommended that additional information on the event be provided in the event abstract, summary or as an attachment. With the limited information that is currently available, it is difficult to identify generically, the specific information that would be needed, but a narrative description answering the following questions may help.

“What happened?”

“Was there a fire?

“Was a fire mitigated (prevented)?”

Based on collected information identified in Table G-1 for each VEWFD system incident, the following important timing information can be determined.

Time available

The time available is the time between the first VEWFD system “Alert” and when a fire is either confirmed or the component is de-energized. It is calculated as;

$$t_{available} = t_{end} - t_{alert}$$

where, t_{end} is the lesser of t_{fire} or $t_{de\text{-}energize}$.

Response time

The response time represents the time between the VEWFD system “alert” being received in the MCR to the time when the first responding plant personnel arrive at the VEWFD system alert location. This is calculated as;

$$t_{response} = t_{arrival} - t_{alert}$$

Time required to locate source of VEWFD system “alert”

The time required to locate the source of the VEWFD system “alert” is dependent on a fire occurring before the first responding plant personnel arrival at the VEWFD system alert location or not. If a fire is confirmed when the first responding plant personnel arrives, then the time required to locate the source is zero:

$$t_{locate} = 0$$

When the first responding plant personnel arrives and no fire is present, the time required to locate the source of the VEWFD system “alert” is calculated as:

$$t_{locate} = t_{identify} - t_{arrival}$$

Time required to de-energize component or cabinet responsible for VEWFD system “alert”

The time required to de-energize the component responsible for the VEWFD system “alert” is the time between the identification of the component and when power is removed from that component (or cabinet). This is calculated as:

$$t_{de-energize} = t_{power\_removed} - t_{identify}$$

Time to suppress

The time to suppress the fire is the time between the start suppression to the time when the fire is controlled and is calculated as:

$$t_{supp} = t_{control} - t_{man-supp}$$

APPENDIX H
USER GUIDE FOR VEWFD EVENT TREE NON-SUPPRESSION PROBABILITY CALCULATION TOOL

H.1 Objectives

This appendix provides instruction on the use of the electronic spreadsheets (Microsoft Excel) that have been developed to help support estimation of the probability of non-suppression per the risk scoping study presented in Part II of this report. This appendix identifies the information needed to perform the calculation and guidance on how to use the electronic spreadsheets.

H.2 In-Cabinet Spreadsheet

The in-cabinet spreadsheet will estimate the probability of non-suppression for fire scenarios where smoke detection is located within an electrical cabinet (enclosure). The assumptions and limitations presented in Section 13 of this report apply to the use of this spreadsheet. The electronic spreadsheet is found on the CD enclosed on the back cover of this report and is also available on the NRC NUREG publication website.

H.2.1 Required input for in-cabinet spreadsheet calculation

The user must obtain the following information regarding the fire scenario under evaluation before attempting a calculation using the in-cabinet spreadsheet:

(1) Type of in-cabinet smoke detection system
- a. aspirated smoke detection (ASD)
- b. spot-type

(2) Type of electrical enclosure (cabinet) being protected
- a. control
- b. power

(3) Technology of in-cabinet smoke detection
- a. ASD VEWFD Cloud Chamber (CC)
- b. ASD VEWFD Light Scattering (LS)
- c. Spot-type VEWFD sensitive spot (SS)
- d. Spot-type conventional Ionization (ION)

(4) Cabinet ventilation
- a. naturally ventilated cabinet
- b. forced ventilation <u>less than</u> 100 cabinet air changes per hour
- c. forced ventilation <u>greater than</u> 100 cabinet air changes per hour

(5) Detection configuration
- a. 1 to 10 cabinets only

(6) Redundant fire detection within room (if credited)
- a. conventional smoke / heat (spot or linear)
- b. ASD VEWFD

(7) Type of automatic suppression (if credited)
- a. none
- b. carbon dioxide

c. halon
d. wet pipe sprinkler system
e. deluge or pre-action sprinkler system

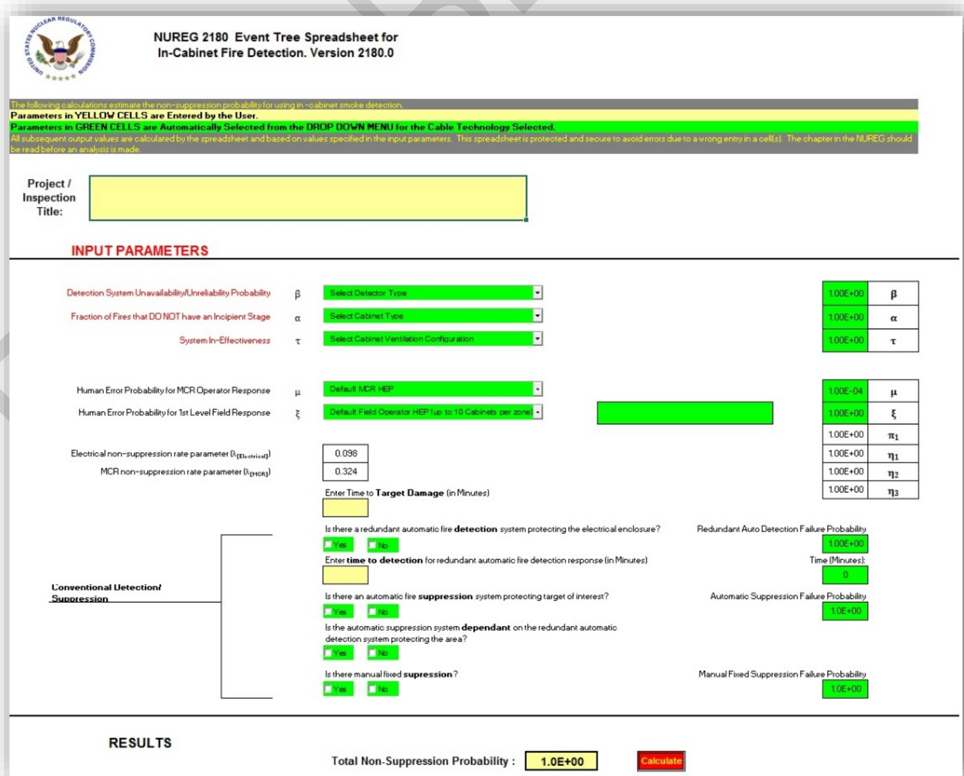
(8) Automatic suppression system dependence on detection (if credited)
(9) Fixed manual suppression failure probability (if credited)

The user must obtain the following values (point estimates - typically mean values) before attempting a calculation using the in-cabinet spreadsheet:

(1) Time to damage (in minutes) of the target of interest for the fire scenario.
(2) Time to detection (in minutes) of redundant fire detection system.
(3) Conventional non-suppression rate parameter for
  a. Electrical
  b. Main control room

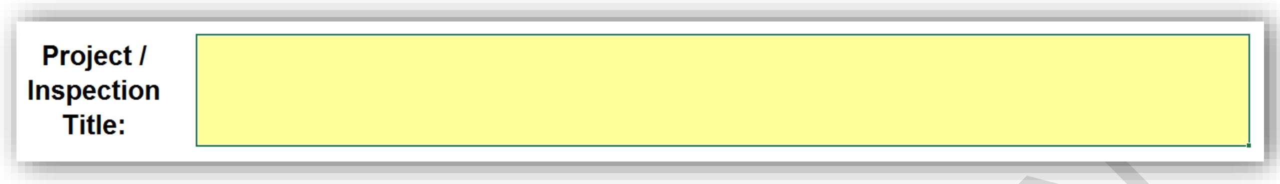
H.2.2 Detailed Discussion on In-Cabinet Spreadsheet Input Parameters

The discussion that follows provides a step-by-step procedure for completing the electronic spreadsheets. Before entering any data into the sheet, it is recommended that the sheet be reset by selecting the black "Reset" button followed by the "Yes" radio box. This will ensure that previous entries do not become incorporated in to the current evaluation. The sheet is setup following a similar format as NUREG-1805, "Fire Dynamics Tools (FDT^s)," spreadsheets. As such, the top portion of the sheet is where the input is entered, result is presented next to the red box entitled "Total Non-suppression Probability," and supporting information such as the solved event trees are presented below the result.



Step 1: Project / Inspection Title

Input field allows user to provide a detailed description of the scenario being evaluated.



Step 2: Select In-Cabinet Detector Type

Drop down menu allows selection from one of three options;

- ASD Very Early Warning
- Spot
- User Defined

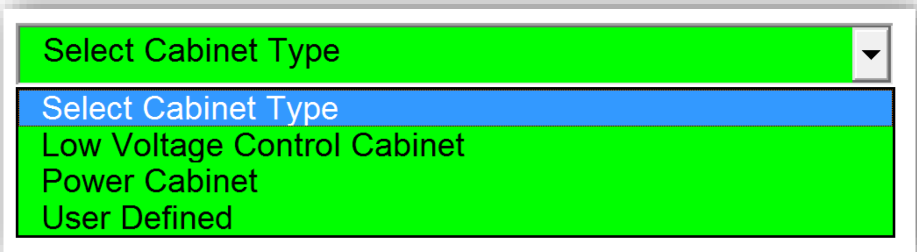
Selection of the detector type determines the point estimate to use for "β" representing the detection unit combined unreliability and unavailability. The basis for ASD very early warning point estimates is provided in Section 7.2. The estimate used for spot type detection are taken from NUREG/CR-6850 (EPRI 1011989), "Fire PRA Methodology for Nuclear Power Facilities," estimated at 0.05.

- Select "ASD Very Early Warning" for fire scenarios consisting of ASD VEWFD systems installed within the electrical cabinet. This selection assigns a point estimate 3.6×10^{-3} for "β".
- Select "Spot" for fire scenarios consisting of spot-type smoke detectors located within the electrical cabinet. This includes conventional ionization configured to at least a 1.0% obscuration / ft. sensitivity; as well as, sensitive spot-type detectors that are configured to meet the 0.2 % obscuration / ft. minimum sensitivity. This selection assigns a point estimates of 0.05 for "β."
- Select "User Defined" to use a point estimate other than those estimated in the report. It is recommended that justification be provided to support any "User Defined" point estimates.

Step 3 : Select Cabinet Type

Drop down menu allows selection from one of three options;

- Low Voltage Control Cabinet
- Power Cabinet
- User Defined

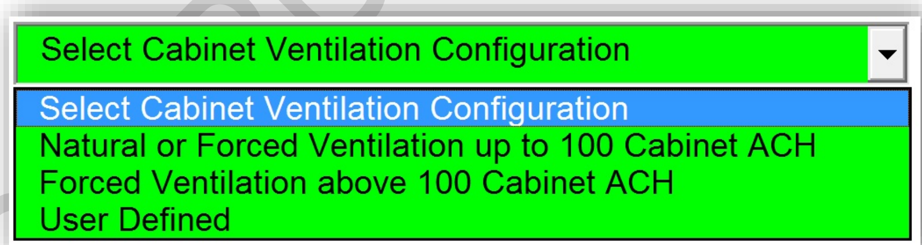


Selection of the cabinet type determines the point estimate to use for "α" representing the fraction of fires that have an incipient phase of sufficient duration to support enhanced suppression. The basis for these point estimates is provided in Section 7.1 and Appendix D.

- Select "Low Voltage Control Cabinet" for fire scenarios contain components operating at a nominal voltage of 250 volts or less. Selecting "Low Voltage Control Cabinet" assigns a point estimate 0.28 for α.
- Select "Power Cabinets" for fire scenarios involving electrical cabinets that have any component operating at voltages greater than 250 volts. Selecting "Power Cabinet" assigns a point estimate 0.50 for α.
- Select "User Defined" to use a point estimate other than those developed in this report. It is recommended that justification be provided to support any "User Defined" point estimates.

<u>Step 4a: Select Cabinet Ventilation Configuration</u>

Drop down menu allows selection from one of three options;
- Natural <u>or</u> Forced Ventilation up to 100 Cabinet ACH
- Forced Ventilation above 100 Cabinet ACH
- User Defined



Selection of the cabinet ventilation configuration in Step 4a, followed by the selection of the detector technology in Step 4b, determines the point estimate to use for "τ" representing the in-effectiveness of the system to detect the fire threat in its low-energy incipient stage. The basis for the in-effectiveness point estimates are presented in Section 7.2.3.

- Select "Natural <u>or</u> Forced Ventilation up to 100 Cabinet ACH" for fire scenarios consisting of electrical cabinets that are either naturally ventilated with louvers or grates on at least one side of the cabinet, or with mechanical forced ventilation (fans or blowers) that ventilate the cabinet at up to 100 cabinet air changes per hour. No point estimate is assigned until Step 4b is complete.

- Select “Forced Ventilation above 100 Cabinet ACH” for fire scenarios consisting of electrical cabinets that are mechanically ventilated with a ventilation rate above 100 cabinet air changes per hour. No point estimate is assigned until Step 4b is complete.

- Select “User Defined” to use a point estimate other than those estimated in the report. It is recommended that justification be provided to support any “User Defined” point estimates.

<u>Step 4b: Select Detection Technology</u>

After Step 4a is complete, a drop down menu appears allowing for selection of the detection technology;

- Ionization Spot (ION)
- Photoelectric Spot (PHOTO)
- VEWFD Sensitive Spot (SS)
- ASD VEWFD Cloud Chamber (CC)
- ASD VEWFD Light Scatter 1 (LS1)
- ASD VEWFD Light Scatter 2 (LS2)

- Select “Ionization Spot (ION)” for fire scenarios consisting of ionization spot-type detectors located within the electrical cabinet on or near the cabinet ceiling. The ionization type detector should have an Alarm sensitivity set point of 1.0%obscuration / ft. or more sensitive. This selection assigns a point estimate of either 0.10 or 0.79 for “τ,” depending on the cabinet ventilation rate.
- Select “Photoelectric Spot (PHOTO)” for fire scenarios consisting of photoelectric spot-type detectors located within the electrical cabinet on or near the cabinet ceiling. The photoelectric type detector should have an Alarm sensitivity set point of 2.1%obscuration / ft. or more sensitive. This selection assigns a point estimate of 0.77 for “τ,” for naturally <u>or</u> forced ventilation up to 100 Cabinet ACH. Note that there is no data available from this testing program for the performance of a photoelectric spot detector within an electrical cabinet with forced ventilation greater than 100 ACH.
- Select “VEWFD Sensitive Spot (SS)” for fire scenarios consisting of VEWFD spot-type detectors located within the electrical cabinet on or near the cabinet ceiling. The VEWFD sensitive spot type detector should have an Alert sensitivity set point of 0.2%obscuration / ft. above background or more sensitive. This selection assigns a point estimate of 0.26 for “τ,” for naturally <u>or</u> forced ventilation up to 100 Cabinet ACH Note that there is no data available from this testing program for the performance of a

photoelectric spot detector within an electrical cabinet with forced ventilation greater than 100 ACH.

- Select “ASD VEWFD Cloud Chamber (CC)” for fire scenarios consisting of aspirated smoke detections utilizing a cloud chamber technology and configured as a VEWFD system. The ASD sampling ports located within the electrical cabinet on or near the cabinet ceiling. The ASD VEWFD CC detector should have a port Alert sensitivity set point of 0.2%obscuration / ft. above background or more sensitive. This selection assigns a point estimate of either 2.7×10^{-03} or 1.9×10^{-02} for “τ,” depending on the cabinet ventilation rate.
- Select “ASD VEWFD Light Scattering 1 (LS1)” or “ASD VEWFD Light Scattering 2 (LS2)” for fire scenarios consisting of aspirated smoke detections utilizing a Light Scattering technology and configured as a VEWFD system. The ASD sampling ports located within the electrical cabinet on or near the cabinet ceiling. The ASD VEWFD LS detector should have a port Alert sensitivity set point of 0.2%obscuration / ft. above background or more sensitive. This selection assigns a point estimate of either 0.53 (LS1) / 1.9×10^{-01} (LS2) or 0.37 (LS2) for “τ,” depending on the cabinet ventilation rate. Note that there is no data available from this testing program for the performance of the LS1 detector within an electrical cabinet with forced ventilation greater than 100 ACH.

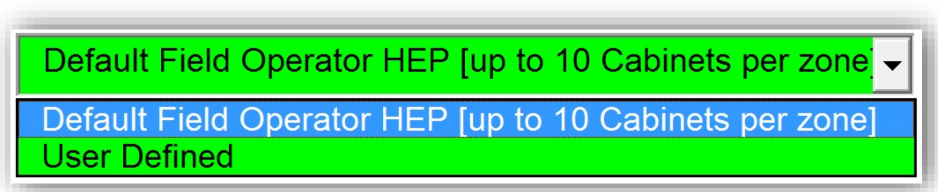
Step 5: Select Human Error Probability for Main Control Room Response

Drop down menu assumes a main control room (MCR) human error probability of 1×10^{-04}, but also allows for a user defined HEP estimate. If the “User Defined” option is selected, a point estimate different from the default can be entered. It is recommended that justification be provided to support any “User Defined” point estimates.

Step 6: Select Number of Cabinets

Selection of the number of cabinets assigns a HEP for the field operator response to the VEWFD system “alert” notification. The drop down allows selection from two options;

- Default Field Operator HEP [up to 10 Cabinets per zone]
- User Defined



- Use the default for fire scenarios consisting of ASD VEWFD systems that protect up to 10 electrical cabinets (sometimes referred to as vertical sections). This assigns a HEP

per the type of technology used (ASD VEWFD CC, ASD VEWFD LS, SS LS or ION spot). The basis for these estimates are presented in Section 10.6.

- Select "User Defined" to use a point estimate other than those estimated in the report. It is recommended that justification be provided to support any "User Defined" point estimates.

Step 7: Ensure Proper Non-Suppression Rate Parameters

The spreadsheet use the non-suppression rate parameters published in 2015 in NUREG-2169 (EPRI 3002002936) titled, "Nuclear Power Plant Fire Ignition Frequency and Non-Suppression Probability Estimation Using the Updated Fire Events Database: United States Fire Events Experience Through 2009." In that report, the electrical non-suppression rate parameter is estimated at 0.098, while the main control room non-suppression rate parameter is estimated at 0.324. These are the default used in the spreadsheet. If other suppression rate parameters are used, enter those value(s) in the corresponding fields. It is recommended that justification be provided to support any "user defined" estimates.

Electrical non-suppression rate parameter ($\lambda_{[Electrical]}$)	0.098
MCR non-suppression rate parameter ($\lambda_{[MCR]}$)	0.324

Step 8: Enter Time to Target Damage Estimate

To conduct the detection/suppression analysis, a fire scenario time to target damage (in minutes) input is required. This estimate is typically based on fire modeling results. This estimate is entered in the yellow input box.

Enter Time to **Target Damage** in Minutes

The time to target damage does not include any estimate for the incipient stage duration. Section 11 provides additional information.

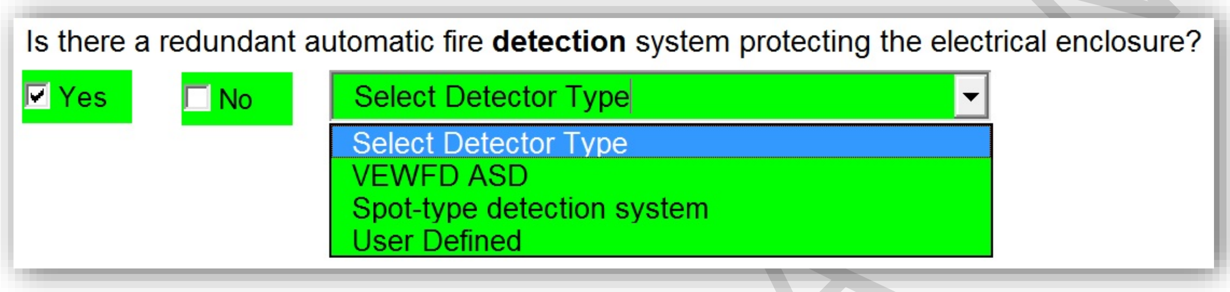
Step 9: Enter Conventional Detection / Suppression Information

The last set of input required to calculate the non-suppression probability is related to conventional suppression and detection systems in the fire scenario protecting the target(s) of interest or the potential ignition sources. The input required is associated with redundant automatic fire detection and suppression systems, and any manual fire suppression capability. The input is entered by answering questions related to the redundant systems, user supplied input, and drop down menu selections.

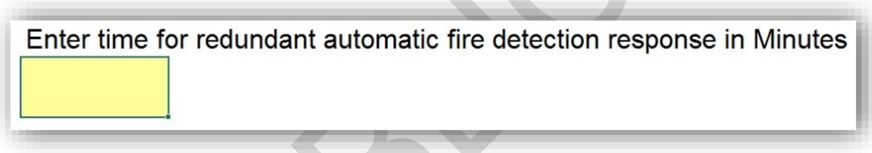
The first question relates to any existing automatic fire detection system protecting the target(s) of interest and redundant from the in-cabinet fire detection system. For example, spot-type detection located at the ceiling of the room that has a different annunciator in the MCR would be considered a redundant automatic fire detection system, as would spot heat detectors, or a

VEWFD ASD system. If there is no automatic fire detection system present, or no credit of that system is being taken, select the "No" check box and continue to the automatic suppression question.

If a redundant fire detection system is present, select the "Yes" check box. Once this is done, a drop down menu will appear. From the dropdown menu, select the type of redundant automatic fire detection system (VEWFD ASD, Spot-type Detection, or User Defined). This selection assigns an associated unreliability estimate (failure probability) to the redundant automatic fire detection system. If the "User Defined" option is selected, a failure probability for the redundant system should be entered in the box to the right.



After the failure probability is assigned, a time to detection for the redundant automatic fire detection system must be entered. This time must be a positive value and entered in minutes.

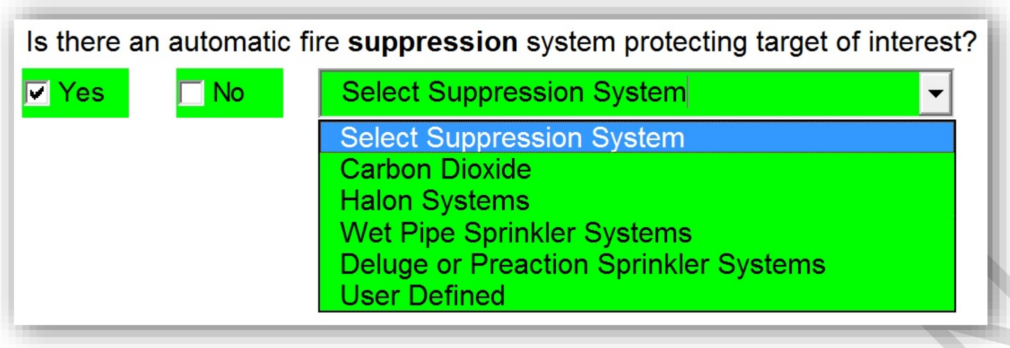


The next two questions relate to automatic fire suppression systems that are protecting the target(s) of interest.

- If there is no automatic fire suppression system present, or no credit of that system is being taken, select the "**No**" check box. Selecting "No" will automatically answer "No" to the subsequent question regarding the suppression system dependency on fire detection. Continue to the manual fixed suppression question.
- If there is an automatic fire suppression system present, select "**Yes**." Once this is done, a dropdown menu will appear. From the dropdown menu, select the type of automatic fire suppression system (Carbon Dioxide, Halon System, Wet Pipe, Deluge, Pre-action sprinkler systems, or User Defined). This selection assigns an unreliability estimate (failure probability) to the automatic fire suppression system.

> When crediting automatic suppression systems, the **analyst must** first determine that the automatic suppression will actuate prior to the predicted time to fire damage or else auto suppression fails.

- If the "User Defined" option is selected, a failure probability for the redundant system should be entered in the box to the right.

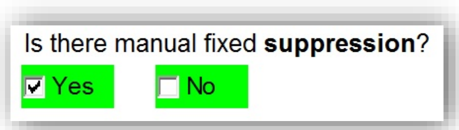


Several types of automatic fire suppression systems are dependent on an automatic fire detection system for actuation. The failure probability estimates for these systems are listed below and taken from NUREG/CR-6850. If other systems are specified or if updated failure probabilities are desired to be used, select "User Defined" and enter the failure probability in the "Enter Value" field to the right.

- Carbon Dioxide : 4.0×10^{-02}
- Halon System : 5.0×10^{-02}
- Wet Pipe Sprinkler Systems : 2.0×10^{-02}
- Deluge or Pre-action Sprinkler Systems : 5.0×10^{-02}

The next questions ask if there is such a dependency and then assigns a failure probability to that automatic fire detection system for which the automatic suppression system is dependent upon. By selecting "Yes," the spreadsheet assumes that the automatic suppression system is dependent on the redundant automatic fire detection system specified previously. If "No" is selected, go to the next question.

The last question in the conventional detection / suppression portion of the input fields is related to manual fixed suppression. If there is manual fixed suppression that will be credited for the fire scenario under evaluation, select "Yes" and then enter the Manual Fixed Suppression Failure Probability on the field to the right. Note that there is no default failure probability for manual fixed suppression. If "Yes" is selected, it is recommended that the user provide justification for the failure probability used. Otherwise, select "No."

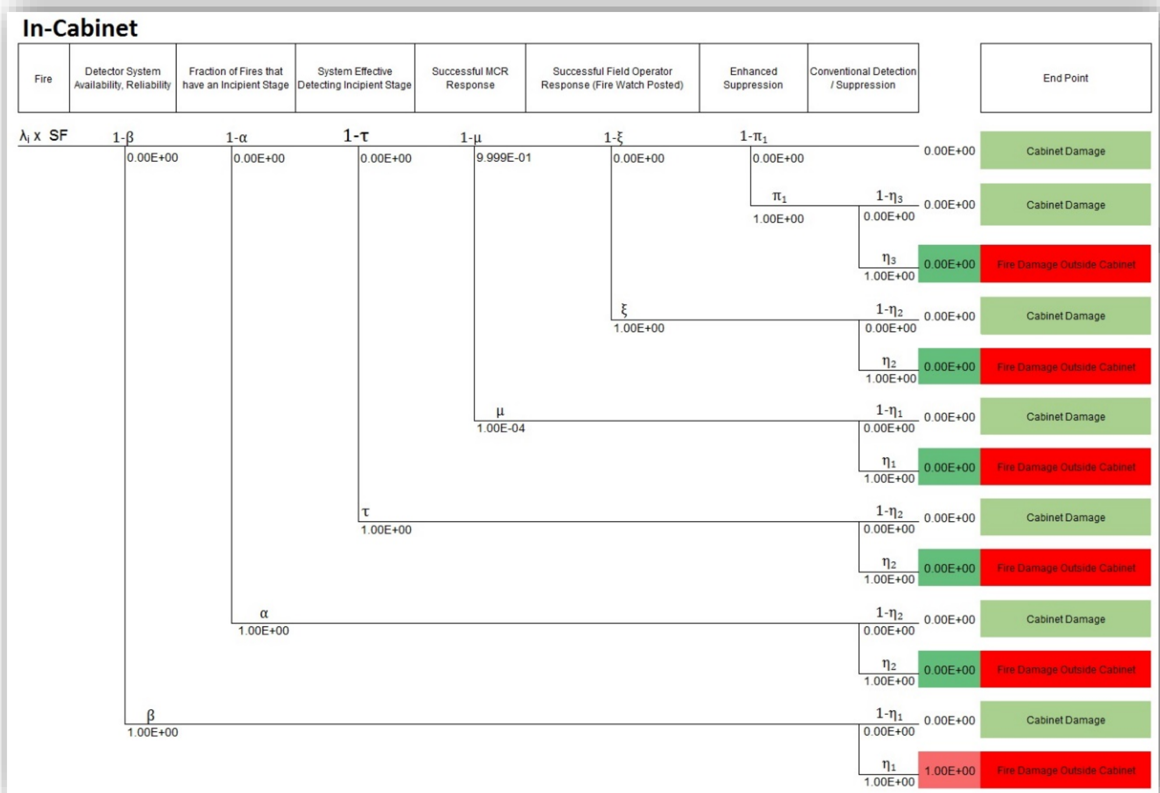


Step 10: Review Solution

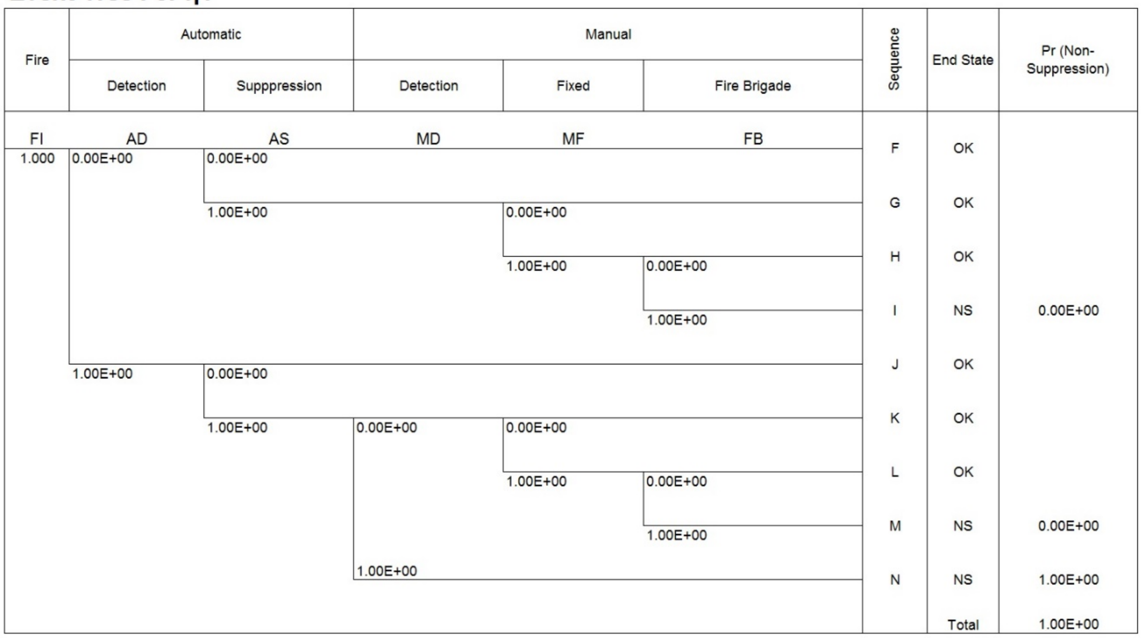
After all of the required input is entered into the spreadsheet, the solution will be presented as the total Non-Suppression Probability.

The result is calculated from the sum of the failure end states (fire damage outside cabinet) from the in-cabinet event tree presented in Section 6.4. The solved event tree is provided below the

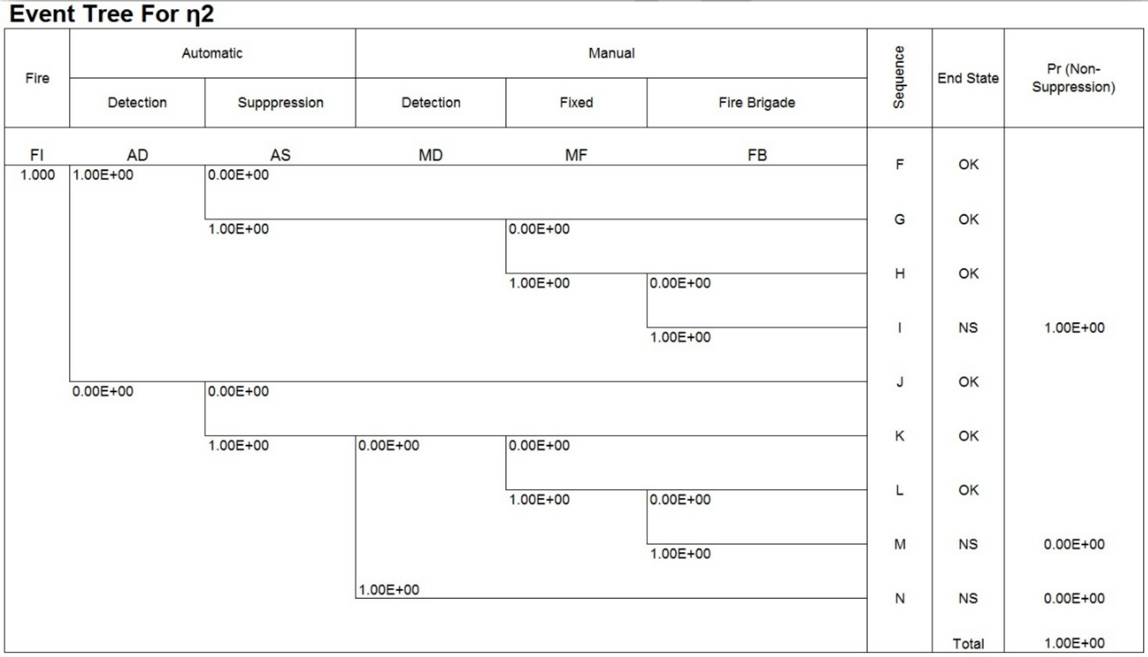
result, including the supporting NUREG/CR-6850 Appendix P detection/suppression event trees.



Event Tree For η1



Event Tree For η2



H.3 Area-Wide Spreadsheet

The Area-wide spreadsheet will estimate the probability of non-suppression for fire scenarios where ASD VEWFD systems have sampling ports either near the ceiling or across air return grilles. The assumptions and limitations presented in Section 13 of this report apply to the use of this spreadsheet. The electronic spreadsheet is found on the CD enclosed on the back cover of this report and is also available on the NRC NUREG publication website.

H.3.1 Required input for area-wide spreadsheet calculations

The user must obtain the following information regarding the fire scenario under evaluation before attempting a calculation using the in-cabinet spreadsheet:

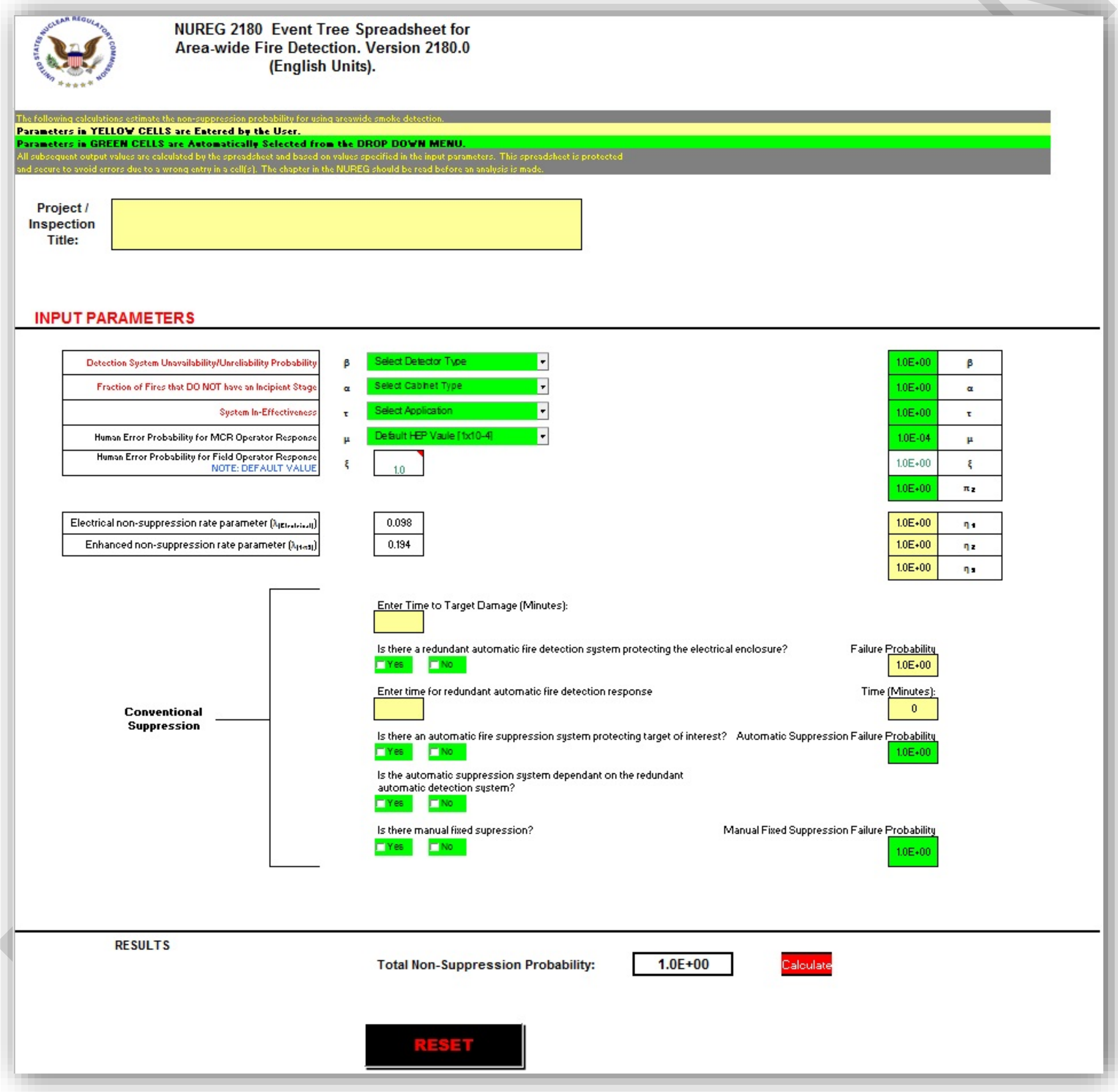
(1) Type of area-wide smoke detection system
  a. aspirated smoke detection (ASD)
  b. spot-type
(2) Type of electrical enclosure (cabinet) being protected
  a. control
  b. power
(3) Technology of area-wide smoke detection
  a. ASD VEWFD Cloud Chamber (CC)
  b. ASD VEWFD Light Scattering (LS)
  c. spot-type VEWFD sensitive spot (SS)
(4) Room ventilation (HVAC)
(5) Detection configuration
  a. ceiling
  b. air return grille
(6) Redundant fire detection within room
  a. conventional smoke / heat (spot or linear)
  b. ASD VEWFD
(7) Type of automatic suppression
  a. none
  b. carbon dioxide
  c. halon
  d. wet pipe sprinkler system
  e. deluge or pre-action sprinkler system
(8) Automatic suppression system dependence on detection
(9) Fixed manual suppression

The user must obtain the following values (point estimates - typically mean values) before attempting a calculation using the in-cabinet spreadsheet:

(1) Time to damage (in minutes) of the target of interest for the fire scenario.
(2) Time to detection (in minutes) of redundant fire detection system.
(3) Conventional non-suppression rate parameter for
  a. Electrical

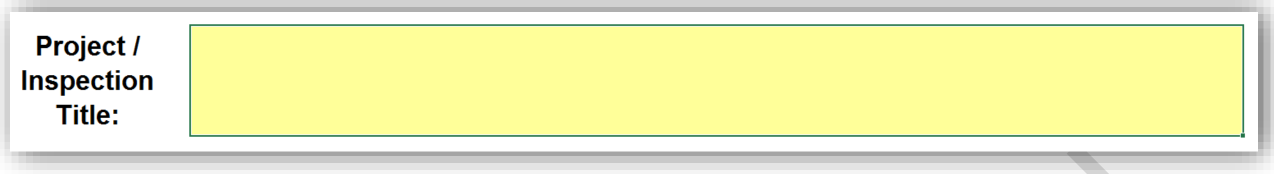
H.3.2 Detailed Discussion on Area-wide Spreadsheet Input Parameters

The discussion that follows provides a step-by-step procedure for completing the electronic spreadsheets. Before entering any data into the sheet, it is recommended that the sheet be reset by selecting the black “Reset” button followed by the “Yes” radio box. This will ensure that previous entries do not become incorporated in to the current evaluation. The sheet is setup following a similar format as NUREG-1805, “Fire Dynamics Tools (FDTs),” spreadsheets. As such, the top portion of the sheet is where the input is entered, result is presented next to the red box entitled “Total Non-suppression Probability,” and supporting information such as the solved event trees are presented below the result.



Step 1: Project / Inspection Title

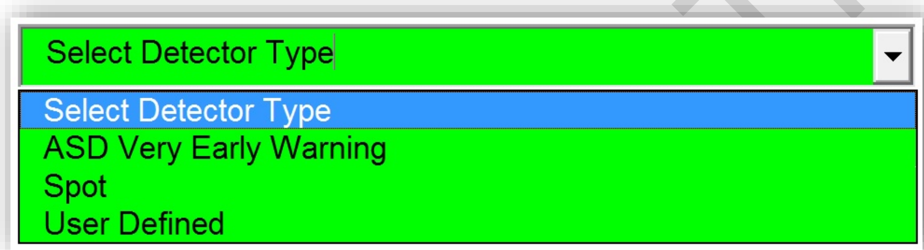
Input field allows user to provide a detailed description of the scenario being evaluated.



Step 2: Select Area-wide Detector Type

Drop down menu allows selection from one of three options;

- ASD Very Early Warning
- Spot
- User Defined



Selection of the detector type determines the point estimate to use for “β” representing the detection unit combined unreliability and unavailability. The basis for ASD very early warning point estimates is provided in Section 7.2. The estimate used for spot type detection are taken from NUREG/CR-6850 (EPRI 1011989), “Fire PRA Methodology for Nuclear Power Facilities,” estimated at 0.05.

- Select “ASD Very Early Warning” for fire scenarios consisting of ASD VEWFD systems installed within the electrical cabinet. This selection assigns a point estimate 3.6×10^{-03} for “β”.

- Select “Spot” for fire scenarios consisting of spot-type smoke detectors located within the electrical cabinet. This includes conventional ionization, as well as, sensitive spot-type detectors that are configured to meet the 0.2 % obscuration / ft. minimum sensitivity. This selection assigns a point estimates of 0.05 for “β.”

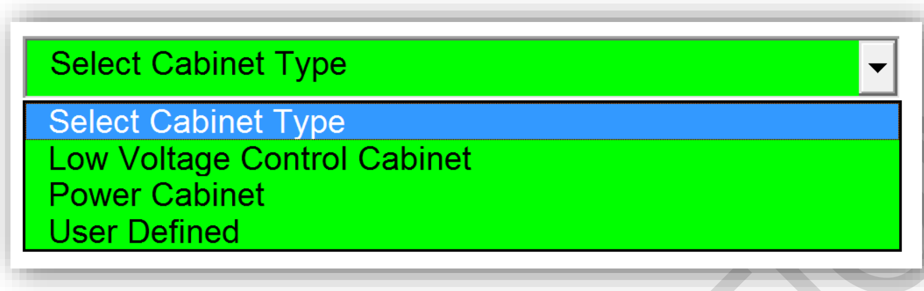
- Select “User Defined” to use a point estimate other than those estimated in the report. It is recommended that justification be provided to support any “User Defined” point estimates.

  NOTE: If an air return grill application is being used, the failure probability of air handling unit should be considered as a contributor to the unreliability of the VEWFD system. Since the air return grill application is dependent on the HVAC, the HVAC system failure probability should be considered and included in the “β” point estimate. For this case, the “User Defined” option should be selected.

Step 3: Select Cabinet Type

Drop down menu allows selection from one of three options;

- Low Voltage Control Cabinet
- Power Cabinet
- User Defined



Selection of the cabinet type determines the point estimate to use for "α" representing the fraction of fires that have an incipient phase of sufficient duration to support enhanced suppression. The basis for these point estimates is provided in Section 7.1 and Appendix D.

- Select "Low Voltage Control Cabinet" for fire scenarios contain components operating at a nominal voltage of 250 volts or less. Selecting "Low Voltage Control Cabinet" assigns a point estimate 0.28 for α.

- Select "Power Cabinets" for fire scenarios involving electrical cabinets that have any component operating at voltages greater than 250 volts. Selecting "Power Cabinet" assigns a point estimate 0.50 for α.

- Select "User Defined" to use a point estimate other than those developed in this report. It is recommended that justification be provided to support any "User Defined" point estimates.

Step 4a: Select Application

Drop down menu allows selection from one of three options;

- Air Return Grill
- Ceiling
- User Defined

Selection of the cabinet ventilation configuration in Step 4a, followed by the selection of the room ventilation configuration and detector technology in Step 4b, determines the point estimate to use for "τ" representing the in-effectiveness of the system to detect the fire threat in its low-

energy incipient stage. The basis for the in-effectiveness point estimates are presented in Section 7.2.3.

- Select “Air Return Grill” for fire scenarios consisting of ASD VEWFD systems protecting a room where the ASD sampling ports are located across the air return grill. No point estimate is assigned until Step 4b is complete.

- Select “Ceiling” for fire scenarios consisting of ASD VEWFD or spot-type VEWFD systems protecting the room where the ASD sampling ports or VEWFD spot-type detectors are located at or near the ceiling of the room. No point estimate is assigned until Step 4b is complete.

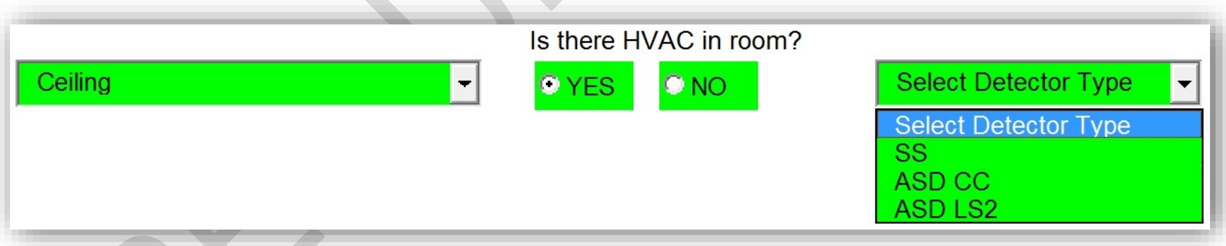
- Select “User Defined” to use a point estimate other than those estimated in the report. It is recommended that justification be provided to support any “User Defined” point estimates.

<u>Step 4b: HVAC configuration</u>

- If “Air Return Grill” was selected in Step 4a, the question “Is there HVAC in room?” appears along with two radio button options. If the room under evaluation has heating, ventilation, and air-conditioning (HVAC) select “Yes.” If it does not, select “No.”

  Note that air return grill applications require active air handling and as such, if “no” is selected for that configuration, the application is assumed to be ineffective (i.e., β = 1). Drop down menu allows selection from one of three options;

- If “Ceiling” was selected in Step 4b, no HVAC question will appear and proceed to Step 4c.



Step 4c: <u>Select Detection Technology</u>

Unless “User Defined” was selected in Step 4a, a “Select Detector Type” drop down box will appear that allows for the selection of the detector type used.

- VEWFD Sensitive Spot (SS)
- ASD VEWFD Cloud Chamber (CC)
- ASD VEWFD Light Scatter 2 (LS2)

- Select “VEWFD Sensitive Spot (SS)” for fire scenarios consisting of VEWFD spot-type detectors located at or near the ceiling of the room. The VEWFD sensitive spot type detector should have an Alert sensitivity set point of 0.2%obscuration / ft. above

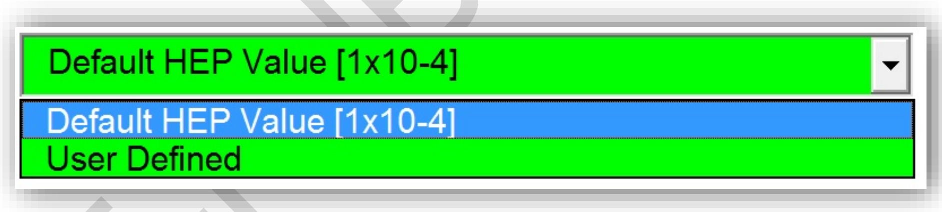
background or more sensitive. This selection assigns a point estimate of 0.57 for “τ.” The estimate is only applicable for ceiling mounted SS detectors. The SS detectors were not evaluated in this program for their response when installed across an air return grill.

- Select “ASD VEWFD Cloud Chamber (CC)” for fire scenarios consisting of aspirated smoke detections utilizing a cloud chamber technology and configured as a VEWFD system. The ASD sampling ports located at or near the room ceiling or across the air return grill. The ASD VEWFD CC detector should have a port Alert sensitivity set point of 0.2%obscuration / ft. above background or more sensitive. This selection assigns a point estimate of either 0.32 or 0.30 for “τ,” depending on the application.

- Select “ASD VEWFD Light Scattering 2 (LS2)” for fire scenarios consisting of aspirated smoke detections utilizing a Light Scattering technology and configured as a VEWFD system. The ASD sampling ports located at or near the room ceiling or across the air return grill. The ASD VEWFD LS detector should have a port Alert sensitivity set point of 0.2%obscuration / ft. above background or more sensitive. This selection assigns a point estimate of either 0.11 or 0.52 for “τ,” depending on the application. Note that there is no data available from this testing program for the performance of the LS1 detector.

<u>Step 5: Select Human Error Probability for Main Control Room Response</u>

Drop down menu assumes a main control room (MCR) human error probability of $1x10^{-04}$, but also allows for a user defined HEP estimate. If the “User Defined” option is selected, a point estimate different from the default can be entered. It is recommended that justification be provided to support any “User Defined” point estimates.



<u>Step 6: Develop a Human Error Probability for 1st Level Field Response (ξ)</u>

The spreadsheet automatically assigns a 100% failure probability for the 1st level field response. As discussed in Section 10, the large variability in the area-wide applications could not support development of a generic HEP. This is not to say that one could not be developed and justified for a plant specific scenario. If such a plant specific HEP were to be developed, it is recommended that a process such as that presented in Sections 9 and 10 be followed to support such an estimate. As with all other user defined inputs, it is recommended that justification be provided.

<u>Step 7: Ensure Proper Non-Suppression Rate Parameters</u>

The spreadsheet use the electrical non-suppression rate parameter published in 2015 in NUREG-2169 (EPRI 3002002936) entitled, “Nuclear Power Plant Fire Ignition Frequency and Non-Suppression Probability Estimation Using the Updated Fire Events Database: United States Fire Events Experience Through 2009.” In that report, the electrical non-suppression

rate parameter is estimated at 0.098. In addition to this rate parameter, a new rate parameter was developed in this report to develop a non-suppression curve representing the field operator in the room responsible for the VEWFDS alert fails to promptly sup press the fire quickly enough to prevent damage to PRA targets <u>outside the cabinet</u>. Development of this parameter (λ_{enh}=0.194) is presented in Section 11.1. These are the default used in the spreadsheet. If other suppression rate parameters are used, enter those value(s) in the corresponding fields. It is recommended that justification be provided to support any "user defined" estimates.

Electrical non-suppression rate parameter ($\lambda_{[Electrical]}$)	0.098
Enhanced non-suppression rate parameter ($\lambda_{[1-\pi 3]}$)	0.194

Step 8: Enter Time to Target Damage Estimate

To conduct the detection/suppression analysis, a fire scenario time to target damage (in minutes) input is required. This estimate is typically based on fire modeling results. This estimate is entered in the yellow input box.

Enter Time to **Target Damage** in Minutes

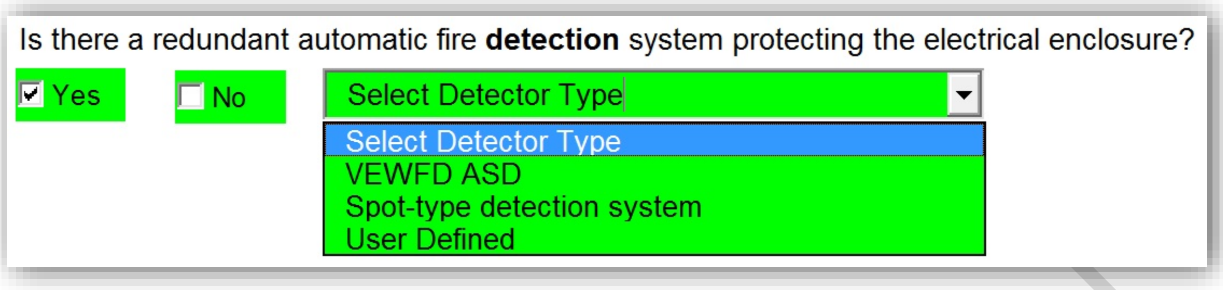
The time to target damage does not include any estimate for the incipient stage duration. Section 11 provides additional information.

Step 9: Enter Conventional Detection / Suppression Information

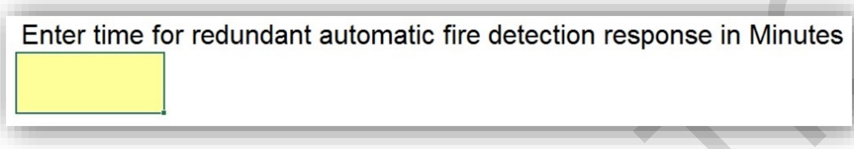
The last set of input required to calculate the non-suppression probability is related to conventional suppression and detection systems in the fire scenario protecting the target(s) of interest or the potential ignition sources. The input required is associated with redundant automatic fire detection and suppression systems, and any manual fire suppression capability. The input is entered by answering questions related to the redundant systems, user supplied input, and drop down menu selections.

The first question relates to any existing automatic fire detection system protecting the target(s) of interest and redundant from the area-wide VEWFD fire detection system. For example, spot-type detection located at the ceiling of the room that has a different annunciator in the MCR would be considered a redundant automatic fire detection system, as would spot heat detectors, or second VEWFD ASD system (provided that it is independent of the primary system). If there is no automatic fire detection system present, or no credit of that system is being taken, select the "No" check box and continue to the automatic suppression question.

If a redundant fire detection system is present, select the "Yes" check box. Once this is done, a drop down menu will appear. From the dropdown menu, select the type of redundant automatic fire detection system (VEWFD ASD, Spot-Type Detection, or User Defined). This selection assigns an associated unreliability estimate (failure probability) to the redundant automatic fire detection system. If the "User Defined" option is selected, a failure probability for the redundant system should be entered in the box to the right.



After the failure probability is assigned, a time to detection for the redundant automatic fire detection system must be entered. This time must be a positive value and entered in minutes.



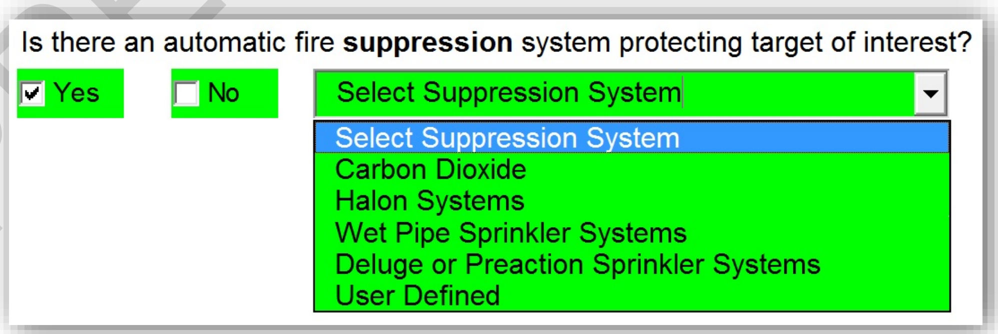
The next two questions relate to automatic fire suppression systems that are protecting the target(s) of interest.

- If there is no automatic fire suppression system present, or no credit of that system is being taken, select the "**No**" check box. Selecting "No" will automatically answer "No" to the subsequent question. Continue to the manual fixed suppression question.

- If there is an automatic fire suppression system present, select "Yes." Once this is done, a dropdown menu will appear. From the dropdown menu, select the type of automatic fire system (Carbon Dioxide, Halon System, Wet Pipe, Deluge, Pre-action sprinkler systems, or User Defined). This selection assigns an unreliability estimate (failure probability) to the automatic fire suppression system.

> When crediting automatic suppression systems, the **analyst must** first determine that the automatic suppression will actuate prior to the predicted time to fire damage or else auto suppression fails.

- If the "User Defined" option is selected, a failure probability for the redundant system should be entered in the box to the right.



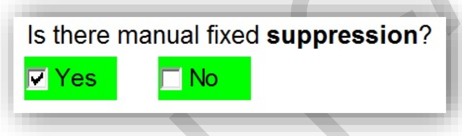
Several types of automatic fire suppression systems are dependent on an automatic fire detection system for actuation. The failure probability estimates for these systems are listed below and taken from NUREG/CR-6850. If other systems are specified or if updated failure

probabilities are desired to be used, select "User Defined" and enter the failure probability in the "Enter Value" field to the right.

- Carbon Dioxide : 4.0×10^{-02}
- Halon System : 5.0×10^{-02}
- Wet Pipe Sprinkler Systems : 2.0×10^{-02}
- Deluge or Preaction Sprinkler Systems : 5.0×10^{-02}

The next questions ask if there is such a dependency and then assigns a failure probability to that automatic fire detection system for which the automatic suppression system is dependent upon. By selecting "Yes," the spreadsheet assumes that the automatic suppression system is dependent on the redundant automatic fire detection system specified previously. If "No" is selected, go to the next question.

The last question in the conventional detection/suppression portion of the input fields is related to manual fixed suppression. If there is manual fixed suppression that will be credited for the fire scenario under evaluation, select "Yes" and then enter the Manual Fixed Suppression Failure Probability on the field to the right. Note that there is no default failure probability for manual fixed suppression. If "Yes" is selected, it is recommended that the user provide justification for the failure probability used. Otherwise, select "No."

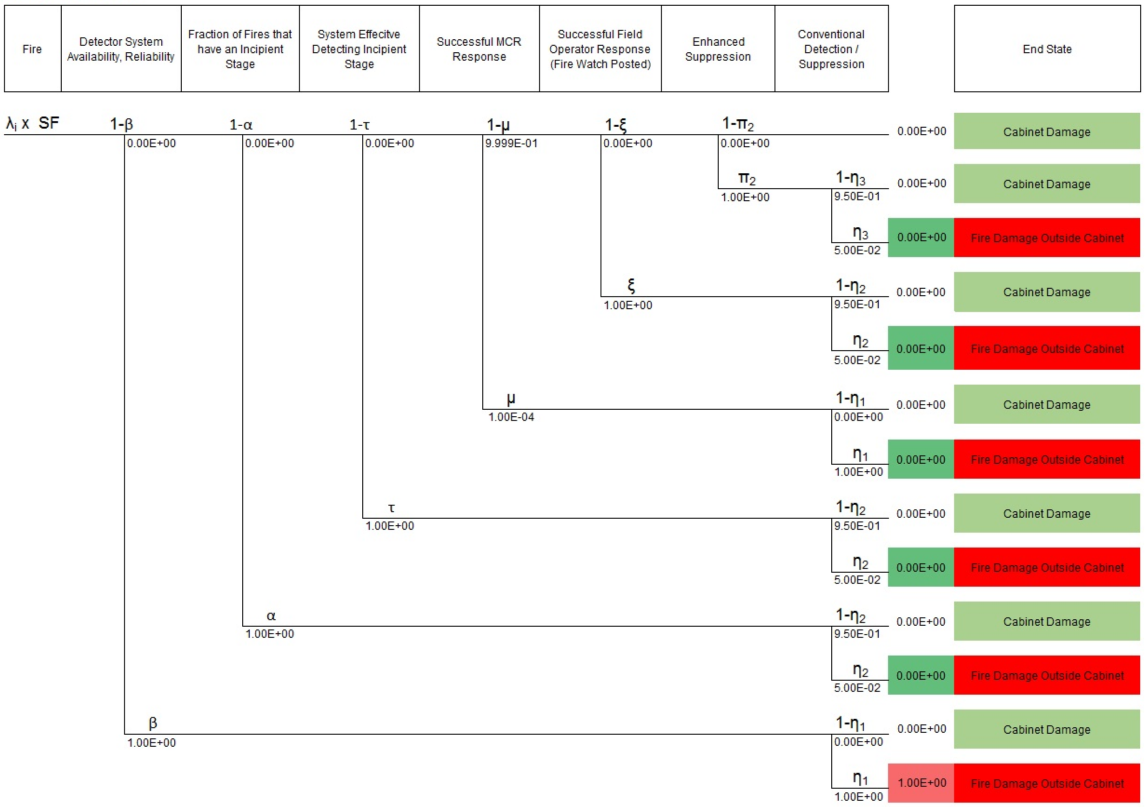


Step 10: Review Solution

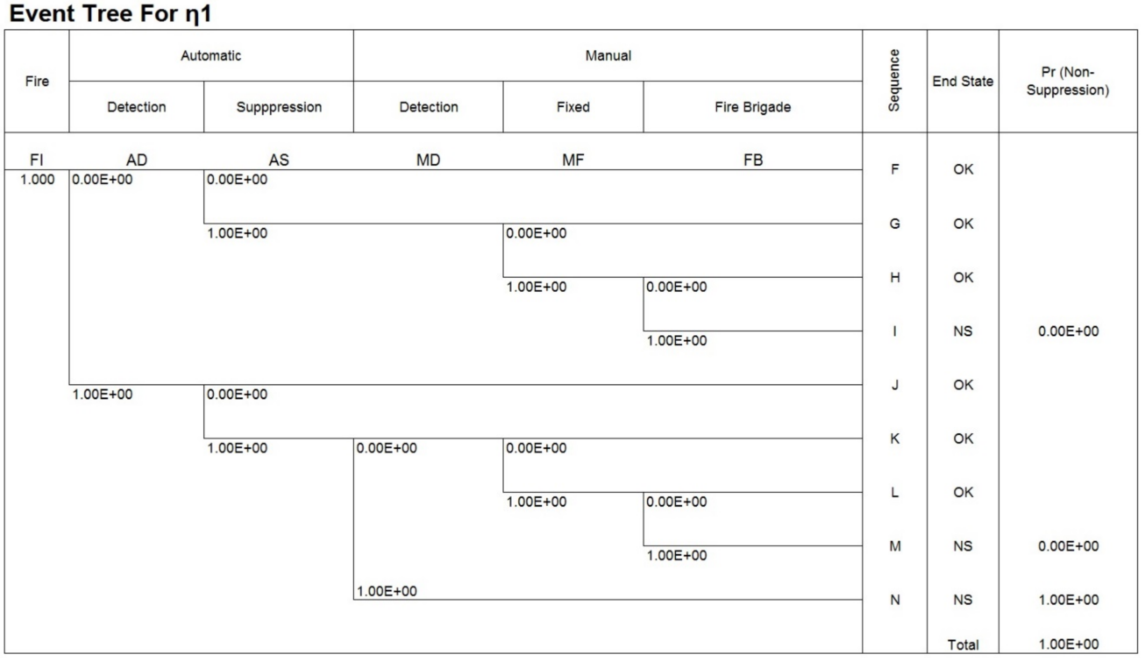
After all of the required input is entered into the spreadsheet, the solution will be presented as the total Non-Suppression Probability.

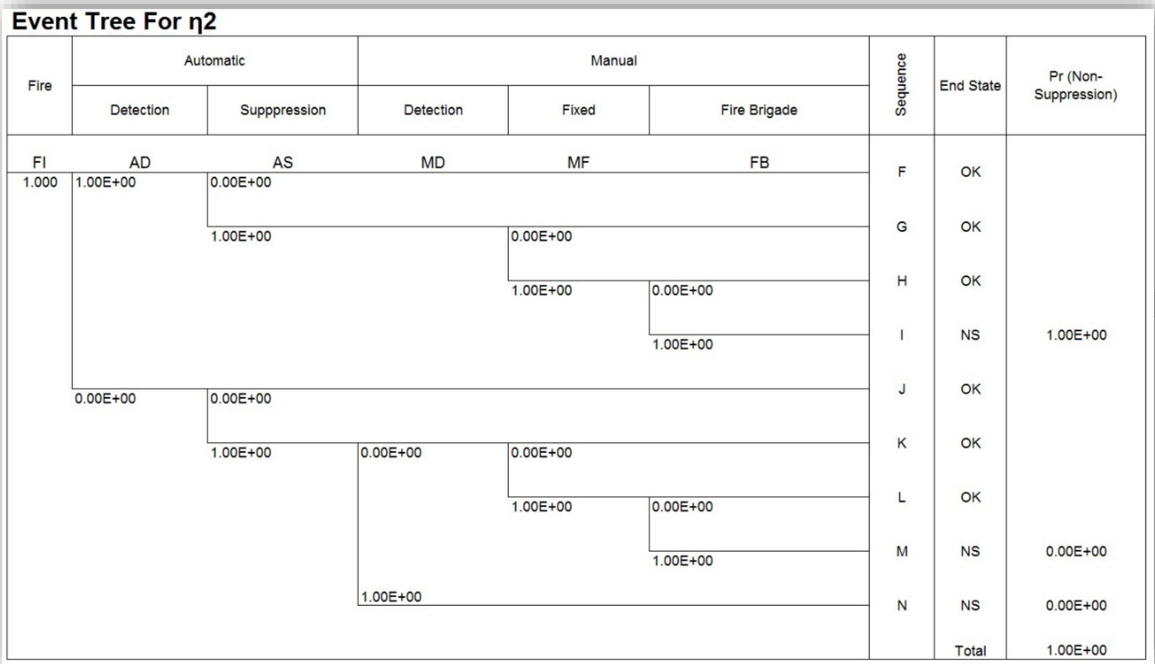
The result is calculated from the sum of the failure end states (fire damage outside cabinet) from the area-wide event tree presented in Section 6.4. The solved event tree is provided below the result, including the supporting NUREG/CR-6850 Appendix P detection/suppression event trees.

Area-wide



Event Tree For η1




Event Tree For η2
Fire
Automatic
Detection
Supppression
Manual
Detection
Fixed
Fire Brigade
Sequence
End State
Pr (Non-Suppression)
FI
AD
AS
MD
MF
FB
1.000
1.00E+00
0.00E+00
1.00E+00
0.00E+00
1.00E+00
0.00E+00
1.00E+00
0.00E+00
0.00E+00
1.00E+00
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0.00E+00
1.00E+00
0.00E+00
1.00E+00
1.00E+00
F OK
G OK
H OK
I NS 1.00E+00
J OK
K OK
L OK
M NS 0.00E+00
N NS 0.00E+00
Total 1.00E+00