# STATISTICAL CHARACTERIZATION OF THE TIME TO REACH PEAK HEAT RELEASE RATE FOR NUCLEAR POWER PLANT ELECTRICAL ENCLOSURE FIRES[a]

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**Abstract:** Since publication of NUREG/CR-6850 (EPRI 1011989), EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities in 2005, phenomenological modeling of fire growth to peak heat release rate (HRR) for electrical enclosure fires in nuclear power plant probabilistic risk assessment (PRA) has typically assumed an average 12-minute rise time. [1] One previous analysis using the data from NUREG/CR-6850 from which this estimate derived (Gallucci, "Statistical Characterization of Cable Electrical Failure Temperatures Due to Fire, with Simulation of Failure Probabilities") indicated that the time to peak HRR could be represented by a gamma distribution with alpha (shape) and beta (scale) parameters of 8.66 and 1.31, respectively. [2] Completion of the test program by the US Nuclear Regulatory Commission (USNRC) for electrical enclosure heat release rates, documented in NUREG/CR-7197, Heat Release Rates of Electrical Enclosure Fires (HELEN-FIRE) in 2016, has provided substantially more data from which to characterize this growth time to peak HRR. [3] From these, the author develops probabilistic distributions that enhance the original NUREG/CR-6850 results for both qualified (Q) and unqualified cables (UQ). The mean times to peak HRR are 13.3 and 10.1 min for Q and UQ cables, respectively, with a mean of 12.4 min when all data are combined, confirming that the original NUREG/CR-6850 estimate of 12 min was quite reasonable.

Via statistical-probabilistic analysis, the author shows that the time to peak HRR for Q and UQ cables can again be well represented by gamma distributions with alpha and beta parameters of 1.88 and 7.07, and 3.86 and 2.62, respectively. Working with the gamma distribution for All cables given the two cable types, the author performs simulations demonstrating that manual non-suppression probabilities, on average, are 30% and 10% higher than the use of a 12-min point estimate when the fire is assumed to be detected at its start and halfway between its start and the time it reaches its peak, respectively. This suggests that adopting a probabilistic approach enables more realistic modeling of this particular fire phenomenon (growth time).

**Keywords:** Fire Growth, Peak Heat Release Rate, Electrical Enclosures, Nuclear Power Plants

## 1. INTRODUCTION

NUREG/CR-7197 presented graphical results from over 100 fire tests in representative nuclear power plant enclosures showing the HRR vs. time for each fire. [3] The author reviewed all of these and determined that the graphical representations enabled an estimate of the time to reach peak HRR to be determined for 114 of these tests. In the process of developing the final version of NUREG/CR-7197, its authors provided similar estimates. Comparison of the author's estimates with these indicated agreement with roughly two-thirds of those estimates. For the remainder, the author revised the previous estimates, which were not retained in the final version of NUREG/CR-7197. All estimates were developed by visual inspection as shown, e.g., in Figure 1. The results for all tests reported in NUREG/CR-7197 are shown in Table 1 (for cable type, Q = qualified; UQ = unqualified).[b,c]

It is important to note that the analysis here is intended for use corresponding to the level of fidelity involved with fire phenomenological modeling when incorporated into PRA for nuclear power plant applications. Currently, fire PRAs typically assume a point estimate of 12 min for the time to reach peak HRR for an electrical enclosure fire,

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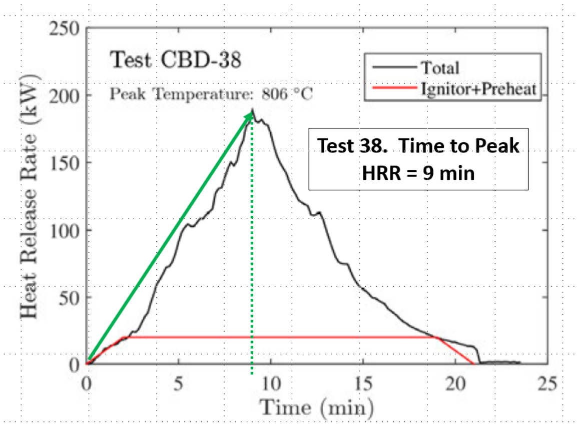
[a] This paper was prepared by an employee of the U.S. Nuclear Regulatory Commission. The views presented do not represent an official staff position. The U.S. Nuclear Regulatory Commission has neither approved nor disapproved its technical content.

[b] A "qualified" cable is typically one that has passed the IEEE (Institute of Electrical and Electronics Engineers)-383 flame spread test. [6] The "qualified" vs. "unqualified" classification corresponds closely to cables with thermoset (TS) and thermoplastic (TP) insulation, respectively. Cables are generally classified into two types, based on the jacketing material for the electrical conductors: (1) TP polymers that can be deformed and/or liquefied by heat addition and can be cooled down to solid form; and (2) TS polymers which cannot. In general, TS polymers have better mechanical properties, are stiffer and can withstand higher temperatures during longer periods of time than TP polymers.

[c] The reader interested in the details of the HELEN-FIRE tests is referred to NUREG/CR-7197 itself or a summary by the author as Appendix II of reference [7].

based on only 22 data from a variety of different tests reviewed in NUREG/CR-6850 (see Section 2 in this paper). [1] Thus, it is evident the level of phenomenological fidelity in fire PRA has a much lower threshold than a fire modeling practitioner might encounter in working with computer fire phenomenological models where the various influencing parameters are directly modeled and can be varied to affect the results. In fire PRA applications, only an "average expected" behavior over the wide variety of electrical enclosures present at a nuclear power plant need be modeled. As the HELEN-FIRE tests were designed and indicated, very few of these influencing factors can be controlled. As such, the HELEN-FIRE results are representative of this "average behavior" and are appropriate for analysis to be used in fire PRA for nuclear power plants. Additionally, while the analysis presented here is intended for use in nuclear power plant fire applications, there is no *a priori* exclusion for use in other technologies where the characteristics of an electrical enclosure fire match reasonably well with those from the HELEN-FIRE tests on which the analysis is based or the assumptions employed in the simulation, e.g., similar type of response to a fire alarm indicating an electrical enclosure fire at a facility.



Test 38. Time to Peak HRR = 9 min

**FIGURE 1**. **HELEN-FIRE HRR vs. Time Plot [3]**

**TABLE 1**. **Summary of Selected Electrical Enclosure Fire Measurements**

| Test | Preheat? (0 = No; 1 = Yes) | Cable Type | Door ([O]pen; [C]losed) | Time to Peak HRR (min) |
|---|---|---|---|---|
| **1** | 0 | Q | O | 40 |
| **2** | 0 | Q | O | 1 |
| **3** | 0 | Q | O | 15 |
| **4** | 0 | Q | O | 10 |
| **5** | 0 | Q | O | 15 |
| **6** | 0 | Q | O | 8 |
| **7** | 0 | Q | O | 8 |
| **8** | 0 | Q | O | 1 |
| **9** | 0 | Q | O | 2 |
| **10** | 0 | Q | O | 1 |
| **11** | 0 | Q | O | 8 |
| **12** | 0 | Q | C | 45 |
| **13** | 0 | Q | C | 16 |
| **14** | 0 | Q | O | 7 |
| **15** | 0 | Q | O | 34 |
| **16** | 0 | Q | O | 1 |
| **17** | 0 | Q | O | 6 |

| Test | Preheat? (0 = No; 1 = Yes) | Cable Type | Door ([O]pen; [C]losed) | Time to Peak HRR (min) |
|---|---|---|---|---|
| **18** | 0 | Q | O | 15 |
| **19** | 0 | Q | C | 40 |
| **20** | 0 | Q | C | 40 |
| **21** | 0 | Q | C | 22 |
| **22** | 0 | Q | C | 5 |
| **23** | 0 | U | O | 13 |
| **24** | 0 | Q | C | 35 |
| **25** | 0 | Q | C | 22 |
| **26** | 0 | Q | C | 1 |
| **27** | 1 | Q | C | 2 |
| **28** | 1 | Q | C | 6 |
| **29** | 0 | Q | C | 8 |
| **30** | 0 | Q | C | 8 |
| **31** | 1 | Q | C | 13 |
| **32** | 1 | Q | C | 4 |
| **33** | 0 | Q | C | 6 |
| **34** | 0 | Q | C | 7 |
| **35** | 0 | Q | O | 8 |
| **36** | 0 | Q | C | 13 |
| **37** | 0 | Q | C | 6 |
| **38** | 0 | Q | C | 9 |
| **39** | 0 | Q | C | 13 |
| **40** | 0 | Q | C | 8 |
| **41** | 0 | Q | C | 15 |
| **42** | 0 | Q | C | 18 |
| **43** | 0 | Q | C | 10 |
| **44** | 0 | Q | C | 19 |
| **45** | 1 | Q | C | 16 |
| **46** | 0 | Q | C | 19 |
| **47** | 0 | Q | C | 17 |
| **48** | 0 | Q | O | 18 |
| **49** | 0 | Q | C | 15 |
| **50** | 0 | Q | C | 13 |
| **51** | 0 | Q | O | 6 |
| **52** | 0 | U | O | 4 |
| **53.1** | 0 | U | C | 5 |
| **53.2** | 0 | U | O | 6 |
| **54** | 0 | U | O | 17 |
| **55** | 0 | U | C | 17 |
| **56** | 1 | U | C | 6 |
| **57** | 1 | U | C | 3 |
| **58** | 1 | U | C | 6 |

| **Test** | **Preheat? (0 = No; 1 = Yes)** | **Cable Type** | **Door ([O]pen; [C]losed)** | **Time to Peak HRR (min)** |
|---|---|---|---|---|
| **59** | 0 | U | O | 18 |
| **60** | 1 | U | C | 8 |
| **61** | 1 | Q | C | 17 |
| **62** | 1 | Q | C | 4 |
| **63** | 1 | Q | C | 25 |
| **64** | 1 | Q | C | 14 |
| **65** | 1 | Q | C | 16 |
| **66** | 1 | U | C | 17 |
| **67** | 0 | U | C | 9 |
| **68** | 0 | U | C | 11 |
| **69** | 1 | U | C | 13 |
| **70** | 0 | Q | C | 4 |
| **71** | 0 | Q | C | 14 |
| **73** | 1 | Q | C | 5 |
| **74** | 1 | Q | C | 13 |
| **75** | 1 | Q | C | 12 |
| **76** | 0 | Q | C | 9 |
| **77** | 1 | Q | C | 17 |
| **78** | 0 | Q | C | 13 |
| **79.1** | 0 | Q | C | 8 |
| **79.2** | 0 | Q | O | 15 |
| **80** | 1 | Q | O | 29 |
| **81** | 0 | Q | C | 18 |
| **82.1** | 1 | U | C | 5 |
| **82.2** | 1 | U | O | 9 |
| **83** | 0 | U | O | 5 |
| **84** | 1 | Q | O | 19 |
| **85** | 0 | Q | C | 13 |
| **86** | 0 | Q | O | 9 |
| **87** | 1 | Q | C | 12 |
| **88** | 0 | U | C | 2 |
| **89** | 0 | U | C | 10 |
| **90** | 1 | Q | C | 20 |
| **91** | 1 | Q | C | 15 |
| **92** | 1 | Q | C | 6 |
| **93** | 0 | U | C | 10 |
| **94** | 0 | Q | C | 13 |
| **95** | 0 | U | C | 16 |
| **96** | 1 | U | C | 9 |
| **97** | 0 | U | C | 20 |
| **98** | 0 | Q | C | 8 |
| **99** | 0 | U | O | 9 |

| Test | Preheat? (0 = No; 1 = Yes) | Cable Type | Door ([O]pen; [C]losed) | Time to Peak HRR (min) |
|---|---|---|---|---|
| **100** | 0 | Q | C | 27 |
| **101** | 0 | Q | C | 10 |
| **102** | 0 | Q | O | 6 |
| **103** | 0 | U | C | 13 |
| **104** | 1 | U | O | 6 |
| **105** | 0 | U | C | 7 |
| **106** | 0 | U | C | 14 |
| **107** | 1 | Q | O | 13 |
| **108** | 0 | Q | C | 7 |
| **109** | 1 | Q | C | 14 |
| **110** | 1 | U | C | 15 |
| **111** | 1 | Q | O | 3 |
| **112** | 0 | U | O | 11 |

## 2. ANALYSIS

The total of 114 times to peak HRR were next analyzed via three pairings: (1) Q vs. UQ cable types; (2) Closed vs. Open door position; and (3) Preheated vs. Not Preheated tests. The resulting statistics for each are shown in Table 2. Included are the statistics for all 114 tests together and those from statistical analysis of the times to peak HRR reported in NUREG/CR-6850. [2,3]

**TABLE 2. Results from Statistical Analysis of Pairings for Times to Peak HRR**

| Comparison | # of Data | Mean (min) | StDv (min) | Median (min) |
|---|---|---|---|---|
| **Qualified** | 83 | 13.3 | 9.51 | 13.0 |
| **Unqualified** | 31 | 10.1 | 4.90 | 9.0 |
| **Closed** | 78 | 13.1 | 8.43 | 13.0 |
| **Open** | 36 | 11.0 | 8.92 | 8.5 |
| **Not Preheated** | 80 | 12.8 | 9.36 | 10.0 |
| **Preheated** | 34 | 11.5 | 6.52 | 12.5 |
| **All** | 114 | 12.4 | 8.60 | 11.0 |
| **NUREG/CR-6850** | 22 | 11.4 | 3.86 | 10.5 |

The means range only from 10.1 to 13.3 min; the medians range from 8.5 to 13.0 min. More variation exists among the standard deviations, from 3.86 to 9.51 min, as might be expected given the variation in the number of data (from 22 to 114). Overall, there is small variation among the various groups, which is verified by pairwise comparison between the pairings via a Kolmogorov-Smirnov (K-S) statistical test.[d] While it may prove convenient to keep the pairings with the widest variation in mean separate (Q vs. UQ, with a difference of 3.2 min), combining all the data is

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[d] The K-S test also confirms the poolability of the data for all the tests with those cited in NUREG/CR-6850.

statistically valid. And, while the differences in means between the groups within each pairing are small, each shows an expected trend, i.e., the time to reach peak HRR is slightly quicker for UQ vs. Q, Open vs. Closed, and preheated vs. not preheated.

## 2.1 Effect on Manual Non-Suppression Probability

Proceeding with only the Q vs. UQ pairing, comparison of the effect of the means as input to manual non-suppression probability (NSP) for electrical fires from NUREG-2169 indicate the following:[e] [4]

The ratio of manual NSP for Q vs. that for UQ will be 27% lower due to the 3.2-min difference.

The ratio of manual NSP for Q vs. that for All will be 8% lower due to the 0.9-min difference.

The ratio of manual NSP for UQ vs. that for All will be 26% higher due to the 2.3 min difference.

This indicates that treating Q and UQ separately for time to reach peak HRR provides some relaxation in manual NSP for Q but not for UQ, albeit no more than 27%. Nonetheless, this could translate into a meaningful reduction in the fire risk for a particular application.

## 2.2 Probability Distributions

For the Q and UQ time to peak HRR data, distributional fits based on the "Estimated-Distribution" function from Mathematica® were obtained for the gamma, lognormal and Weibull distributions. [5] Figures 2 and 3 show the results from these fitting exercises.

For Q cables, there is essentially no difference between the gamma and Weibull fits, with some difference noticeable for the lognormal. Either of the first two would be a reasonable choice. For UQ cables, the gamma fit is intermediate between the lognormal and Weibull, which show the largest relative variation. The gamma appears to be a reasonable choice. Therefore, gamma distributions of the following form are selected to characterize the time to reach peak HRR for both Q and UQ cables, with the parameters shown (including those for All cables, i.e., the full data set of Q and UQ, discussed below):

$$f(t) = \frac{t^{\alpha-1}e^{-x/\beta}}{\beta^{\alpha}\Gamma(\alpha)}$$

$$\alpha\ (scale\ parameter) = 1.88\ (Q); 3.86\ (UQ); 2.12\ (All)$$

$$\beta\ (shape\ parameter) = 7.07\ (Q); 2.62\ (UQ); 5.87\ (All)$$

The corresponding statistics are shown in Table 3 (including those for All cables, i.e., the full data set of Q and UQ, discussed below). As indicated by the standard deviations and the 5th and 95th %iles, the distribution for UQ is somewhat "tighter" than that for Q. Part of this is the consequence in the relative number of data for each group (31 for UQ vs. 83 for Q). Also, as expected, the values for All fall between those for Q and UQ, leaning closer to those for Q due to the preponderance of data (discussed below).

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[e] Manual non-suppression probability (NSP) is the likelihood that a fire is not suppressed prior to fire-induced damage (electrical malfunction) preventing the component supported electrically from performing its desired function. It is calculated as follows: $Manual\ NSP = e^{-\lambda t}, t \geq 0$. "λ" is a time constant, i.e., the reciprocal of the mean time to suppress a fire (e.g., if this mean time is 10 min, λ = 0.1/min). "t" starts when the fire initiates and assumes its maximum value when measured up to the time at which component failure would preclude performance of the desired function. This is usually determined by the thermal-hydraulic phenomenology involved with precluding damage to the reactor core. This maximum value of "t" is subsequently reduced by the time it takes for the fire to be detected (for unoccupied areas, usually the response time of any fire detectors) + the time for manual response to the fire (e.g., "arriving on the scene") + the time to initiate suppression activities (e.g., unlock and begin discharge of a fire extinguisher or open a valve and begin application of hose water). Any delays in these times reduce "t" and make it more likely that the fire will not be suppressed. [4]

Given the relative similarity between the results for Q and UQ, for convenience further analysis focused on their combination (All), for which the same Mathematica® approach was applied. Figure 4 shows the results from the fitting exercise. Since different distributions appeared to yield better fits for different ranges over the spectrum of time to peak HRR, with the gamma and Weibull fitting nearly identically for the shorter times and the former lying intermediate between the other two at the longer times, the gamma was again chosen as representative, with the parameters and statistics shown above. Using this last distribution for All cables, a series of stochastic simulations were conducted to estimate the manual NSPs for electrical fires that would result for a range of response times.

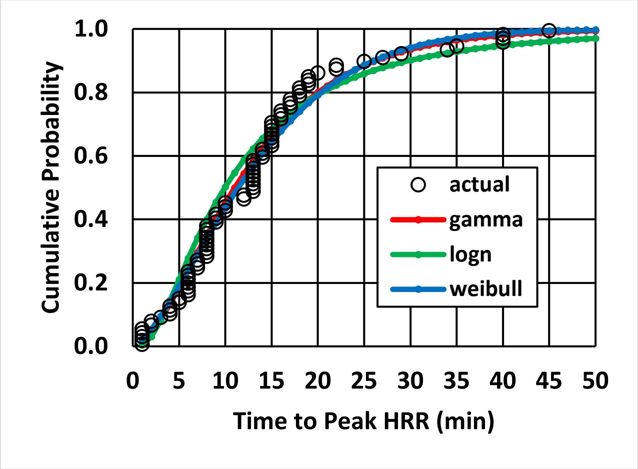

**FIGURE 2**. Distributional Fits for Times to Peak HRR – Qualified Cables

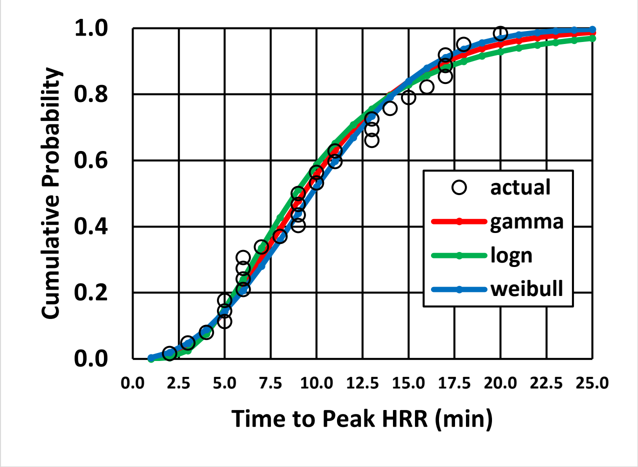

**FIGURE 3**. Distributional Fits for Times to Peak HRR – Unqualified Cables

**TABLE 3**. Statistics for Gamma Distributional Fits to Time to Peak HRR

| Cable Type | 5th %ile (min) | Median (min) | Mean (min) | 95th %ile (min) | StDv (min) |
|---|---|---|---|---|---|
| Qualified | 2.18 | 11.02 | 13.29 | 32.15 | 9.69 |
| Un-qualified | 3.73 | 9.27 | 10.13 | 19.82 | 5.16 |
| All (Both) | 2.37 | 10.54 | 12.43 | 28.95 | 8.54 |

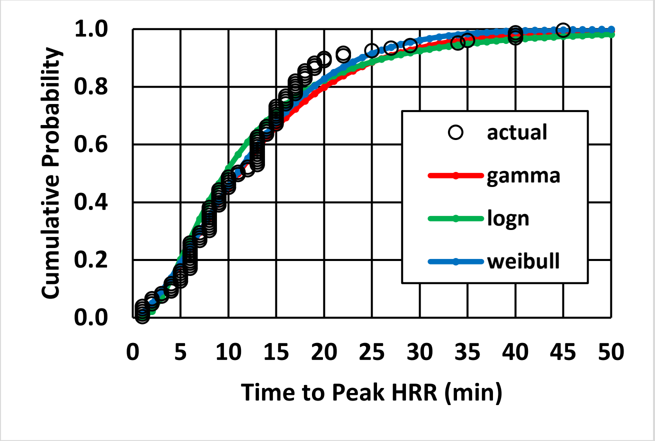

**FIGURE 4**. **Distributional Fits for Times to Peak HRR – All Cables**

## 3. SIMULATIONS

First, the time to reach peak HRR was simulated from the gamma distribution for All cables (10,000 random samples). Each of these was paired with a randomly sampled time to respond, which includes the time from fire start to detection to arrival at the fire and initiation of suppression efforts, and based on an assumed lognormal distribution with a median of 10 min (representative for nuclear power plant response to an electrical enclosure fire) and error factor of 1.5, implying a mean of 10.31 min, of the following form:

$$f(\tau) = \frac{e^{(-[\ln \tau - \mu]^2/2\sigma^2)}}{\tau\sigma\sqrt{2\pi}}$$

$$\mu = 2.30;\ \sigma = 0.246$$

Six cases were then considered. The first three assumed that detection of the fire occurred at time zero (when the fire started), with 10, 20 and 30 min to failure after the peak HRR had been reached. For example, if the simulated time to reach peak HRR was 7 min, the assumed times to failure were 17, 27 and 37 min, respectively. The second trio of cases paralleled the first, except now it was assumed that detection did not occur immediately when the fire started, but at the halfway point between time zero and the time at which the peak HRR was reached. For the same example, the assumed times to failure were 13.5, 23.5 and 33.5 min, respectively (since detection was delayed by 7/2 = 3.5 min).

For each of the six cases, the manual NSP for electrical fires was calculated for each of the 10,000 samples based on the NUREG-2169 exponential manual NSP with mean time failure rate = 0.0975/min, assumed to be normally distributed with 90%, two sided confidence bounds of ±0.0120 min, as follows: [4]

$$f(\theta) = \frac{e^{(-[\theta - \mu]^2/2\sigma^2)}}{\sigma\sqrt{2\pi}}$$

$$\mu = 0.0975;\ \sigma = 0.00729$$

Note that the manual NSP is assumed to have a floor (minimum) value of 0.001, imposed during the simulation. This was reached in all the Case 1 simulations, but only below the 5th %ile. For each of the six cases, the 10,000 samples were processed to yield the manual NSPs shown in Table 4.

**TABLE 4**. **Results from Simulation of Manual NSPs**

| Case | Time to Failure after Peak (min) | Time when Detected (min) | Manual NSP | | | | |
|---|---|---|---|---|---|---|---|
| | | | $5^{th}$ %ile | Median | Mean | $95^{th}$ %ile | Std Dev |
| **1.1** | **10** | **0 (fire starts)** | 0.0588 | 0.367 | 0.405 | 0.917 | 0.256 |
| **1.2** | **20** | | 0.219 | 0.139 | 0.156 | 0.348 | 0.106 |
| **1.3** | **30** | | 0.00801 | 0.0523 | 0.0595 | 0.135 | 0.0415 |
| **2.1** | **10** | **Halfway to Peak** | 0.235 | 0.598 | 0.606 | 1.000 | 0.234 |
| **2.2** | **20** | | 0.0872 | 0.225 | 0.237 | 0.428 | 0.108 |
| **2.3** | **30** | | 0.0316 | 0.0849 | 0.0902 | 0.166 | 0.0430 |

As expected, when the time to detection is delayed (Case 2 trio), the manual NSP is higher than its corresponding Case 1 since there is less time available to suppress the fire. Within each trio, the manual NSP decreases with increasing time to failure after the peak HRR is reached since more time becomes available to suppress.

### 3.1 Probabilistic vs. Point Estimate

To compare these results from what would be expected using a point estimate approach, the mean manual NSPs for each case (from Table 4) were compared against the manual NSP that would result from using the NUREG/CR-6850 point estimate of 12 min for the time to reach peak HRR, i.e., using 12 min for the Case 1 trio but only 12/2 = 6 min for the Case 2 trio (e.g., for Case 1.1, compare 0.405 to the following):

$$\exp([-0.0975/\text{min}][12\text{ min} + \text{Time\_to\_Failure\_after\_Peak} - 10.31\text{ min} - \text{Time\_when\_Detected}]) =$$

$$\exp([-0.0975/\text{min}][12 + 10 - 10.31 - 0) =$$

$$\exp(-[0.0975/\text{min}][11.69\text{ min}]) = 0.320$$

where 10.31 min = Mean Time_to_Respond

The results from this comparison are shown in Table 5.

**TABLE 5. Comparison of Simulated Mean to Point Estimate of Manual NSP**

| Case | Time to Failure after Peak (min) | Time when Detected (min) | Manual NSP Point Estimate | Ratio of Manual NSP(mean) to NSP(pt. est.) |
|---|---|---|---|---|
| **1.1** | **10** | **0 (fire starts)** | 0.320 | 1.27 |
| **1.2** | **20** | | 0.121 | 1.29 |
| **1.3** | **30** | | 0.0454 | 1.31 |
| **2.1** | **10** | **Halfway to Peak** | 0.574 | 1.06 |
| **2.2** | **20** | | 0.216 | 1.10 |
| **2.3** | **30** | | 0.0816 | 1.11 |

In all six cases, the ratio for the simulated mean manual NSP to that calculated from the NUREG/CR-6850 point estimate is higher by approximately 30% when the fire is detected at its start (i.e., using a fixed 12 min to reach peak HRR for the Case 1 trio) and 10% when the fire is detected halfway between its start and the time at which it reaches its peak HRR (i.e., using 12/2 = 6 min for the Case 2 trio). This suggests that the NUREG/CR-6850 approach is somewhat non-conservative because it yields lower manual NSPs, the extent of under-estimation varying from approximately 10% to 30%. This point estimation could be adjusted by just increasing the calculated manual NSP by 10% to 30% or subtracting 1 to 3 min, respectively, from the time available for suppression prior to calculating the NSP.

## 4. CONCLUSION

The assumption of an average growth time to peak HRR of 12 minutes has been typical for fire phenomenological modeling in nuclear power plant PRA since recommended by NUREG/CR-6850 in 2005. This was based on 22 tests where the rise time ranged from 4 to 18 min and was subsequently shown to follow a gamma distribution with alpha (scale) and beta (shape) parameters of 8.66 and 1.31, respectively. More recent experiments by the US NRC in the HELEN-FIRE program expanded the number of applicable tests to 114. From these, the author developed probabilistic distributions that enhance the original NUREG/CR-6850 results for both qualified and unqualified cables. The mean times to peak HRR are 13.3 and 10.1 min, respectively, with a mean of 12.4 min when all data are combined, confirming that the original NUREG/CR-6850 value of 12 min was quite reasonable as a point estimate.

Via statistical-probabilistic analysis of these data, the author shows that the time to peak HRR for each cable type can again be well represented by gamma distributions with alpha and beta parameters for Q, UQ and All cables of 1.88 and 7.07; 3.86 and 2.62; and 2.12 and 5.87, respectively. Working with the gamma distribution for All cables, given the relatively minor difference between the Q and UQ distributions, the author employs a probabilistic vs. point estimate approach to estimate the time to reach peak HRR for nuclear power plant electrical enclosure fires. Use of the mean times to reach peak HRR from the simulations yields manual non-suppression probabilities that, on average, are 30% and 10% higher than the use of a 12-min point estimate when the fire is assumed to be detected at its start and halfway between its start and the time it reaches its peak, respectively. This suggests that the NUREG/CR-6850 point estimate of 12 min yields somewhat non-conservative results for fire phenomenological modeling of the time for electrical enclosure fires to reach peak HRR. Adopting a probabilistic approach, i.e., modeling the times to reach peak HRR as the probabilistic distributions developed here, enables more realistic modeling of this particular fire phenomenon (growth time).

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