RISK-REDUCTION CREDIT FOR VERY EARLY WARNING FIRE DETECTION AT NUCLEAR POWER PLANTS: FROM FAQ TO FICTION

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In 2004, the U.S. Nuclear Regulatory Commission (NRC), with support from the commercial nuclear power industry, adopted the 2001 Edition of National Fire Protection Association (NFPA) Standard 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants," as the means by which commercial nuclear power licensees could comply with Title 10 of the Code of Federal Regulations, Part 50.48[c], to replace deterministic fire protection licensing bases with ones that are risk-informed and performance-based. To facilitate licensee "transitions" to the new licensing bases via NFPA 805, a "Frequently Asked Questions" (FAQs) program, established early during the pilot-plant phase, was expanded to enable use of consensus technical "short-cuts" for fire probabilistic risk assessment (PRA) methods. These "Fire PRA FAQs" enabled licensees, with NRC approval, to bypass more traditional means of establishing acceptable PRA method enhancements on an interim basis, pending eventual confirmation by test programs and/or more detailed analyses. The NRC approved several, of which perhaps the most substantial in providing risk reduction benefits was FAQ 08-0046 on "Incipient Fire Detection Systems," more accurately characterized as "Very Early Warning Fire Detection Systems" (VEWFDSs). Controversial from the start, the hidden story behind this FAQ's initial adoption is relevant to examination of the NRC NUREG report that later replaced it and remains in effect today. This article examines this backstory, tracing recommendations that were proposed and bypassed, then examines alternatives to the current guidance. These alternatives, which maximize possible risk reduction credit for VEWFDSs at nuclear power plants, remain at least a factor of two less than the current peak NUREG-2180 risk-reduction factor even before the latter accounts for the possibility of fire pre-emption altogether.

Key Words: Fire Detection, Early Warning, "Incipient" Fire Stage, Probabilistic Risk Assessment, Reactor Regulation

1. Introduction

In 2004, the U.S. Nuclear Regulatory Commission (NRC), with support from the commercial nuclear power industry, adopted the 2001 Edition of National Fire Protection Association (NFPA) Standard 805, *Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants* [1], as the means by which commercial nuclear power licensees could comply with Title 10 of the Code of Federal Regulations, Part 50.48[c], to replace deterministic fire protection licensing bases with ones that are risk-informed and performance-based. To facilitate licensee "transitions" from their existing to the new licensing bases via NFPA 805, a "Frequently Asked Questions" (FAQs) program, established early during the pilot-plant phase, was expanded to enable use of consensus technical "short-cuts" for fire probabilistic risk assessment (PRA) methods in the fire PRAs required to receive approval for transition. These "Fire PRA FAQs" enabled licensees, with NRC approval, to bypass more traditional means of establishing acceptable PRA method enhancements, such as topical reports submitted for NRC review and approval by reactor Owners Groups, on an interim basis, pending eventual confirmation by test programs and/or more detailed analyses. The NRC approved several that were incorporated into Supplement 1 to NUREG/CR-

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1 This paper was prepared by a former employee of the U.S. NRC. The views presented do not nor ever did represent an official NRC position, only those of the author. The author was the first to receive a PhD in nuclear engineering based on a thesis specifically related to fire PRA in power plants and worked for over 35 years in nuclear risk, reliability and safety analysis under both governmental and commercial auspices. He was hired at the NRC in 2003 as the expert in fire PRA for the Office of Nuclear Reactor Regulation and participated in the NFPA-805 program from the start of the pilot process in 2005 until being "phased out" in mid-2014.

6850 (EPRI 1011989) [2], of which perhaps the most substantial in providing risk reduction benefits in terms of reducing both core damage frequency (CDF) and large early release frequency (LERF), the metrics by which transitional acceptability was measured consistent with Regulatory Guide (RG) 1.174 [3], was FAQ 08-0046 on "Incipient Fire Detection Systems," [4] more accurately characterized as "Very Early Warning Fire Detection Systems" (VEWFDSs). Controversial from the start, the hidden story behind this FAQ's initial adoption is relevant to examination of the NRC NUREG report that later replaced it and remains in effect today. This article examines this backstory, tracing recommendations that were proposed and bypassed, then examines alternatives to the current guidance which also still remain mostly hidden from public view.

2. FAQ 08-0046

One of the two pilot-plant licensees during the early phases of the NFPA-805 program assessed a plant location with a significantly high fire risk (CDF and LERF), at least in terms of acceptability with respect to the numerical metrics of RG-1.174. Lowering this risk to enable approval of transition could be accomplished in several ways, ranging from more expensive, such as rerouting cables, installing new fire suppression systems, or adding new electrical raceway fire barriers systems, to less expensive. The licensee proposed a less expensive installation of a VEWFDS, based on proven use of these advanced detection technologies primarily in the telecommunications industry and, to a lesser extent, at some nuclear power plants, especially in Canada. However, to achieve the needed risk reduction in this high fire risk location with only VEWFDS installation, a reduction factor of 100 was proposed by the licensee, based in part on a report by the Electric Power Research Institute (EPRI) [5] that estimated a risk reduction factor as high as 167 for this technology. [6] The EPRI method was submitted for approval to the NRC as FAQ 08-0046, where its review was assigned to the fire PRA expert and experienced fire protection engineers in the Office of Nuclear Reactor Regulation (NRR). As the EPRI method was based largely on manufacturer claims, the NRC reviewers sought a more experimental basis to estimate the potential risk reduction, the value of which proposed by the licensee and EPRI seemed uncharacteristically high with respect to established risk reduction enhancements approved through the more traditional means, such as topical reports.

Independently, the NRR reviewers, with documented test results acquired by the Office of Nuclear Regulatory Research (RES) from Xtralis®, the vendor of one of the leading VEWFDS technologies (VESDA®), performed its own evaluation, which suggested that any risk reduction credit would be much more modest, a best estimate reduction factor of around five (geometric mean of a range from three to 10). [6] The NRC reviewers drafted a final version of the FAQ for management approval with this more limited risk reduction credit. However, the pilot-plant licensee, upon learning of the proposed final FAQ, balked at what it considered too little credit and suggested that it might no longer participate in the NFPA-805 pilot program. During a brief absence of the fire PRA expert, the draft final form of this FAQ was transferred from the original team and reassigned to NRR Senior Level Advisors and selected RES staff, with less fire protection expertise and any fire PRA expertise reduced to a consulting role.

This new team relied heavily on the EPRI report, eschewing use of any of the information assembled and being used by the original team, and ultimately produced what was issued as FAQ 08-0046, with a maximum risk reduction credit of 50, which subsequently proved to be in error as discussed below. While not as high as originally desired, this suited the pilot-plant licensee, enabling them to complete transition without considering the more expensive modifications in the critical location. This also suited NRR's purpose to facilitate transition of this pilot plant as expeditiously as possible. The NRR avoided a Differing Professional Opinion (DPO) from the original FAQ reviewers by agreeing to allow their version of the FAQ to be published as an American Nuclear Society (ANS) conference paper [6], but officially endorsed only the replacement version of FAQ 08-0046 that was issued. As a result, pilot-plant and non-pilot licensees used the FAQ with the risk reduction factor of 50 as needed to demonstrate substantial risk reduction via their NFPA-805 transitions, thereby receiving approval. While not all such plants installed VEWFDSs or took full credit if they did, eventually nearly half of the commercial fleet transitioned under NFPA 805. (Note: The ANS conference paper, which addressed only VEWFDS installed inside an electrical cabinet, was subsequently updated using the Xtralis® data to estimate the risk reduction credit for "area-wide" VEWFDS installation. The result was that the previous credit for in-cabinet installation would be halved.)

2.1 A "FAQ-tual" Error

As mentioned above, the FAQ subsequently was found to be in error, although this was not publicized until several years later during the development of NUREG-2180 (discussed below). The error resulted from an omission in the "simplified" event tree used in the FAQ to enable the factor of 50 reduction in risk to be misapplied to the electrical enclosure where the fire initiates, rather than only to fire spread beyond the enclosure. This is illustrated in Figure 1.

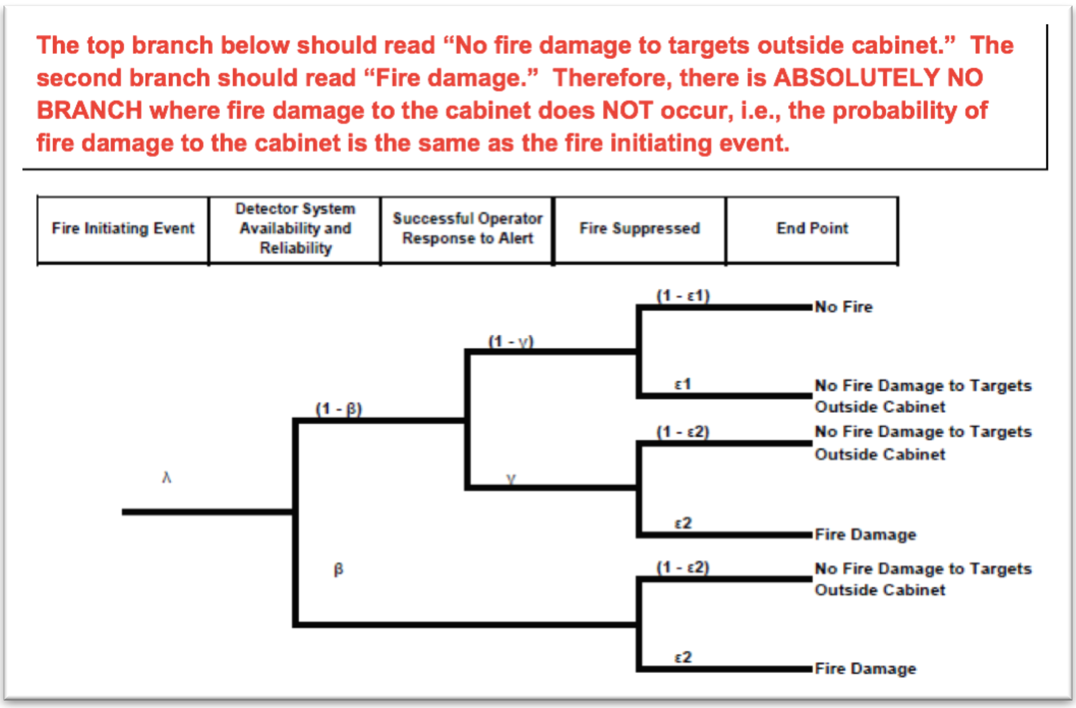


FIGURE 1. Error in FAQ 08-0046 "Simplified" Event Tree

The effect from this error is shown by the event trees in Figure 2.

With the erroneous event tree in Figure 1, assigning the default values to the various branch probabilities, one would estimate a probability of no fire damage = 0.979, that for fire damage only to the cabinet as 0.021 and fire damage to the cabinet and beyond as 2.0E-5 (see Figure 2). In reality, there was always fire damage within the cabinet (probability = 1), with the probability of that damage extending beyond the cabinet as 0.001. Therefore, there would be an under-estimate by a factor of 1/0.021 ≈ 50 that fire damage at least within the cabinet occurred if the simplified event tree was used. Likewise, there would be a similar under-estimate by a factor of 0.001/2.0E-5 ≈ 50 that fire damage occurred both within the cabinet and beyond.

FAQ Applied Erroneously

λ	β	γ	ε	end
1	0.99	0.99	0.999	9.79E-01
			0.001	9.80E-04
		0.01	0.999	9.89E-03
			0.001	9.90E-06
	0.01		0.999	9.99E-03
			0.001	1.00E-05
				2.09E-02
			SUMS	1.99E-05
				1.00E+00

The green branch corresponds to no fire damage (0.979). The three orange branches represent the fire damage being limited only to the cabinet (0.021). The two red branches represent the fire damaging not only the cabinet, but spreading outside to potentially damage other targets (2.0E-5).

FAQ Applied Correctly

λ	β	γ	ε	end
1	0.99	0.99	0.999	9.79E-01
			0.001	9.80E-04
		0.01	0.999	9.89E-03
			0.001	9.90E-06
	0.01		0.999	9.99E-03
			0.001	1.00E-05
				9.99E-01
			SUMS	1.00E-03
				1.00E+00

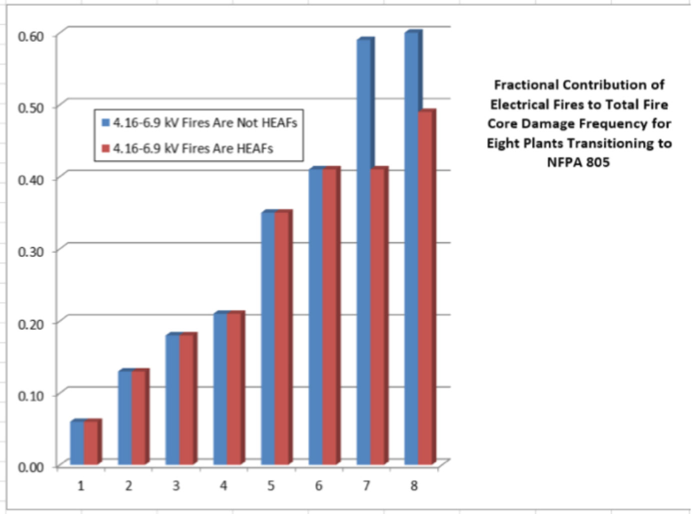
The three orange branches represent the fire damage being limited only to the cabinet (0.999). The three red branches represent the fire damaging not only the cabinet, but spreading outside to potentially damage other targets (0.001).

FIGURE 2. Illustration of Effect from Error in FAQ 08-0046

2.2. Potential Effect on NFPA-805 Transitions

Figure 3 indicates that the contribution from electrical enclosure fires to fire risk (measured in terms of CDF) typically ranges from six to 60% (Note: HEAF = high energy arcing fault).

4.16-6.9 kV Fires Are Not HEAFs	4.16-6.9 kV Fires Are HEAFs
0.06	0.06
0.13	0.13
0.18	0.18
0.21	0.21
0.35	0.35
0.41	0.41
0.59	0.41
0.60	0.49
Mean	Mean
0.32	0.28
Std Dev	Std Dev
0.21	0.16



(There are two sets of data because, for two plants it was unclear whether or not they treated 4.16-6.9 kV fires as HEAFs, so the contributions could vary for those two.)

FIGURE 3. Contribution from Electrical Fires to Total Fire CDF for Eight NFPA-805 Plants

This resulted from review of eight NFPA-805 applications based on the descriptions of the dominant fire scenarios. These scenarios were reviewed and the contribution to the core damage frequency of all the dominant scenarios from those attributable to fire damage from electrical cabinets was calculated. This fractional contribution to core damage frequency was assumed to be representative for the total. Since these VEWFDSs are credited to protect against fires in electrical enclosures, the risk reduction credit applies directly to the risk arising from these fires. The potential effect from this under-estimate on plants crediting FAQ 08-0046 for transition to their new risk-informed, performance-based fire protection licensing basis under 50.48(c) is shown below to be quite significant, potentially enough to have precluded transition (e.g., unless other modifications were proposed).

Consider that, at the time FAQ 08-0046 was issued (November 2009), only one other acceptable method for crediting in-cabinet VEWFDS existed, namely that from NUREG/CR-6850 (EPRI 1011989), since Reference [6] never was officially available as an alternative:

> *If a high-sensitivity smoke detection system is credited, the failure probability of the system should be considered. If in-cabinet smoke detection devices are installed in the electrical cabinet postulated as the ignition source, the analyst should assume that the fire will be detected in its incipient stage. This incipient stage is assumed to have a duration of 5 minutes. In order to account for these 5 minutes, the analysts should add them to the time to target damage (or, equivalently, add them to the time available for suppression)*. [2]

Given an additional 5 minutes available for suppression, the non-suppression probability for an electrical fire inside a cabinet would be exp(-0.0975[t + 5]), i.e., a decrease by a factor of exp(-0.0975t)/exp(-0.0975[t + 5]) = exp([0.0975][5]) = 1.6, which is 50/1.6 ≈ 30 times lower. [2] (Non-suppression probability is assumed to decrease exponentially with available time, with a characteristic mean time to suppress which, for electrical fires, is 1/[0.0975/min] ≈ 10 min.) The potential effect on risk reduction credit for reducing the credit by a factor of 30 indicates that the total fire risk would increase by a factor from 2.74 to 18.4, as follows:

> For the minimum (6%) case: CDF (w/o credit from FAQ 08-0046) = (30)(0.06) + (1 – 0.06) = 2.74, i.e., 174% higher than CDF (with credit from FAQ 08-0046)
>
> For the maximum (60%) case: CDF (w/o credit from FAQ 08-0046) = (30)(0.6) + (1 – 0.6) = 18.4, i.e., 1,740% higher than CDF (with credit from FAQ 08-0046)

These can easily be scaled by relaxing the assumption that all the electrical fire scenarios were reduced by FAQ 08-0046. E.g., if only half in each case:

> 6% case: CDF = (30)(0.06/2) + (1 – 0.06/2) = 1.87 (87% increase)
>
> 60% case: CDF = (30)(0.6/2) + (1 – 0.6/2) = 9.70 (870% increase)

The effects on the changes in risk, i.e., the risk increases from NFPA-805 transition/implementation relative to the "idealized, compliant" plant, are the same. These are potentially significant increases in both the change in ("delta-") and overall plant ("total") risks which could have precluded transitions under NFPA 805 without physical or procedural modifications, or more detailed fire risk analysis employing fire phenomenological modeling, unnecessary with this potentially significant under-estimation. For example, if a plant transitioned with a small risk (CDF) increase ("delta-risk"), say 1E-6/y, but a medium total risk (CDF), say 7E-5/y, both of which were acceptable under RG 1.174 as lying in Acceptance Region II/III, the change under the full 60% case would result in a delta-risk now at 2E-5/y and total risk at 1E-3/y, pushing it into Non-Acceptance Region I. Similarly, if a plant transitioned with a medium delta-risk, say 4E-6/y, but a small total risk, say 1E-5/y, both of which were acceptable under RG 1.174 as lying in Acceptance Region II, the change under the full 60% case would result in a delta-risk now at 7E-5/y and total risk now at 2E-4/y, pushing it into Non-Acceptance Region I.

3. NUREG-2180

The intention with all NFPA-805 FAQs was to eventually change their endorsement from interim to final via formal NRC acceptance in a Regulatory Guide. To confirm or replace FAQ 08-0046, the DELORES-VEWFIRE program was started by RES, which ultimately evolved into NUREG-2180. [7] While the author argued that this be pursued with a "clean slate," i.e., not tied to the original FAQ or prematurely incorporating human reliability analysis (HRA), RES rejected the author's following recommendations:

> *[This] ... argues for abandoning the FAQ* [08-00]*46 approach and its indefensible event tree entirely for a new mind set, devoid of the industry-driven notions based on speculation and wishful thinking designed to justify unjustifiably large credit for VEWFDS to enable* [pilot plant name] *and others to reduce risk ... FAQ* [08-00]*46 was guilty of over-modeling. We should avoid a similar mistake with [these] ... test results and approach the entire concept more holistically, as I (and others originally assigned to the FAQ) attempted through the ANS paper. Without the long-term tests I've advocated, we cannot quantify any ignition-avoidance effect from VEWFDS. The only quantifiable aspect is the bonus in suppression response time as a result of some earlier warning that a fire is about to occur, well beyond the "first molecule" phase. And, already, tests such as*

those by Xtralis® have shown this benefit to be quite limited, 5-10 minutes at most, which translate into no more that factors of 2-3 reduction in non-suppression probability for electrical fires. (e/mail "RE: VEWFD system information on fraction of fires exhibiting an incipient phase," Gallucci to multiple recipients, June 6, 2014)

NUREG-2180 was completed in December 2016. The author expressed several major concerns with this report, discussed below, thereby prompting a formal Non-Concurrence of its endorsement by NRR. [13] Prior to this, there was a significant delay in its issuance, as it was essentially complete at least a year earlier. However, since it now reduced the maximum risk reduction credit from the FAQ's 50 to an idealized factor of around five (eventually reaching nine when formally issued), the nuclear industry strove hard to delay. if not preclude, it altogether. (Note that this reduction factor only addresses "enhanced suppression." Additional reduction, not quantified in NUREG-2180, may be available for "pre-empting" the fire altogether, making it possible to once again approach, if not altogether attain, the original FAQ reduction factor of 50. Nonetheless, the nuclear industry remained dissatisfied.) As a result, NUREG-2180 underwent several comment periods with the Nuclear Energy Institute (NEI), resulting in relaxation of assumptions while enabling FAQ 08-0046 to remain in effect for licensees still in the process of NFPA-805 transition. As evidenced by the results from the DELORES-VEWFIRE tests, the "bonus" time achievable by the tested VEWFDSs (two of the light-sensitive [LS] variety, including VESDA®, and one utilizing a cloud chamber [CC]) was minimal at best. [8] In fact, only the CC showed, on average, some "bonus" time in detecting a fire during the pre-flaming stage, that being on the order of 10 minutes. And this was open to speculation because of the difficulty in aligning the calibration for the CC technology to the NFPA-76 standard [9] that would have enabled an equal comparison with the LS technologies.

Given these results and the confirmation that FAQ 08-0046 had substantially over-credited the risk reduction attainable through VEWFDSs, the author urged NRR to rescind the FAQ while the ongoing delay by the nuclear industry continued to stymie issuance of NUREG-2180. There was considerable reluctance on the part of NRR management to do this, and it only was accomplished [10] after the author indicated his intention to submit a DPO for failure to rescind the erroneous FAQ. As expected, it met with considerable objection on the part of the nuclear industry. [11] Nonetheless, NUREG-2180 was finally completed and issued in December 2016, an improvement over FAQ 08-0046, but still allowing significant risk reduction for VEWFDSs due to non-conservatisms/idealizations discussed below. Because of this, and the failure to adequately address the author's concerns regarding NUREG-2180 from the Non-Concurrence (effectively preserving NUREG-2180 "as is"), the author filed DPO 2016-004 after the NUREG was issued. [14]

3.1. <u>Weaknesses of NUREG-2180</u>

The primary assumption in NUREG-2180 is that "enhanced suppression" drives any benefit to be derived from the use of VEWFDSs. To model this "enhanced suppression," the report makes several non-conservative/idealized assumptions. First, for a VEWFDS installation inside an electrical enclosure ("in-cabinet"), the report assumes that non-suppression probability can be characterized by the curve for Main Control Board (MCB) fires, as per the NUREG-2169 (EPRI 3002002936) revision to NUREG/CR-6850 (EPRI 1011989). [12] This itself is based on the following overly optimistic assumptions.

First, as evidenced in the chapters related to HRA, operators are assumed to "drop everything" when a VEWFDS "alert" signal occurs and dispatch responders to the scene immediately. To assume operators will "drop everything" is unrealistic and non-conservative, an inappropriate assumption for use in PRA (which strives for realism and, where not achievable, some conservatism – but never non-conservatism/idealization). Alleged to be based on adherence to representative plant procedures, the reality of the situation is that any response, especially to a pre-combustion alert when no fire is manifest or likely to manifest in the near-term, would be "relaxed," perhaps alerting an auxiliary operator to check on the alert while making the rounds. Nonetheless, given sufficient time between the alert and the fire manifesting itself, it seems reasonable to assume that the potential fire location could reliably be identified. Therefore, even with the idealization, it appears unnecessary to perform such detailed HRA for identifying the fire source, hence the author's original recommendation not to *a priori* include HRA. This is especially true given that, even after arriving on the scene, the responder is assumed to make no suppression attempt, i.e., the entire value of the early alert is merely to get someone stationed at the location in case a fire actually manifests. Only then would suppression be attempted. (Of course, much of this depends on the "addressability" of the VEWFDS, i.e., its ability to isolate the location of the pre-combustion phenomenon to an individual electrical cabinet. This would vary with the type of VEWFDS and how it is configured. Note that it could be matched even using conventional spot detection if the detectors were placed inside every electrical cabinet, so any advantage from addressability depends highly upon the assumptions for the comparison.)

Compounding this non-conservative assumption are two others. First, the suppression activity, if and when it occurs, is assumed to be characterized as if the fire were occurring in the continuously-occupied, multi-manned Main Control Room (MCR), where the nature of the electrical fires can be quite different (typically much less severe) than encountered in electrical enclosures beyond the MCB. This can be significant, since the mean time to suppress a fire in the MCB is only 3.1 minutes, while that for a non-MCB electrical fire is 10.2 minutes, over three times longer. Second, the responder is assumed to remain in place indefinitely, i.e., regardless of if, or when, the fire actually manifests, a responder will be there poised and ready to suppress the fire. This is akin to assuming that operators will abandon the MCR itself even if it remains habitable due to unreliable indications from a non-MCR fire. While licensee procedures may require this, the NRC learned during its NFPA-805 audits that this would rarely, if ever, occur. Only loss of habitability, to the extent where even self-contained breathing apparatuses would not permit remaining, would drive MCR abandonment. Clearly, if the fire does not manifest until after the responder leaves, any benefit from VEWFDS is no more than that from any other post-flaming fire signal, except perhaps a bit quicker activation.

NUREG-2180 develops a "new" electrical fire curve that assumes a responder is poised and ready when an electrical enclosure fire starts. For this, the mean time to suppress is 5.2 minutes (1/[0.194/min] = 5.2 min). This somewhat approximates what one might expect when a continuous fire watch, complete with suppression means at hand, is established. In fact, this is comparable to the pre-NUREG-2169 non-suppression curve for welding fires where a continuous fire watch is established, although not with the current NUREG-2169 version, where the mean time to suppress is now 9.3 minutes. Of course, this remains overly optimistic by assuming that the responder remains in place indefinitely but, if one were to accept this non-conservatism, at least seems a reasonable extension as opposed to using the MCB curve.

Curiously, the idealized non-suppression curve assumptions do not always impact the results. This in itself is troubling in that the benefit of VEWFDS is touted in NUREG-2180 as enabling "enhanced suppression." Therefore, one would expect the choice of non-suppression curve to be highly significant to the results. In Chapter 12, four examples are presented, three dealing with in-cabinet VEWFDS, one with "area-wide" (typically mounted at the ceiling of the room). The following sensitivity study compares the results calculated for non-suppression probability for selected cases when the NUREG-2169 electrical non-suppression curve is substituted for the MCB curve (Cases 1-3) and "new" electrical fire curve (Case 4):

Case 1. Aspirating Smoke Detection (ASD) CC with conventional "spot" detection (SD) – non-suppression probability using MCB fire curve = 0.11; using new electrical fire curve = 0.16; using NUREG-2169 electrical fire curve = 0.31. Ionization Detection (ION) without conventional SD – non-suppression probability using MCR fire curve = 0.17; using new electrical fire curve = 0.22; using NUREG-2169 electrical fire curve = 0.34. (Note: Of the four cases, this yields the minimal non-suppression probability of 0.11, which corresponds to the reported risk reduction factor of 1/0.11 ≈ 9.)

Case 2. ASD CC with conventional SD – non-suppression probability using MCR fire curve = 0.11; using new electrical fire curve = 0.16; using NUREG-2169 electrical fire curve = 0.31. ION without conventional SD – non-suppression probability using MCR fire curve = 0.30; using new electrical fire curve = 0.31; using NUREG-2169 electrical fire curve = 0.34.

Case 3. ASD CC with conventional SD – non-suppression probability using MCR fire curve = 0.17; using new electrical fire curve = 0.21; using NUREG-2169 electrical fire curve = 0.31. ASD LS without conventional SD – non-suppression probability using MCR fire curve = 0.25; using new electrical fire curve = 0.26; using NUREG-2169 electrical fire curve = 0.31.

Case 4. ASD CC (ceiling-mounted) with conventional SD – non-suppression probability using new electrical fire curve = 0.31; using NUREG-2169 electrical fire curve = 0.31.

The effect of changing non-suppression curves varies. The maximum variation occurs for Cases 1 and 2 (ASD CC), where the non-suppression probability using the non-conservative MCB fire curve rises by about 50% if the better new electrical fire curve is used and by nearly a factor of three if the appropriate NUREG-2169 electrical fire curve is used. The effects in Cases 1 to 3 of these changes are less pronounced for the ION or ASD LS detector. For Case 4 (area-wide), there is effectively no change between non-suppression probabilities using either the new or NUREG-2169 electrical fire curve. Given the substantial difference in the mean times to suppress between these two curves (5.2 vs. 10.2 min), some difference would be expected. Of course, all of these cases crediting the MCB fire or new electrical fire curve are based on the idealized assumption that the responder remains in place indefinitely until the fire manifests (if ever).

Previously mentioned was another concern, as highlighted in Reference [8], that only the CC technology showed, on average, some "bonus" time in detecting a fire during the pre-flaming stage, that being on the order of 10 minutes. With a VESDA®-type technology being among the others tested (LS), it is curious that only one technology showed any mean benefit, especially in light of the VESDA® results previously analyzed. [6] While NUREG-2180 offers methods to adjust the CC results for different calibrations, the base-case reported results still come from the CC tests with the sensitivity higher than that for the others. These results are nearly always the most optimistic (highest reduction factor) in the Example cases. One would have expected some benefit, on average, for the other VEWFDS technologies, even if not as much as for the CC. This is also disconcerting regarding the results as it suggests an uneven "playing field" for the comparisons.

4. Risk-Reduction Credit for VEWFDS Using Selected Results from NUREG-2180

As promised, alternatives to NUREG-2180, which still use selected results from that study, but not its methodology, are presented. First is a simple scoping analysis, which establishes the maximum risk reduction one might expect with maximum permissible credits applied. Second is a more detailed analysis.

4.1 Scoping Analysis

Assume as a base case either no detection at all or just some type of ceiling-mounted detection, such that no fire can be detected during the pre-flaming ("incipient") phase. Therefore, any suppression must occur only after the fire is detected and then only after flaming (or significant smoke or other indication of fire). For simplicity, assume the response time after being subtracted from the time available for successful suppression had the fire been detected at time zero (when it started) is T. Therefore, the probability of non-suppression is just exp(-0.098T), where the 0.098/min term (approximating 0.0975 as 0.098) is the inverse of the mean time to suppress an electrical enclosure fire (~10 min).

(1) Now, install the most effectively possible VEWFDS (in-cabinet, per-cabinet addressability, etc.). Assume half of all electrical enclosure fires are such that they are detectable during the pre-flaming phase. With perfect human response and complete pre-emption, half of all electrical enclosure "potential" fires will never occur, leaving only 50% to be detected after the pre-flaming stage, as in the base case. However, now credit the VEWFDS as providing much earlier detection for these remaining fires (remember none of these could be detected during pre-flaming [maybe grew too fast, not the "right" type of fire, etc.]) than the base case, say 10 min, such that the probability of non-suppression (for the remaining 50% of the fires) is reduced by providing an extra 10 min, i.e., 0.5 x exp(-0.098[T+10]). Compared to the base case, this is a reduction by a factor of exp(-0.098T)/{0.5 x exp(-0.098[T+10])} = 2 x exp(0.98) = 5.3.

Thus, for totally effective pre-emption of half of all such fires and quicker detection/suppression (for the remaining half), the maximum reduction factor from VEWFDS is around five.

(2) If one stretches to assume that 75% of all these fires are detectable in the pre-flaming stage, this doubles the reduction factor to exp(-0.098T)/{0.25 x exp(-0.098[T+10])} = 4 x exp(0.98) = 10.7.

If one limits the "bonus" time for VEWFDS detection to five instead of 10 min (in line with NUREG/CR-6850's original intent and the original data from the Xtralis® tests), the reduction factors are decreased to the following values:

exp(-0.098T)/{0.5 x exp(-0.098[T+5])} = 2 x exp(0.49) = 3.3 (vs. 5.3 previously)
exp(-0.098T)/{0.25 x exp(-0.098[T+5])} = 4 x exp(0.49) = 6.5 (vs. 10.7 previously).

4.2 Detailed Analysis

This makes use of some of the results from NUREG-2180, but not the methodological approach. For any detector, define two opportunities for successful detection: (1) during the pre-flaming stage; (2) during the post-flaming stage. Therefore, failure to detect would require failure during both stages, the occurrence of which can be represented as D_t (total detection failure) = D_1 (pre-flaming) x D_2 (post-flaming). For a conventional ceiling-mounted detector, e.g., ionization, $D_1 = 1$ (no opportunity to detect during pre-flaming). This then simplifies to $D_{t,c} = D_{2,c}$, where the "c" subscript represents "conventional." The corresponding non-suppression probability "N" for electrical enclosure fires then becomes $N_{t,c} = D_{2,c} + (1 – D_{2,c})N_{2,c}$, where $N_{2,c} = \exp(-0.0975T)$, "T" being the "time available for suppression" from start of the post-flaming stage until loss of the supported component cannot be tolerated. Note that this must include a "penalty" (reduction) for the responder to arrive at the fire and begin suppression activities. For illustrative purposes, assume $D_{2,c} = 0.05$, the maximum value from NUREG/CR-6850, and T = 20 min (time from start of fire until loss of supported component cannot be tolerated) minus 10 min (time delay before responder can initiate suppression) = 10 min. This yields $N_{t,c} = 0.41$. Note that this applies to all electrical enclosure fires regardless of whether or not there is a pre-flaming stage of any significance, since the ceiling-mounted conventional detector never has an opportunity to detect during that stage.

Now, consider VEWFDS, either in-cabinet (designated by subscript "i") or area-wide (designated by subscript "a"). Depending upon the type of electrical enclosure fire, there will be different probabilities of opportunity to detect during the pre-flaming stage, namely a 0.72 chance for low voltage fires, or a 0.50 chance for the rest as reported in NUREG-2180 (hence the use of 50% and 75% as the VEWFDS-detectable percentages in the preceding scoping analysis). Treating the in-cabinet and area-wide equally for now and using the subscript "v' to designate VEWFDS, one can express the non-suppression probability as follows, using "F" as the fraction of fires potentially detectable during the pre-flaming stage (i.e., 0.72 or 0.50): (Note that all fires are assumed detectable in the post-flaming stage)

$$N_{t,v} = F\{(D_{1,v} + [1 - D_{1,v}]N_{1,v})(D_{2,v} + [1 - D_{2,v}]N_{2,v})\} + (1 - F)(D_{2,v} + [1 - D_{2,v}]N_{2,v}) + U_v$$

The terms inside the { } represent the non-suppression probability for those fires potentially detectable during the pre-flaming stage. Inside the first set of ( ) is the combined probability of non-detection during the pre-flaming stage plus the probability of non-suppression after transition from pre- to post-flaming given detection was successful. Inside the second set of ( ) is the combined probability of non-detection during the post-flaming stage plus the probability of non-suppression during this stage given detection was successful. The next term (multiplied by 1 – F) addresses those fires not detectable during the pre-flaming stage and is analogous to those detectable during the pre-flaming stage that were not detected or, if detected, were not suppressed. Finally, there is a term accounting for the unavailability of the VEWFDS being the same failure for both the pre- and post-flaming stages, i.e., a common-cause failure.

During the pre-flaming stage, failure to detect can occur if the detector is unavailable, unreliable or ineffective. For an ASD CC, these three values from NUREG-2180 are 0.0016, 0.0020 and 0.0027, yielding $D_{1,v} = 0.0047$ when the first value (0.0016) is recognized as the common-cause failure U_v and, therefore, not included in $D_{1,v}$. During the post-flaming stage, it is assumed that any unreliability or ineffectiveness, given there is now a flame, will be negligible compared to the unavailability, such that $D_{2,v} \approx 0$ given the common-cause failure $U_v = 0.0016$ still applies. Given that the fire has been detected during the pre-flaming stage, there are two failure modes that lead to non-suppression $N_{1,v}$: (1) Failure of the human responder to arrive in time and be poised to suppress the fire before the pre-flaming stage transitions to post-flaming; (2) Failure of the responder to suppress the fire.

For (1), make use of the simplifying assumption that the pre-flaming stage does not transition to post-flaming before the responder arrives and is poised to suppress, leaving the only failure being that of the responder to respond. This implicitly assumes that the degree of addressability of the VEWFDS does not affect the ability of the responder to arrive and be poised to suppress before the transition from pre- to post-flaming, a simplifying assumption. (Note: This assumption is somewhat generous when comparing area-wide to in-cabinet VEWFDS, since the former likely has a lower degree of addressability than the latter. This potential difference will be accounted for when considering the non-suppression curves.) For ASD CC, the total human error probability representing this failure is 0.00046, the value again taken from NUREG-2180. For (2), the responder has arrived and is poised to suppress the fire, a probability of essentially 1.0 (1 – 0.00046 = 0.99954). Therefore, non-suppression is represented solely by the non-suppression probability derived from the appropriate non-suppression curve considering the time available for suppression, which, using the above example, could now be as much as the full 20 min if the responder is already poised to suppress when the post-flaming begins (no delay). This will depend upon whether the VEWFDS is in-cabinet or area-wide, as there could be some time delay for the latter to be poised to suppress when the pre-flaming stage transitions to post-flaming.

4.2.1 In-Cabinet VEWFDS

For in-cabinet VEWFDS, assume that the responder is in place and poised to suppress the fire when the transition from pre- to post-flaming occurs (in-cabinet VEWFDS, vs. area-wide, should have the higher degree of addressability). Therefore, no delay in initiating suppression activities when the flaming starts is assumed, leaving the full 20 min available for suppression, i.e., T = 20 min. Additionally, the choice of non-suppression curve is that "newly derived" for electrical fires from NUREG-2180 where a responder was present from the start, for which the corresponding non-suppression probability would be exp(-0.194 x 20) = 0.021. Combined with the possibility of no response, the combined non-suppression probability "during the pre-flaming stage" becomes $N_{1,i} = 0.00046 + 0.021 = 0.021$ (recall subscript "i" for in-cabinet, now replacing previous subscript "v"). (Note that the phrase "during the pre-flaming stage" does not construe any possibility for suppressing the fire during that stage – any fire suppression can occur only during the post-flaming stage. It merely implies that the ability to implement post-flaming suppression was manifested during the pre-flaming stage.)

If the fire is not detected during the pre-flaming stage, then the in-cabinet VEWFDS can be assumed to respond similarly to the conventional ceiling-mounted detector, but presumably more quickly. At the higher calibration setting, the ASD CC indicated a mean "bonus" response time of ~10 min. If one assumes that the previous time delay of 10 min assumed for the conventional ceiling-mounted detector included 5 min for the responder to reach the fire (and another 5 min between the start of post-flaming and the detector response), one can now assume that the time available for the responder given the in-cabinet VEWFDS detects the now flaming fire when it starts is reduced only by the time delay for the responder to reach the fire, i.e., 5 min. Therefore, for in-cabinet VEWFDS that does not detect during the pre-flaming stage, the non-suppression probability will use the same non-suppression curve as that for the conventional ceiling-mounted detector, but with T = 20 min – 5 min = 15 min available for suppression instead of only 10 min, i.e., since the responder is not in place at the time the fire starts, the original electrical fire non-suppression curve remains applicable. Therefore $N_{2,i} = \exp(-0.0975 \times 15) = 0.23$. One can now calculate the total non-suppression probability for in-cabinet VEWFDS considering all types of electrical enclosure fires as follows:

$$N_{t,i} = F\{(D_{1,v} + [1 - D_{1,v}]N_{1,i})(D_{2,v} + [1 - D_{2,v}]N_{2,i})\} + (1 - F)(D_{2,v} + [1 - D_{2,v}]N_{2,i}) + U_v$$

where:

$F = 0.72$ (low voltage) or 0.50 (other)
$D_{1,v} = 0.0047$
$N_{1,i} = 0.021$
$D_{2,v} \approx 0$
$N_{2,i} = 0.23$
$U_v = 0.0016$

Therefore, $N_{t,i} = 0.070$ (low voltage) or 0.12 (other).

4.2.2 Area-Wide VEWFDS

For area-wide VEWFDS, the assumptions are the same as for the in-cabinet case with the following considerations. For the in-cabinet case, the full 20 min were assumed to be available for the responder in place to suppress the fire once it transitioned from pre- to post-flaming. Since the degree of addressability has previously been assumed not to affect the responder's ability to arrive and be poised to suppress the fire before the transition from pre- to post-flaming, the full 20 min remain available. (Note: As a sensitivity, this assumption was relaxed and reduced the time available for area-wide VEWFDS from 20 min to 17.5 min. The changes were as follows: $N_{1,a} = 0.034$ and $N_{t,a} = 0.090$ [low voltage] and 0.15 [other]. Despite the increase by a factor of ~50 in $N_{1,a}$, the $N_{t,a}$ values changed little from 0.088 [low voltage] and 0.15 [other].) As with the in-cabinet VEWFDS, if the fire is not detected during the pre-flaming stage, then the area-wide VEWFDS can be assumed to respond similarly to the conventional ceiling-mounted detector, but with a speed intermediate between that for the conventional ceiling-mounted detector and that for the in-cabinet VEWFDS. Previously a 10-min time delay was assumed for the conventional detector, but only 5 min for the in-cabinet VEWFDS. The average of these will be assumed for area-wide, i.e., 7.5 min. Therefore, for area-wide VEWFDS that does not detect during the pre-flaming stage, the non-suppression probability will use the same non-suppression curve as that for the conventional ceiling-mounted detector, but with T = 20 min – 7.5 min = 12.5 min available for suppression, i.e., since the responder is not in place at the time the fire starts, the original electrical fire non-suppression curve remains applicable. Therefore $N_{2,a} = \exp(-0.0975 \times 12.5) = 0.30$. One can now calculate the total non-suppression probability for area-wide VEWFDS considering all types of electrical enclosure fires as follows (note use of subscript "a"):

$$N_{t,a} = F\{(D_{1,v} + [1 - D_{1,v}]N_{1,a})(D_{2,v} + [1 - D_{2,v}]N_{2,a})\} + (1 - F)(D_{2,v} + [1 - D_{2,v}]N_{2,a}) + U_v$$

where:

$F = 0.72$ (low voltage) or 0.50 (other)
$D_{1,v} = 0.0047$
$N_{1,a} = 0.021$ (taken as same as $N_{1,i}$)
$D_{2,v} \approx 0$
$N_{2,a} = 0.30$
$U_v = 0.0016$

Therefore, $N_{t,a} = 0.089$ (low voltage) or 0.15 (other).

4.2.3 Comparison of technologies

For conventional ceiling-mounted detection with the assumptions in this analysis, the total non-suppression probability was 0.41. The corresponding values for in-cabinet VEWFDS based on the ASD CC were 0.070 (low voltage) and 0.12 (other), reductions by factors of 5.8 and 3.4, respectively. The corresponding values for area-wide VEWFDS based on the ASD CC were 0.089 (low voltage) and 0.15 (other), reductions by factors of 4.6 and 2.7, respectively. Roughly speaking, it appears that the difference between in-cabinet and area-wide VEWFDS for the ASD CC when compared to conventional ceiling-mounted detection is small, with overall reductions in non-suppression probability of approximately five (low voltage) and three (other).

5. Conclusion

In the author's DPO on NUREG-2180 [14], three alternatives to the NUREG were offered (discussed below) based on three independent analyses (Reference [6] and the scoping and detailed analyses performed above) strongly suggesting that, even after crediting the probability of pre-empting the fire altogether via a VEWFDS, the maximum risk reduction in all cases corresponds to a factor of about five. Note that this counters the NUREG-2180 reduction factor of nine, which does not include credit for pre-emption, implying that, even using NUREG-2180 as a replacement for rescinded FAQ 08-0046, it seems likely that a reduction factor approaching the original 50 can be attained. In the DPO, the Office Director for NRR acknowledged the "technical defensibility" and validity of these alternatives, as concluded by the DPO Panel Report.

The first alternative would be a return to the original credit for in-cabinet high-sensitivity smoke detection from Appendix P of NUREG/CR-6850 (EPRI1011989), previously quoted in Section 2.1. [2] The adding of five minutes to the time available for suppression would result in a risk reduction factor via the non-suppression probability for electrical fires of exp([0.098/min][5 min]) = 1.6. The second option would be to refer back to the paper produced by the original set of reviewers for FAQ 08-0046. [6] There a reduction factor at a best estimate of five was recommended. The failure of two of the three tested VEWFD technologies in NUREG-2180 to show any time "bonus" on average [8] and the complications associated with the inability to verify consistent calibration of the CC technology argues for the lower end of this range, perhaps no higher than the geometric mean of the range from three to 10 ($[3 \times 10]^{0.5} \approx 5$). The third option makes use of some of the results from NUREG-2180, but not the methodological approach, as presented in Section 4. For conventional ceiling-mounted detection, the total non-suppression probability was 0.41. The corresponding values for in-cabinet VEWFDS based on the ASD CC were 0.070 (low voltage) and 0.12 (other), reductions by factors of 5.8 and 3.4, respectively. The corresponding values for area-wide VEWFDS based on the ASD CC were 0.089 (low voltage) and 0.15 (other), reductions by factors of 4.6 and 2.7, respectively. Roughly speaking, it appears that the difference between in-cabinet and area-wide VEWFDS for the ASD CC when compared to conventional ceiling-mounted detection is small, with overall reductions in non-suppression probability of approximately five (low voltage) and three (other). This aligns well with the quantitative results from the second option. (As previously noted, Reference [6], which addressed only VEWFDS installed inside an electrical cabinet, was subsequently updated using the Xtralis® data to estimate the risk reduction credit for "area-wide" VEWFDS installation. The result was that the previous credit for in-cabinet installation would be halved. The recent detailed analysis suggests comparable reduction factors for in-cabinet vs. area-wide, the latter being only slightly less.)

6. References

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