CNWRA COMMENTS ON DRAFT NUREG-2230 (08/09/2019)

INTRODUCTION

Center for Nuclear Waste Regulatory Analyses (CNWRA®) staff completed a detailed review of draft NUREG-2230, "Methodology for Modeling Fire Growth and Suppression Response for Electrical Cabinet Fires in Nuclear Power Plants" dated June 2019 (hereafter referred to as "draft NUREG-2230") for the Office of Nuclear Reactor Regulation (NRR) of the U.S. Nuclear Regulatory Commission (NRC). Two types of comments resulted from this review. The first type involves substantive and technical comments, which are discussed first below. This is followed by a list of some editorial comments. Finally, it is proposed that the Monte Carlo simulation described in Appendix B is redone. A proposed revision of Appendix B can be found in Attachments B and C.

SUBSTANTIVE COMMENTS

General

As the reader is going through the document, it is difficult to determine and keep track of which event data were used in the development of each of the elements of the methodology listed in Section 1.1. It would be helpful to include a summary table (e.g., in an Appendix) that specifies the period in the event databases that was used for each element. For example, the table would show that event data for the period between 2000 and 2014 were used to determine the split fractions reported in Table 3-2. The table would also explain why the period was chosen. In the example, the reason is that earlier event data was not sufficiently detailed to classify a cabinet fire as interruptible or growing. A reference to the table could be included in Section 1, Introduction.

Substantive Comments on Section 3

Page 3-1, lines 5-11

There is some repetition in the first paragraph of Section 3.1, which makes it confusing for the reader. It is suggested to delete the first four sentences in the section, i.e., start with "Following the approach described in NUREG/CR-6850 …"

Alternatively, the four sentences could be a separate introductory paragraph. If these four sentences are retained, it is suggested to reword the fourth sentence as follows: "In other words, these are fires that were not fully involved, did not impact surrounding equipment, or did not damage cable trays or conduit nearby."

Page 3-8, line 4

Replace "… Section 3.3 …" with "… Section 3.3.1 …"

Page 3-9, Table 3-2

Revise table caption to read "Interruptible and growing split fractions based on 2000-2014 event data".

Page 3-9, lines 11-12

It is stated that a unique suppression rate associated with the MCR already exists. It is suggested to add a reference to NUREG-2169.

Page 3-11, lines 8-10

This sentence is confusing. Some minor rewording is suggested as follows: "The interruptible and growing …counted under Bin 15, as defined in NUREG/CR-6850, based on events that occurred between 1990 and 2014."

Page 3-11, lines 10-13

It is stated that 14 of the Bin 15 electrical cabinet events in "this period" did not contain enough information to categorize them as interruptible or growing fires. The preceding sentence seems to imply that this statement refers to the period between 1990 and 2014. However, it is assumed that the period is actually limited to the years between 1990 and 1999 because between 2000 and 2014 the event database contained sufficient information to categorize cabinet fires as interruptible or growing. Please confirm or clarify.

According to Table A-2, it appears that there were 39 Bin 15 fires in the event database for the period between 1990 and 1999. Nine events are assigned a fire classification of interruptible fires, while six are considered growing fires. Ignoring incident number 20357 for which P_{ns} is undetermined leads to 14 events that occurred between 1990 and 1999 and that were included in the analysis to determine the additional fire suppression rates. Please confirm that these events are the 14 events that are referred to in the aforementioned statement. If so, explain why the remaining 25 events in Table A-2 were not included.

In line 12 it is stated that half of the count and suppression time was split evenly between the two classifications. However, Table A-2 indicates that nine of the fourteen cabinet fires were considered interruptible and only five were classified as growing. Please clarify.

Finally, what are the criteria that were used to classify any of these 14 cabinet fires as interruptible or growing? If the events were indeed split evenly between the two classifications, it is worth mentioning that this approach is conservative compared to using the split fractions in Table 3-2 to estimate how many of the 14 cabinet fires were interruptible.

Page 3-12, line 15

Add “The latter is usually 24 hours (see NUREG-2122).” at the end of the paragraph.

Page 3-12, line 25

The generic frequency for the MCB provided is 2.05E-3 and reference is made to NUREG 2178, Volume 2. Section 8.3.1 of NUREG 2178, Volume 2 shows this generic fire frequency split by power mode, either Full Power Initiating Event (FPIE) or Low Power Shut Down (LPSD). It seems appropriate to apply a split fraction to refine the generic frequency, but the floor value analysis only uses the value for FPIE.

What is justification for not considering LPSD conditions in the development of the generic fire frequency for the MCB?

Page 3-12, line 30

Replace “… (NUREG-2230) …” with “… (see Table 3-9) …”

Page 3-13, line 2

Provide a basis for the 300-700 range of the number of cabinets counted as ignition sources in a single unit NPP. This seems inconsistent with the average plant-wide count of 750 in Table 6.2.3 of IMC 0308 Attachment 3 Appendix F.

Page 3-13, line 10

Provide a basis for the 10%-30% range of the apportioning factor (fraction of the control, auxiliary and reactor building floor area representing the MCR).

Page 3-13, lines 19-21 and Equation (3-2)

Delete the sentence "This results … 1.21E-4/day." because this calculation is incorrect, as it does not account for the random variables (total number of cabinets in the plant and apportioning of the area of the MCR). Instead, change Equation 3-2 as follows:

$$Pr(t \leq 24\ h) = (3.7\text{E-}03)/365 \approx 1\text{E-}05 \quad (3\text{-}2)$$

Page 3-13, line 33

According to NUREG-2178, Volume 1, the 98th percentile peak HRR of a large open electrical enclosure with thermoplastic cable contents is 1,000 kW. Five minutes after ignition the fire in such a cabinet would grow to 174 kW. Three minutes after ignition the HRR is 63 kW. A value closer to 3 minutes may be a more appropriate lower limit for the range.

Page 3-14, line 2

Explain how the non-suppression floor value for a dual unit MCR was estimated.

Page 3-14, line 19

Replace "… Section 3.5 …" with "… Section 3.5.1 …"

Page 3-17, Table 3-9

The frequency for electrical cabinet fires is for AA power modes (not separated by AP or AL power modes). Moreover, the power mode in the table is AA, but the PRA type is FPIE. This is confusing, since it is explained in Chapter 8 of Volume 2 of NUREG 2178 that the split between FPIE and LPSD is related to power mode.

Please explain why the frequency is split by power modes for the MCB but not for electrical cabinet fires. Clarify the difference between PRA types and power modes and how that affects the fire frequencies used in the analysis.

Substantive Comments on Section 4

Page 4-3, line 18 and Table 4-1

The averages of the pre-growth, growth, steady burning and decay durations may not be the most representative or appropriate values to use. For example, if the dataset consists

of a large number of values that are clustered together and a relatively small number of values that are much larger, is likely to be the more representative statistic to use. It is suggested to add a row with the median values at the bottom of Table 4-1 as shown below, and to use the median when that is more representative or conservative.

Table 4-1
HRR timing for interruptible electrical cabinet fires

Test	Units in Minutes			
	Pre-Growth Period	**Time to Peak**	**Steady Burning**	**Time to Decay**
⋮	⋮	⋮	⋮	⋮
Average	**8**	**7**	**5**	**13**
Median	**6**	**6**	**3**	**13**

Using the more conservative values of the average or the median leads to pre-growth and time-to-peak values of 6 minutes each, followed by 5 minutes of steady burning and a linear decay to a HRR of zero over a period of 13 minutes.

Page 4-5, line 16 and Table 4-2

The previous comment applies to the HRR profile for growing fires. The additional row with the median values for the data in Table 4-2 is shown below.

Again, using the more conservative values of the average or the median leads to a time to peak of approximately 10 minutes, followed by 9 minutes of steady burning and a linear decay to a HRR of zero over a period of 26 minutes.

Table 4-2
HRR timing for growing electrical cabinet fires

Test	Units in Minutes		
	Time to Peak	**Steady Burning**	**Time to Decay**
⋮	⋮	⋮	⋮
Average	**12**	**9**	**26**
Median	**10**	**5**	**19**

Page 4-7, lines 7-14

The median time to decay in Table 4-2 is 19 minutes, which is identical to the decay time in NUREG/CR-6850. Using the median decay time of 19 minutes (instead of the mean

decay time of 26 minutes) provides a rational basis for softening the effect of long duration fires with relatively low intensity in the later stages of the experiments.

Page 4-7, lines 24-26 and Page 4-8, lines 1-8

On page 4-7, the final recommended guidance allows the analyst to select a time of up to 8 minutes for pre-growth of the fire (0 kW). On page 4-8, it is explained why a period of 4 minutes was selected in the examples discussed in Chapter 6.

It is likely that users of this document will use the examples from Chapter 6 as a template and use a 4-minute growth time by default. Consider adding language to explain by example how an appropriate value of the pre-growth time can be estimated for a specific NPP and set of conditions. Alternatively, if 4 minutes is the recommended pre-growth time, consider modifying the language on page 4-7 to be consistent and provide justification for this recommendation.

Substantive Comments on Section 5

Page 5-3, lines 8-9

Replace “The P_{ns} for each profile is summed together to determine the total scenario specific NSP.” with “The total scenario-specific NSP is determined as the weighted sum based on the split fractions of the P_{ns} for each profile.”

Page 5-6, Table 5-2 and lines 1-2

The Monte Carlo analysis will have to be redone and the resulting probabilities of no detection in Table 5-2 will need to be updated. Details are provided in the technical comment section on Appendix B.

Substantive Comments on Section 6

Page 6-3, line 5

Start a new paragraph with “Because the MCC …” because this sentence starts the discussion of the development of the solution of the NSP event tree according to the new methodology, while the previous sentence ends the discussion of the solution obtained according to the methodology in NUREG/CR-6850 Appendix P.

Substantive Comments on Section 7

General

It would be helpful to include Table 7-3 in the executive summary.

Substantive Comments on Appendix A

Table A-2

Explain in the text how cabinet fires that occurred between 1990 and 1999 were classified as interruptible or growing (see comments on Page 3-11, lines 10-13).

Substantive Comments on Appendix B

In light of the comments provided below, it appears that the Monte Carlo analysis described in Appendix B will need to be redone. Appendix B in draft NUREG-2230 is reproduced in Attachment A. A proposed revised draft of Appendix B incorporating the comments with track changes turned on can be found in Attachment B. A clean copy of the revised Appendix B is provided in Attachment C. The proposed revision of Appendix B includes some editorial changes that are not discussed here. Comments below and parts of the text that require additional discussion are highlighted in yellow.

Page B-1, lines 13-14

The purpose of the Monte Carlo analysis is to determine the probability that a smoke detector will actuate for electrical cabinet fires. A probability is calculated for each type of enclosure that is listed in Table 7-1 of NUREG-2178, Volume 1. To determine this probability, it is not necessary to calculate the time to activation. One only needs to determine for each set of sampled parameters whether the sampled peak HRR is sufficient to result in smoke detector activation. The detector may actuate at a lower HRR, i.e., during the growing phase (i.e., the peak HRR is a sufficient but not a necessary condition for detector activation) but this does not affect the count of Monte Carlo realizations that result in detector activation.

Pages B-1 and B-2, Table B-1

Proposed changes to the table are summarized below.

- Because it is not necessary to calculate the time of smoke detector activation, the HRR profile duration parameters can be deleted.
- Figure B-1 in Section C.2 indicates that a gamma distribution is not a particularly good fit. A better-fitting distribution should be used.
- Two ranges should be defined for the smoke yield, one for TP and another for TS cables. The former should be used for fires of cabinets that contain TP cables, the latter for cabinets with TS/QTP/SIS cables. The SFPE handbook ([29]; Table A.39) provides smoke yield data for two types of TP cable (PE/PVC and PVC/nylon/PVC-nylon). The values range between 0.076 g/g and 0.136 g/g. The range of the smoke yield for TS cables is 0.082-0.175 g/g. Also, some consideration should be given to the fact that the smoke yield values in the SFPE handbook appear to be too high (see Gottuk, D., Mealy, C. and Floyd, J., "Smoke Transport and FDS validation," Proceedings of the Ninth International IAFSS Symposium, pp. 129-140, 2008. doi:10.3801/IAFSS.FSS.9-129). Using smoke yield values that are too high overestimates the probability of smoke detector activation.
- The radiative fraction should be varied. A higher radiative fraction results in a lower convective fraction and, therefore, a lower probability of smoke detector activation. Consequently, varying the radiative fraction is important. NUREG-1805 recommends using a generic value of 0.3 but states that the radiative fraction for different types of fuels varies between 0.15 and 0.60 (see Chapter 5 in NUREG-1805). The low values are for light gaseous fuels, alcohols, etc. and are not relevant here. The radiative fraction for cable fires can be estimated from the ratio of the radiative to the chemical heat of combustion reported in Table A.39 of the SFPE handbook [39]. The resulting range for the radiative fraction of TP cables (PE/PVC and PVC/nylon/PVC-nylon) is 0.37-0.63 with a mean of 0.50 and median of 0.49. For TS cables (EPR/Hypalon, XLPE/XLPE, and XLPE/neoprene) the range is 0.34-0.62 with a mean of 0.47 and median of 0.50. Consequently, a single range of 0.35-0.63 for the two cable types seems reasonable. However, the last part of the previous comment (i.e., the observation that the soot yields in the SFPE handbook are too high) also applies here and indicates that further investigation to find a suitable range for the radiant fraction may be warranted.

Page B-3, Subsection on Ceiling Jet Density

A sentence is added to indicate that the ceiling jet consists primarily of entrained air and that for estimating its density, the combustion products can be neglected.

Pages B-3 and B-4, Subsection on Dilution Factor

There is no need to introduce this factor. This subsection is renamed to “Normalized Ceiling Jet Mass Flow Rate” because that is what is calculated in this subsection.

Page B-4, Subsection on Soot Density

This subsection is renamed to “Soot Mass Concentration” because that is what is calculated in this subsection.

Pages B-5 through B-8, Section B.3

It is proposed that this section be deleted. As mentioned in the comment on Page B-1, lines 13-14, to determine whether a smoke detector will actuate for a set of sampled parameters it is not necessary to calculate the time to activation. Consequently, an evaluation of the capability of models to predict smoke detector activation time has little or no bearing on the validity of the results of the Monte Carlo simulation. Moreover, Figure B-2 indicates that the predictive capability of the two models is very poor. More work is needed to investigate the reasons for the discrepancies and to improve the predictive capability of the models.

Substantive Comments on Appendix D

General

Appendix D does not appear to be referenced anywhere in the main part of the document.

Page D-7, lines 1-2

Based on Table D-1 (page D-4, first two rows), the assumed pre-growth time is also a significant sensitivity parameter. Please add this parameter to the discussion on page D-7 to recognize its impact.

EDITORIAL COMMENTS

Editorial Comments on the Abstract

Page v, line 6

Replace "… data has been …" with "… data have been …" because data is plural.

Editorial Comments on Section 2

Page 2-1, line 26

Replace "… NUREG/CR-7197 …" with "… NUREG/CR-7197 (HELEN-FIRE) [11] …" because it is referred to as HELEN-FIRE in other parts of the document (e.g., captions to Figures 4-1 and 4-2).

Figures 2-1 through 2-5

It would be helpful to increase the size of the colored squares in the legends to the pie charts and used different hatched patterns so that it easier to distinguish the different categories in a B&W hardcopy.

Editorial Comments on Section 3

Page 3-11, line 13

Replace "Due to the limited event information …" with "Due to the limited cabinet fire event information …"

Page 3-12, Table 3-4

Please spell out the column headings in this table, i.e., SS = Sum of Squares, df = Degrees of Freedom, etc.

Page 3-13, lines 7-8

There appears to be a typo in NUREG-2169. The location for Bin 7 in Table 4-4 is described as the "Diesel Generator Room". Based on Table 6-1 in NUREG/CR-6850 this should be "Control/Aux/Reactor Building". It is suggested adding a footnote to point this out.

Page 3-13, lines 33-34

Replace “occurs before a half of the growing time …” with “occurs before half of the growing time …”

Page 3-15, Figure 3-4

“Growth Fire” is referred to as “Growing Fire” in other places. Strictly speaking, the lower limit for the y-axis is 0.00001.

Editorial Comments on Section 4

Page 4-1, line 22

Replace “… Valtion Teknillinen Tutkimuskeskus …” with “… Technical Research Centre of Finland …”

Page 4-1, line 24

Replace “… NUREG/CR-7197 [11].” with “… NUREG/CR-7197 (HELEN-FIRE) [11].”

Page 4-2, line 12

Replace “… (Figure 4.2.A) …” with “… (e.g., Figure 4.2.A) …”

Page 4-2, line 13

Replace “… (Figure 4.2.B) …” with “… (e.g., Figure 4.2.B) …”

Page 4-3, line 19

Replace “… Chesapeake Bay Detachment (CBD) …” with “… (NIST) …” because CBD is essentially unknown and the tests were conducted by NIST.

Page 4-5, line 17

Replace “… Chesapeake Bay Detachment (CBD) …” with “… (NIST) …”

Editorial Comments on Section 5

Page 5-3, line 10

Replace "… are conceptually similarly …" with "… are conceptually similar …"

Page 5-27, lines 29-30

Replace "… an motor control center (MCC) …" with "… a motor control center (MCC) …" or with "an MCC".

Attachment A

Appendix B of Draft NUREG-2230

(Consisting of 8 Pages)

B

INTERRUPTIBLE AND GROWING FIRE MONTE CARLO SAMPLING

B.1 Monte Carlo Simulation for Characterizing the Time and Probability of Automatic Smoke Detection

The Monte Carlo sampling technique to approximate the probability of automatic smoke detection is calculated given the possible range of determining factors.

The Monte Carlo simulation consists of four parts, as follows:

1. Generate a fire heat release rate profile over time (randomized peak heat release rate [HRR]). See Section 4.2.
2. Calculate the time-dependent smoke concentration at a randomized radial distance and ceiling height above the fuel source. See Section B.2.
3. Calculate the time response of the simulated smoke detector given randomized activation optical density (OD) values. See Section B.2.
4. Average all smoke detection results over 20,000 occurrences. See Section 5.3.3.1.

The specifics of this process are described in further detail in the following sections with an overall summary of the input parameters provided in Table B-1.

Table B-1
Summary of Monte Carlo parameters for modeling automatic smoke detection

Parameter	Distribution Type	Values	Notes
Peak heat release rate	Gamma	Varies	See NUREG-2178, Tables 4-1 and 4-2
Duration of the pre-growth and growth phases of the HRR profile	Constant	12	Total of pre- and growth phase (see Section 4.1)
Duration of the steady state heat release rate profile stage	Constant	8	Steady burning duration (see Section 4.1)
Duration of the decay state heat release rate profile stage	Constant	19	Decay burning duration (see Section 4.1)
Ceiling height above fuel source	Uniform	1.5 - 6.1 m (5 - 20 ft)	Random value independently sampled assuming a uniform distribution. The range of values is assumed to capture likely ceiling heights in nuclear power plants

Table B-1
Summary of Monte Carlo parameters for modeling automatic smoke detection

Parameter	Distribution Type	Values	Notes
Radial distance to detector	Uniform	0 to 6.5 m (0 – 21.2 ft)	Random value independently sampled assuming a uniform distribution. The range of values are assumed to be within acceptable code compliance distances.
Activation OD	Gamma	α: 4.62, β: 0.07	Average OD Thresholds (see Section C.2)
Soot yield	Uniform	0.076 – 0.175 g/g	Random value independently sampled assuming a uniform distribution. Minimum and Maximum values for electrical cables. (see Section C.2)
HRR radiant fraction	Constant	0.3	Typical fire radiant fraction
Ambient temperature	Constant	25 °C	Typical ambient temperature in an NNP
Ambient pressure	Constant	101325 Pa	Typical ambient pressure in an NPP
Obstructed plume bias	Constant	0.62	Plume calculated conservatively assuming an obstructed plume. See NUREG-2178.

B.2 Automatic Smoke Detection

To determine the detection system activation, several parameters must be calculated assuming that the smoke detector is located within the ceiling jet produced by the fire. These include the following:

- Ceiling jet temperature
- Ceiling jet density
- Average ceiling jet velocity
- Dilution factor
- Soot density
- OD

Ceiling Jet Temperature

As presented in NUREG-1805, Chapter 11, Section 5.1 [24], the Alpert ceiling jet temperature correlations [25] of a fire plume can be calculated using Equations B-1 and B-2.

$$T_{jet} = T_{amb} + B \cdot 16.9\left(\frac{Q^{\frac{2}{3}}}{\left(H_{pau}\right)^{\frac{5}{3}}}\right) \quad \text{for} \quad r_{det}/H \le 0.18 \tag{B-1}$$

$$T_{jet} = T_{amb} + B \cdot 5.38 \left(\frac{\frac{Q^{\frac{2}{3}}}{H_{pau}^{\frac{5}{3}}}}{\left(\frac{r}{H_{pau}}\right)^{\frac{2}{3}}} \right) \quad \text{for} \quad \frac{r_{det}}{H} > 0.18 \tag{B-2}$$

where T_{jet} is the ceiling jet temperature in °C, T_{amb} is the ambient temperature in °C, Q is the total heat release rate (HRR) in kW, H_{pau} is the height of the ceiling above the fuel source in meters, r_{det} is the radial distance from the plume center line to the detector in meters, and *B=0.62* is the obstructed plume bias from NUREG-2178. In this formulation, the reduction in the ceiling jet temperatures is assumed to be equivalently proportional to the obstructed plume correction when applied.

Due to the direct association with the thermal plume, the obstructed plume bias is conservatively included in the estimation of the ceiling jet temperature. The inclusion of this bias results in an increased heat release rate required to reach a detectable OD.

Ceiling Jet Density

The ceiling jet density is the density of the ceiling jet at the radial distance of the smoke detector. This can be computed using the Alpert ceiling jet temperature equations presented previously and the ideal gas law [26] (Equation B-3).

$$\rho_{jet} = \frac{mw_{air} P_{atm}}{(T_{Jet} + 273.15) R_{gas}} \tag{B-3}$$

where ρ_{jet} is the density of the ceiling jet in kg/m^3, mw_{air} is the molecular weight of air equal to 0.0288 kg/mol, P_{atm} is atmospheric pressure equal to 101325 Pa, and R_{gas} is the gas constant equal to 8.314 J/mol·K.

Dilution Factor

The conservation of energy and the first law of thermodynamics [27] can be applied to determine how much entrainment has occurred into the fire plume and ceiling jet in order to achieve the final gas temperature at the detector. A unit mass of fuel can be considered to have an enthalpy equal to its heat of combustion. Post-combustion, the convective fraction of that enthalpy results in a hot fire plume and ceiling jet. Ignoring convective heat loss to the ceiling, at any radial distance in the ceiling jet, the total energy flux at that distance is equal to the convective heat release of the fire. Because smoke detection is expected to occur when the temperature is relatively small, the specific heat of air can be considered a constant, c_p=1 kJ/(kg·K) [24] (Equation B-4).

$$\Delta H_c (1 - X_r) = m_{jet} c_p (T_{jet} - T_{amb}) \tag{B-4}$$

where ΔH_c is the heat of combustion in kJ/kg, $1-X_r$ is the convective fraction equal to 0.7, and m_{jet} is the mass flux of the ceiling jet normalized to 1 kg/s of fuel; this includes both the mass of fuel and the air that has diluted the fuel. A value of 16,000 kJ/kg is assumed for the heat of combustion as suggested by NUREG-7010 [28].

The mass flux of fuel products of combustion in the ceiling jet is very small compared to the total mass flux and can be ignored. This means one can compute a dilution factor, DF, as shown in Equation B-5.

$$DF = \Delta H_c \frac{(1 - X_r)}{(T_{jet} - T_{amb}) + 0.001} \qquad \text{(B-5)}$$

The 0.001 is included in the numerical computation to avoid dividing by zero for cases where the fire size is near zero and the ceiling jet temperature is approximately the same as the ambient temperature.

Soot Density

The dilution factor applies on a per kg of fuel basis. For each kg of fuel consumed, y_s kg of soot are produced. Within the ceiling jet that soot is diluted by the dilution factor, DF, therefore, the overall soot density at the detector, ρ_{soot} can be computed as shown in Equation B-6.

$$\rho_{soot} = \frac{y_s}{DF} \rho_{jet} \qquad \text{(B-6)}$$

Where y_s is the soot yield of the fuel in kg/kg and all other parameters have been identified. The soot yield values used in the Monte Carlo sampling process are taken from the values for electric cables in the SFPE handbook [29; Table A.39]. The soot yield is a random value independently sampled assuming a uniform distribution between the values of 0.076 and 0.175 kg/kg selected as approximate lower and upper bounds for electric cables from the Society of Fire Protection Engineers (SFPE) handbook [29; Table A.39].

Optical Density

The OD measurement quantifies the exponential decay of light passing through a path length of smoke [24]. For smoke detection activation, once the calculated OD exceeds the activation OD, the detector will activate. Equation B-7 is used to calculate OD of the smoke in the ceiling jet at the detector.

$$OD = \frac{(\rho_{soot})(K_m)}{\ln(10)} \qquad \text{(B-7)}$$

where K_m is the specific light extinction coefficient in m^2/kg. A value of 8700 m^2/kg is suggested by Mulholland and Croarkin [30]. This value is then compared against a detector threshold to determine whether a given scenario will activate the detector.

The activation OD values used in the Monte Carlo sampling process were developed from the average OD alarm thresholds for ionization and photoelectric smoke detectors [31]. The values, presented in Table B-2 (and graphically in Figure B-1), are used to fit a gamma distribution. The alpha and beta parameters from this best fit gamma distribution are used in the Monte Carlo sampling process to provide a randomized activation OD for the smoke detection calculation.

Table B-2
Smoke detection OD thresholds

OD Alarm Threshold (%)	Ionization (OD/m)	Photoelectric (OD/m)	Average	Best Fit (Gamma)
0%	0	0	0	0
20%	0.091	0.116	0.103	0.187
50%	0.256	0.319	0.287	0.287
80%	0.390	0.450	0.420	0.420
	Alpha =	4.62	Beta =	0.067

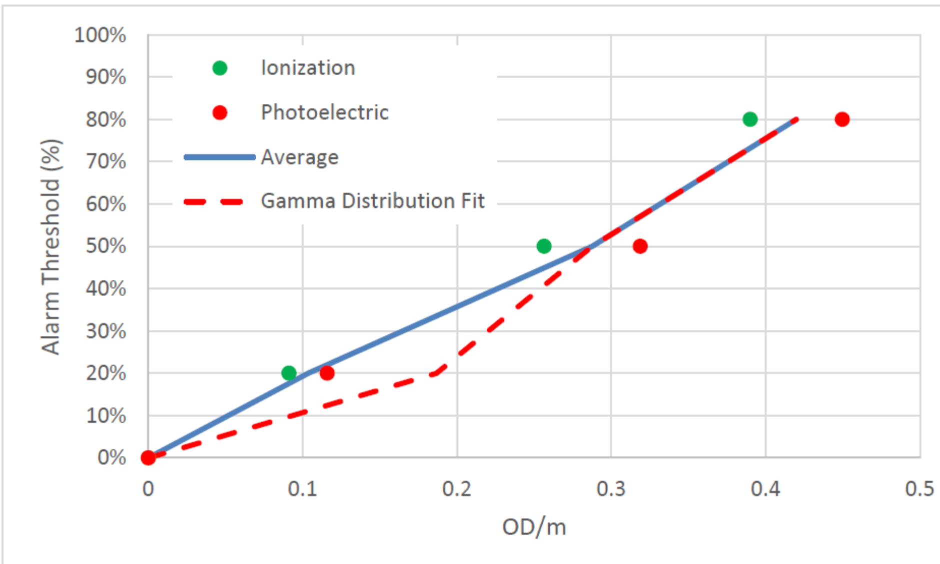


Figure B-1
Alarm threshold OD gamma distribution fit

B.3 OD Smoke Detection Validation

Validation of the OD smoke detection method was performed using results from home smoke alarm performance test results summarized in NIST Technical Note 1455-1 [32]. NIST Technical Note 1455-1 contains data from a series of smoke alarm tests that were used to estimate the performance of smoke detectors in residences. Tests were performed in a manufactured home using various ignition sources (upholstered chair and mattress) and detector locations. For this validation, only the results from detectors located within the same room were used as the ignition source. The results of the Fire Dynamics Tools (FDT^{S}) (temperature rise) smoke detector activation times were a bias of +7% (slower time to detection) and a standard deviation of 58%.

The activation times for three detectors (ionization and photoelectric) over eight of the NIST home smoke alarm test series [32] are used in this validation study. These test series are also used in the validation of smoke detector activation times summarized in Supplement 1 to NUREG-1824 [33]. The inputs used to perform the OD smoke detector validation results are presented in Table B-3.

Table B-3
Optical smoke detection validation parameters

Parameter	Value(s)	Notes
Heat release rate profile (FDT^S validation)	$\dot{Q} = \alpha t^2$ α range: 0.00309 to 0.0104580	As noted in Special Publication 1169 [34], the fire growth was specified by the t-squared growth rate up to a cutoff time of 300 seconds.
Heat release rate profile (FDS validation)	$\dot{Q} = \dot{Q}_0 \left(\frac{t}{\tau}\right)^2$ $\dot{Q}_0$ *: range from 100-350 kW* τ *: 180 seconds* Time offset: range from 10-40 seconds	As noted in the Fire Dynamics Simulator (FDS) Validation Guide [35], the HRR was determined by approximating the fire growth using a t-squared ramp calibrated using the temperature measured in the highest thermocouple in the tree during the experiment.
Vertical separation	2.0 to 2.1 m	Heights specified for applicable tests as presented in Special Publication 1169 [34].
Horizontal separation	1.3 to 1.8 m	Distances specified for applicable tests as presented in Special Publication 1169 [34].
Activation OD	0.42 OD/m	Average OD for an approximate 80% cumulative activation for ionization and photoelectric smoke detectors [31]
Soot yield	0.0975 g/g	Average, unweighted, soot yield for polyurethane (flexible foams), polyester, and wood [29]
Ambient temperature	21 to 26 °C	Ambient temperatures specified for applicable tests as presented in Special Publication 1169 [34].
Heat of combustion	30,000 kJ/g	Approximate, unweighted, soot yield for polyurethane (flexible foams) and polyester [29]
Ambient pressure	101325 Pa	Constant [36]
Gravity	9.81 m/s^2	Constant [36]
Radiative fraction	0.3	The radiant fraction for the fire was set to 0.3, which is at the

Table B-4
Optical smoke detection validation parameters

Parameter	Value(s)	Notes
		lower end of the suggested range of 0.3 – 0.4 [37].
Molecular weight of air	0.029	Constant [36]
Molar gas constant, *R*	8.31 J/mol·K	NIST reference on constant, units and uncertainty, physics.nist.gov

Results are shown in Figure B-2. The bias in the OD smoke detector activation model are +12% assuming the FDT^S validation HRR profile and +24% assuming the FDS validation HRR profiles. The standard deviation is slightly reduced, 50% and 46% for the FDT^S and FDS validation HRRs, respectively. These validation results demonstrate that the OD smoke detection method results in an average over-prediction for modeling the activation times for smoke detectors.

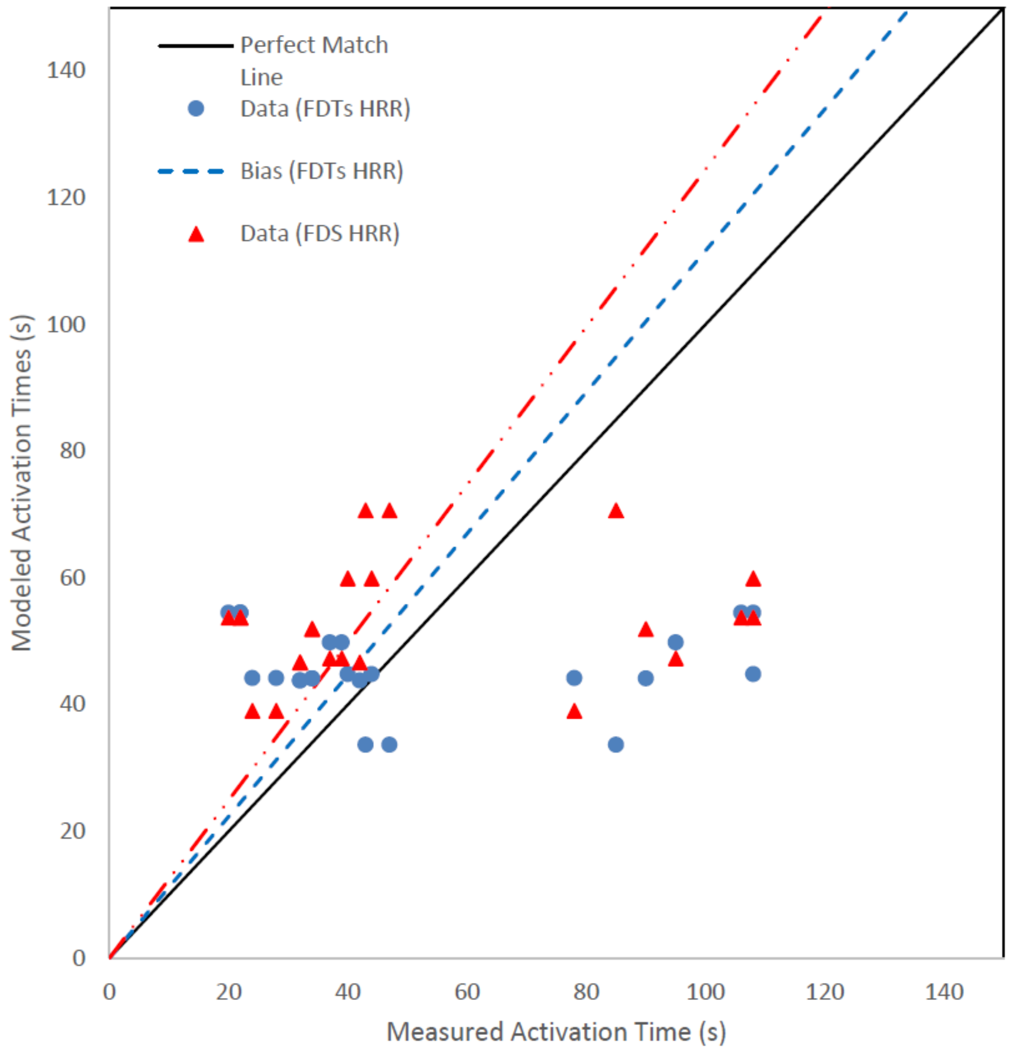


Figure B-2
Results comparing NIST home smoke detector activation times with OD modeled activation times

Attachment B

Proposed Revision of Appendix B

With Track Changes Turned On

(Consisting of 8 Pages)

B

INTERRUPTIBLE AND GROWING FIRE MONTE CARLO SAMPLING

B.1 Monte Carlo Simulation for Characterizing the Time and Probability of Automatic Smoke Detection

The Monte Carlo sampling technique to approximate the probability of automatic smoke detection is calculated given the possible range of determining factors.

The Monte Carlo simulation consists of four parts, as follows:

1. Generate a fire heat release rate profile over time (randomized peak heat release rate [HRR]). See Section 4.2.
2. Calculate the time-dependent smoke concentration at a randomized radial distance and ceiling height above the fuel source. See Section B.2.
3. Calculate ~~the time response of~~whether the simulated smoke detector will activate given randomized activation optical density (OD) values. See Section B.2.
4. Average all smoke detection results over 20,000 occurrences. See Section 5.3.3.1.

The specifics of this process are described in further detail in the following sections with an overall summary of the input parameters provided in Table B-1.

Table B-1
Summary of Monte Carlo parameters for modeling automatic smoke detection

Parameter	Distribution Type	Values	Notes
Peak heat release rate	Gamma	Varies	See NUREG-2178, Tables 4-1 and 4-2
~~Duration of the pre-growth and growth phases of the HRR profile~~	~~Constant~~	~~12~~	~~Total of pre- and growth phase (see Section 4.1)~~
~~Duration of the steady state heat release rate profile stage~~	~~Constant~~	~~8~~	~~Steady burning duration (see Section 4.1)~~
~~Duration of the decay state heat release rate profile stage~~	~~Constant~~	~~19~~	~~Decay burning duration (see Section 4.1)~~
Ceiling height above fuel source	Uniform	1.5 - 6.1 m (5 - 20 ft)	Random value independently sampled assuming a uniform distribution. The range of values is assumed to capture likely ceiling heights in nuclear power plants

Table B-1
Summary of Monte Carlo parameters for modeling automatic smoke detection

Parameter	Distribution Type	Values	Notes
Radial distance to detector	Uniform	0 to 6.5 m (0 – 21.2 ft)	Random value independently sampled assuming a uniform distribution. The range of values are assumed to be within acceptable code compliance distances.
Activation OD	Gamma	α: 4.62, β: 0.07	Average OD Thresholds (see Section CB.2)
Soot yield for TP content Soot yield for TS content	Uniform	0.076 – 0.175 136 g/g 0.082 – 0.175 g/g	Random value independently sampled assuming a uniform distribution. Minimum and Maximum values for electrical cables. (see Section
HRR radiant radiative fraction	ConstantUniform	0.35-0.63	Typical fire radiant fraction. Minimum and Maximum values for electrical cables. ([29], Table A.39)
Ambient temperature	Constant	25 °C	Typical ambient temperature in an NNP
Ambient pressure	Constant	101325 Pa	Typical ambient pressure in an NPP
Obstructed plume bias	Constant	0.62	Plume calculated conservatively assuming an obstructed plume. See NUREG-2178, Volume 2.

B.2 Automatic Smoke Detection

To determine the detection system activation, several parameters must be calculated assuming that the smoke detector is located within the ceiling jet produced by the fire. These include the following:

- Ceiling jet temperature
- Ceiling jet density
- Average ceiling jet velocity
- Dilution factorNormalized ceiling jet mass flow rate
- Soot densitymass concentration
- OD

Ceiling Jet Temperature

As presented in NUREG-1805, Chapter 11, Section 5.1 [24], the Alpert ceiling jet temperature correlations [25] of a fire plume can be calculated using Equations B-1 and B-2.

$$T_{jet} = T_{amb} + B \cdot 16.9 \left(\frac{Q^{\frac{2}{3}}}{\left(H_{pau}\right)^{\frac{5}{3}}} \right) \quad \text{for} \quad r_{det}/H_{pau}H \leq 0.18 \qquad \text{(B-1)}$$

$$T_{jet} = T_{amb} + B \cdot 5.38 \left(\frac{\frac{Q^{\frac{2}{3}}}{H_{pau}^{\frac{5}{3}}}}{\left(\frac{r_{det}r}{H_{pau}}\right)^{\frac{2}{3}}} \right) \quad \text{for} \quad \frac{r_{det}}{H_{pau}H} > 0.18 \qquad \text{(B-2)}$$

where T_{jet} is the ceiling jet temperature in °C, T_{amb} is the ambient temperature in °C, Q is the total heat release rate (HRR) in kW, H_{pau} is the height of the ceiling above the fuel source in meters, r_{det} is the radial distance from the plume center line to the detector in meters, and $B=0.62$ is the obstructed plume bias from NUREG-2178, Volume 1. In this formulation, the reduction in the ceiling jet temperature~~s~~ rise over ambient is assumed to be ~~equivalently~~ proportional to the obstructed plume correction when applied.

Due to the direct association with the thermal plume, the obstructed plume bias is conservatively included in the estimation of the ceiling jet temperature. The inclusion of this bias results in an increased heat release rate required to reach a detectable OD.

Ceiling Jet Gas Density

The ceiling jet density is the density of the ceiling jet at the radial distance of the smoke detector. ~~This~~ The flow rate of the products of combustion in the ceiling jet is very small compared to the flow rate of excess and entrained air. Consequently, the ceiling jet density can be computed using the Alpert ceiling jet temperature equations presented previously and the ideal gas law for air [26] (Equation B-3).

$$\rho_{jet} = \frac{mw_{air} P_{atm}}{\left(T_{Jet} + 273.15\right) R_{gas}} \qquad \text{(B-3)}$$

where ρ_{jet} is the density of the ceiling jet in kg/m^3, mw_{air} is the ~~molecular weight~~molar mass of air equal to 0.0288 kg/mol, P_{atm} is atmospheric pressure equal to 101325 Pa, and R_{gas} is the universal gas constant equal to 8.314 J/mol·K.

~~Dilution Factor~~Normalized Ceiling Jet Mass Flow Rate

The conservation of energy and the first law of thermodynamics [27] can be applied to determine how much entrainment has occurred into the fire plume and ceiling jet in order to achieve the final gas temperature at the detector. A unit mass of fuel can be considered to have an enthalpy equal to its heat of combustion. Post-combustion, the convective fraction of that enthalpy results in a hot fire plume and ceiling jet. Ignoring convective heat loss to the ceiling, at any radial distance in the ceiling jet, the total energy flux at that distance is equal to the convective heat release of the fire. Because ~~smoke detection is expected to occur when the temperature~~ $T_{jet} - T_{amb}$ is relatively small where smoke detection is expected to occur, the specific heat of air can be considered a constant, c_p=1 kJ/(kg·K) [24] (Equation B-4).

$$\Delta H_c(1-X_r) = m_{jet}c_p\left(T_{jet}-T_{amb}\right) \approx m_{jet}\left(T_{jet}-T_{amb}\right) \tag{B-4}$$

where ΔH_c is the heat of combustion in kJ/kg, $1\text{-}X_r$ is the convective fraction equal to 0.7, and m_{jet} is the mass ~~flux~~ flow rate of the ceiling jet normalized to 1 kg/s of fuel; this includes both the mass of fuel and the air that has diluted the fuel. A value of 16,000 kJ/kg is assumed for the heat of combustion as suggested by NUREG-7010 [28]. ~~The mass flux of fuel products of combustion in the ceiling jet is very small compared to the total mass flux and can be ignored. This means one can compute a dilution factor, *DF*,~~The normalized mass flow rate in the ceiling jet can therefore be computed as shown in Equation B-5.

$$\cancel{DF}m_{jet} = \Delta H_c\frac{(1-X_r)}{\left(T_{jet}-T_{amb}\right)+0.001} \tag{B-5}$$

The 0.001 is included in the numerical computation to avoid dividing by zero for cases where the fire size is near zero and the ceiling jet temperature is approximately the same as the ambient temperature.

Soot ~~Density~~Mass Concentration

~~The dilution factor applies on a per kg of fuel basis.~~ For each kg of fuel consumed, y_s kg of soot ~~are~~ is produced. ~~Within the ceiling jet that soot is diluted by the dilution factor, *DF*, t~~Therefore, the overall soot ~~density~~ mass concentration at the detector, ρ_{soot}~~,~~ in kg/m^3 can be computed as shown in Equation B-6.

$$\rho_{soot} = \frac{y_s}{\cancel{DF}m_{jet}}\rho_{jet} \tag{B-6}$$

Where y_s is the soot yield of the fuel in kg/kg and all other parameters have been identified. ~~The soot yield values used in the Monte Carlo sampling process are taken from the values for electric cables in the SFPE handbook [29; Table A.39].~~ The soot yield is a random value independently sampled assuming a uniform distribution between the values of 0.076 and ~~0.175~~0.136 kg/kg selected as approximate lower and upper bounds for TP electric cables from the Society of Fire Protection Engineers (SFPE) handbook [29; Table A.39]. For TS cables, the range is 0.082-0.175 g/g.

Optical Density

The OD measurement quantifies the exponential decay of light passing through a path length of smoke [24]. For smoke detection activation, once the calculated OD exceeds the activation OD, the detector will activate. Equation B-7 is used to calculate OD of the smoke in the ceiling jet at the detector.

$$OD = \frac{(\rho_{soot})(K_m)}{\ln(10)} \tag{B-7}$$

where K_m is the specific light extinction coefficient in m^2/kg. A value for flaming fires of 8700 m^2/kg is suggested by Mulholland and Croarkin [30]. This value is then compared against a detector threshold to determine whether a given scenario will activate the detector.

The activation OD values used in the Monte Carlo sampling process were developed from the average OD alarm thresholds for ionization and photoelectric smoke detectors [31]. The values, presented in Table B-2 (and graphically in Figure B-1), are used to fit a gamma distribution. The alpha and beta parameters from this best fit gamma distribution are used in the Monte Carlo sampling process to provide a randomized activation OD for the smoke detection calculation.

Table B-2
Smoke detection OD thresholds

OD Alarm Threshold (%)	Ionization (OD/m)	Photoelectric (OD/m)	Average	Best Fit (Gamma)
0%	0	0	0	0
20%	0.091	0.116	0.103	0.187
50%	0.256	0.319	0.287	0.287
80%	0.390	0.450	0.420	0.420
	Alpha =	4.62	Beta =	0.067

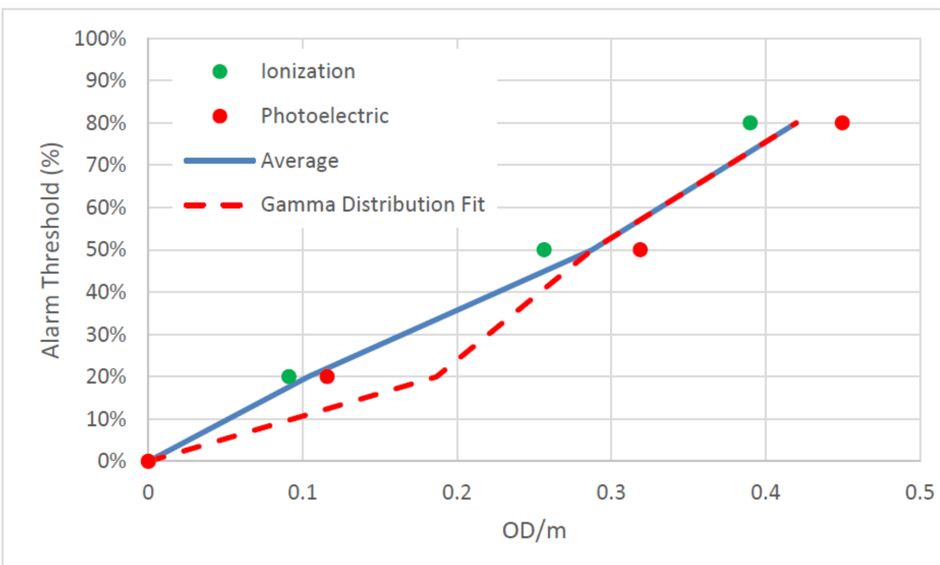


Figure B-1
Alarm threshold OD gamma distribution fit

~~B.3 OD Smoke Detection Validation~~

~~Validation of the OD smoke detection method was performed using results from home smoke alarm performance test results summarized in NIST Technical Note 1455-1 [32]. NIST Technical Note 1455-1 contains data from a series of smoke alarm tests that were used to estimate the performance of smoke detectors in residences. Tests were performed in a manufactured home using various ignition sources (upholstered chair and mattress) and detector locations. For this validation, only the results from detectors located within the same room were used as the~~

ignition source. The results of the Fire Dynamics Tools (FDT[s]) (temperature rise) smoke detector activation times were a bias of +7% (slower time to detection) and a standard deviation of 58%.

The activation times for three detectors (ionization and photoelectric) over eight of the NIST home smoke alarm test series [32] are used in this validation study. These test series are also used in the validation of smoke detector activation times summarized in Supplement 1 to NUREG-1824 [33]. The inputs used to perform the OD smoke detector validation results are presented in Table B-3.

Table B-3
Optical smoke detection validation parameters

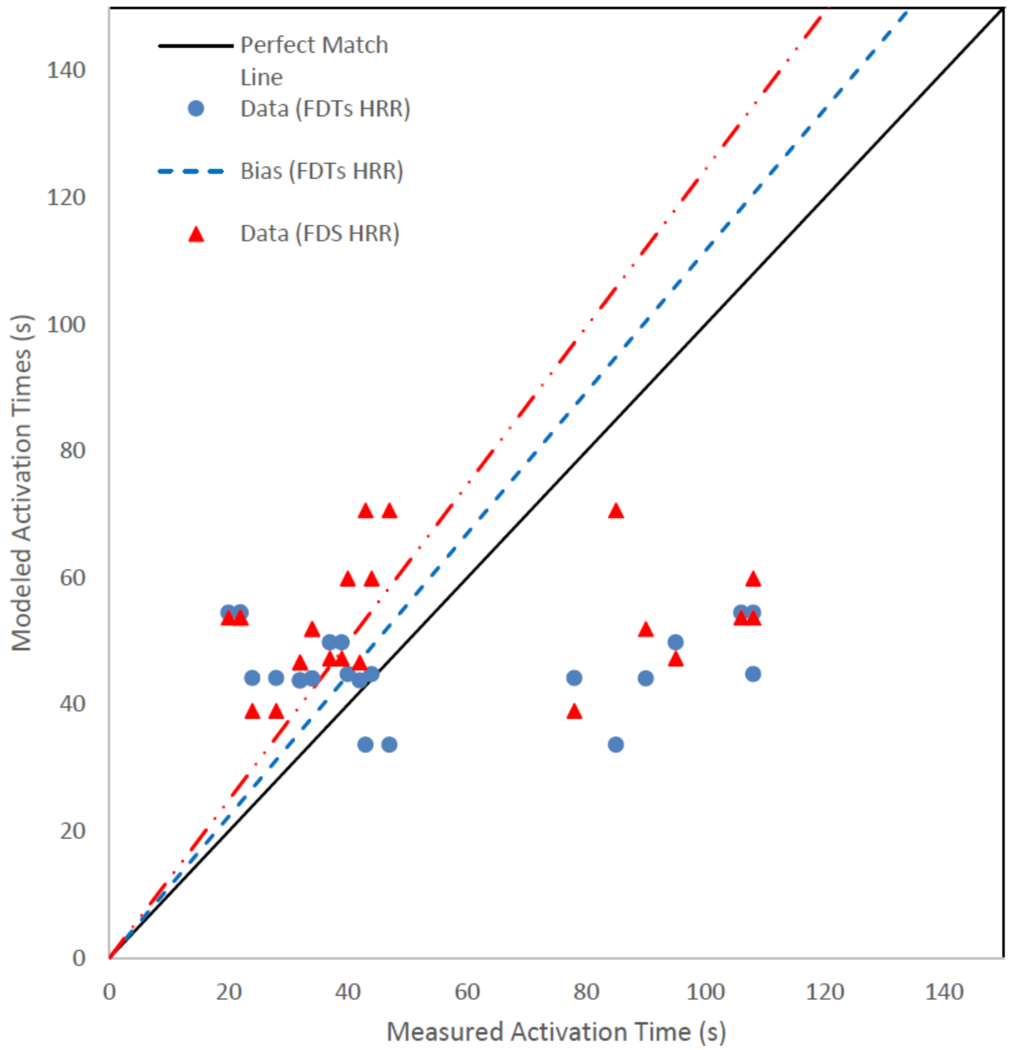
Parameter	Value(s)	Notes
Heat release rate profile (FDT[s] validation)	$\dot{Q} = \alpha t^2$ α range: 0.00309 to 0.0104580	As noted in Special Publication 1169 [34], the fire growth was specified by the t-squared growth rate up to a cutoff time of 300 seconds.
Heat release rate profile (FDS validation)	$\dot{Q} = \dot{Q}_0 \left(\frac{t}{\tau}\right)^2$ $\dot{Q}_0$ *: range from 100-350 kW* τ *: 180 seconds* Time offset: range from 10-40 seconds	As noted in the Fire Dynamics Simulator (FDS) Validation Guide [35], the HRR was determined by approximating the fire growth using a t-squared ramp calibrated using the temperature measured in the highest thermocouple in the tree during the experiment.
Vertical separation	2.0 to 2.1 m	Heights specified for applicable tests as presented in Special Publication 1169 [34].
Horizontal separation	1.3 to 1.8 m	Distances specified for applicable tests as presented in Special Publication 1169 [34].
Activation OD	0.42 OD/m	Average OD for an approximate 80% cumulative activation for ionization and photoelectric smoke detectors [31]
Soot yield	0.0975 g/g	Average, unweighted, soot yield for polyurethane (flexible foams), polyester, and wood [29]
Ambient temperature	21 to 26 °C	Ambient temperatures specified for applicable tests as presented in Special Publication 1169 [34].

Heat of combustion	30,000 kJ/g	Approximate, unweighted, soot yield for polyurethane (flexible foams) and polyester [29]
Ambient pressure	101325 Pa	Constant [36]
Gravity	9.81 m/s^2	Constant [36]
Radiative fraction	0.3	The radiant fraction for the fire was set to 0.3, which is at the

Table B-4
Optical smoke detection validation parameters

Parameter	Value(s)	Notes
		lower end of the suggested range of 0.3 – 0.4 [37].
Molecular weight of air	0.029	Constant [36]
Molar gas constant, *R*	8.31 J/mol-K	NIST reference on constant, units and uncertainty, physics.nist.gov

Results are shown in Figure B-2. The bias in the OD smoke detector activation model are +12% assuming the FDT^S validation HRR profile and +24% assuming the FDS validation HRR profiles. The standard deviation is slightly reduced, 50% and 46% for the FDT^S and FDS validation HRRs, respectively. These validation results demonstrate that the OD smoke detection method results in an average over-prediction for modeling the activation times for smoke detectors.



~~**Figure B-2**~~
~~**Results comparing NIST home smoke detector activation times with OD modeled activation times**~~

Attachment C

Proposed Revision of Appendix B

Clean Copy

(Consisting of 5 Pages)

B

INTERRUPTIBLE AND GROWING FIRE MONTE CARLO SAMPLING

B.1 Monte Carlo Simulation for Characterizing the Time and Probability of Automatic Smoke Detection

The Monte Carlo sampling technique to approximate the probability of automatic smoke detection is calculated given the possible range of determining factors.

The Monte Carlo simulation consists of four parts, as follows:

1. Generate a fire heat release rate profile over time (randomized peak heat release rate [HRR]). See Section 4.2.
2. Calculate the time-dependent smoke concentration at a randomized radial distance and ceiling height above the fuel source. See Section B.2.
3. Calculate whether the simulated smoke detector will activate given randomized activation optical density (OD) values. See Section B.2.
4. Average all smoke detection results over 20,000 occurrences. See Section 5.3.3.1.

The specifics of this process are described in further detail in the following sections with an overall summary of the input parameters provided in Table B-1.

Table B-1
Summary of Monte Carlo parameters for modeling automatic smoke detection

Parameter	Distribution Type	Values	Notes
Peak heat release rate	Gamma	Varies	See NUREG-2178, Tables 4-1 and 4-2
Ceiling height above fuel source	Uniform	1.5 - 6.1 m (5 - 20 ft)	Random value independently sampled assuming a uniform distribution. The range of values is assumed to capture likely ceiling heights in nuclear power plants

Table B-1
Summary of Monte Carlo parameters for modeling automatic smoke detection

Parameter	Distribution Type	Values	Notes
Radial distance to detector	Uniform	0 to 6.5 m (0 – 21.2 ft)	Random value independently sampled assuming a uniform distribution. The range of values are assumed to be within acceptable code compliance distances.
Activation OD	Gamma	α: 4.62, β: 0.07	Average OD Thresholds (see Section B.2)
Soot yield for TP content Soot yield for TS content	Uniform	0.076 – 0.136 g/g 0.082 – 0.175 g/g	Random value independently sampled assuming a uniform distribution. Minimum and Maximum values for electrical cables. ([29], Table A.39)
HRR radiative fraction	Uniform	0.35-0.63	Typical fire radiant fraction. Minimum and Maximum values for electrical cables. ([29], Table A.39)
Ambient temperature	Constant	25 °C	Typical ambient temperature in an NNP
Ambient pressure	Constant	101325 Pa	Typical ambient pressure in an NPP
Obstructed plume bias	Constant	0.62	Plume calculated conservatively assuming an obstructed plume. See NUREG-2178, Volume 2.

B.2 Automatic Smoke Detection

To determine the detection system activation, several parameters must be calculated assuming that the smoke detector is located within the ceiling jet produced by the fire. These include the following:

- Ceiling jet temperature
- Ceiling jet density
- Average ceiling jet velocity
- Normalized ceiling jet mass flow rate
- Soot mass concentration
- OD

Ceiling Jet Temperature

As presented in NUREG-1805, Chapter 11, Section 5.1 [24], the Alpert ceiling jet temperature correlations [25] of a fire plume can be calculated using Equations B-1 and B-2.

$$T_{jet} = T_{amb} + B \cdot 16.9 \left(\frac{Q^{\frac{2}{3}}}{\left(H_{pau}\right)^{\frac{5}{3}}} \right) \quad \text{for} \quad r_{det}/H_{pau} \leq 0.18 \tag{B-1}$$

$$T_{jet} = T_{amb} + B \cdot 5.38 \left(\frac{\frac{Q^{\frac{2}{3}}}{H_{pau}{}^{\frac{5}{3}}}}{\left(\frac{r_{det}}{H_{pau}}\right)^{\frac{2}{3}}} \right) \quad \text{for} \quad \frac{r_{det}}{H_{pau}} > 0.18 \tag{B-2}$$

where T_{jet} is the ceiling jet temperature in °C, T_{amb} is the ambient temperature in °C, Q is the total heat release rate (HRR) in kW, H_{pau} is the height of the ceiling above the fuel source in meters, r_{det} is the radial distance from the plume center line to the detector in meters, and *B=0.62* is the obstructed plume bias from NUREG-2178, Volume 1. In this formulation, the reduction in the ceiling jet temperature rise over ambient is assumed to be proportional to the obstructed plume correction when applied.

Due to the direct association with the thermal plume, the obstructed plume bias is conservatively included in the estimation of the ceiling jet temperature. The inclusion of this bias results in an increased heat release rate required to reach a detectable OD.

Ceiling Jet Gas Density

The ceiling jet density is the density of the ceiling jet at the radial distance of the smoke detector. The flow rate of the products of combustion in the ceiling jet is very small compared to the flow rate of excess and entrained air. Consequently, the ceiling jet density can be computed using the Alpert ceiling jet temperature equations presented previously and the ideal gas law for air [26] (Equation B-3).

$$\rho_{jet} = \frac{mw_{air} P_{atm}}{\left(T_{Jet} + 273.15\right) R_{gas}} \tag{B-3}$$

where ρ_{jet} is the density of the ceiling jet in kg/m^3, mw_{air} is the molar mass of air equal to 0.0288 kg/mol, P_{atm} is atmospheric pressure equal to 101325 Pa, and R_{gas} is the universal gas constant equal to 8.314 J/mol·K.

Normalized Ceiling Jet Mass Flow Rate

The conservation of energy and the first law of thermodynamics [27] can be applied to determine how much entrainment has occurred into the fire plume and ceiling jet in order to achieve the final gas temperature at the detector. A unit mass of fuel can be considered to have an enthalpy equal to its heat of combustion. Post-combustion, the convective fraction of that enthalpy results in a hot fire plume and ceiling jet. Ignoring convective heat loss to the ceiling, at any radial distance in the ceiling jet, the total energy flux at that distance is equal to the convective heat release of the fire. Because $T_{jet} - T_{amb}$ is relatively small where smoke detection is expected to occur, the specific heat of air can be considered a constant, c_p=1 kJ/(kg·K) [24] (Equation B-4).

$$\Delta H_c(1 - X_r) = m_{jet} c_p (T_{jet} - T_{amb}) \approx m_{jet}(T_{jet} - T_{amb}) \quad \text{(B-4)}$$

where ΔH_c is the heat of combustion in kJ/kg, $1\text{-}X_r$ is the convective fraction equal to 0.7, and m_{jet} is the mass flow rate of the ceiling jet normalized to 1 kg/s of fuel; this includes both the mass of fuel and the air that has diluted the fuel. A value of 16,000 kJ/kg is assumed for the heat of combustion as suggested by NUREG-7010 [28]. The normalized mass flow rate in the ceiling jet can therefore be computed as shown in Equation B-5.

$$m_{jet} = \Delta H_c \frac{(1 - X_r)}{(T_{jet} - T_{amb}) + 0.001} \quad \text{(B-5)}$$

The 0.001 is included in the numerical computation to avoid dividing by zero for cases where the fire size is near zero and the ceiling jet temperature is approximately the same as the ambient temperature.

Soot Mass Concentration

For each kg of fuel consumed, y_s kg of soot is produced. Therefore, the overall soot mass concentration at the detector, ρ_{soot}, in kg/m^3 can be computed as shown in Equation B-6.

$$\rho_{soot} = \frac{y_s}{m_{jet}} \rho_{jet} \quad \text{(B-6)}$$

Where y_s is the soot yield of the fuel in kg/kg and all other parameters have been identified. The soot yield is a random value independently sampled assuming a uniform distribution between the values of 0.076 and 0.136 kg/kg selected as approximate lower and upper bounds for TP electric cables from the Society of Fire Protection Engineers (SFPE) handbook [29; Table A.39]. For TS cables, the range is 0.082-0.175 g/g.

Optical Density

The OD measurement quantifies the exponential decay of light passing through a path length of smoke [24]. For smoke detection activation, once the calculated OD exceeds the activation OD, the detector will activate. Equation B-7 is used to calculate OD of the smoke in the ceiling jet at the detector.

$$\rho_{soot} = \frac{(\rho_{soot})(K_m)}{\ln(10)} \quad \text{(B-7)}$$

where K_m is the specific light extinction coefficient in m^2/kg. A value for flaming fires of 8700 m^2/kg is suggested by Mulholland and Croarkin [30]. This value is then compared against a detector threshold to determine whether a given scenario will activate the detector.

The activation OD values used in the Monte Carlo sampling process were developed from the average OD alarm thresholds for ionization and photoelectric smoke detectors [31]. The values, presented in Table B-2 (and graphically in Figure B-1), are used to fit a gamma distribution. The alpha and beta parameters from this best fit gamma distribution are used in the Monte Carlo sampling process to provide a randomized activation OD for the smoke detection calculation.

Table B-2
Smoke detection OD thresholds

OD Alarm Threshold (%)	Ionization (OD/m)	Photoelectric (OD/m)	Average	Best Fit (Gamma)
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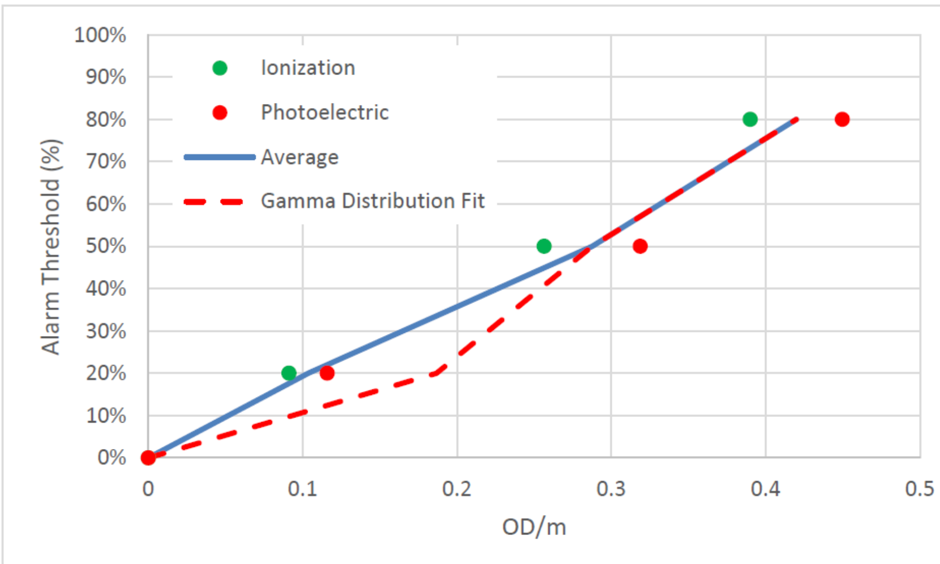

Figure B-1
Alarm threshold OD gamma distribution fit