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Short communication

Statistical characterization of the time to reach peak heat release rate for nuclear power plant electrical enclosure fires[1]

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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-min rise time [1]. One previous analysis using the data from NUREG/CR-6850 from which this estimate derived indicated this 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 and unqualified cables.[2] 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 estimate of 12 min was quite reasonable.

Via statistical-probabilistic analysis, the author shows that the time to peak HRR for qualified and unqualified 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 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).

1. Introduction

In an earlier version of NUREG/CR-7197 issued in October 2014, Table 5-2 included among its summary of "enclosure fire measurements" the time for the piloted fire to reach its peak HRR.[3] While this measurement was removed in the 2016 final version [3], the graphs showing the HRR vs. time for each test were retained, enabling a comparison between the 2014 and 2016 final versions with the recorded time to peak HRR and all the test graphs. Review of these graphs by visual inspection (see Fig. 1) indicated that roughly two-thirds of the 2014 recorded times remained valid. For the remaining one-third, estimates were developed by visual inspection as shown, e.g., in Fig. 1. The results for all tests reported in NUREG/CR-7197 are shown in Table 1 (for cable type, Q = qualified; UQ = unqualified).

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 probabilistic risk assessment (PRA) for nuclear power plant applications. Currently, fire PRAs typically assume a

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[1] 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.

[2] A "qualified" cable is typically one that has passed the IEEE (Institute of Electrical and Electronics Engineers)-383 flame spread test [7]. These correspond closely to cables with thermoset (TS) and thermoplastic (TP) insulation, respectively. Pluralize to 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.

[3] The full listing of "enclosure fire measurements" from Table 5-2 of NUREG/CR-7197, October 2014, consisted of the test identification number, the type of electrical enclosure, the ignition HRR, the preheat HRR (if any), the ambient temperature, the combustible mass, the cable classification, the enclosure door position, the peak HRR, and the total energy release.

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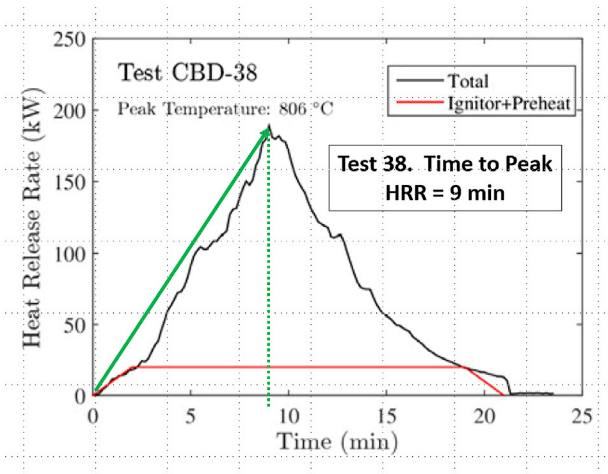

Fig. 1. HELEN-FIRE HRR vs. Time Plot [3].

point estimate of 12 min for the time to reach peak HRR for an electrical enclosure fire, 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.

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].

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.[4] 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 statistically valid. And, while the differences in means between the

[4] The K-S test also confirms the poolability of the data for all the tests with those cited in NUREG/CR-6850. The K-S test employed here is an online version which compares two data sets, quantifying the difference between the data from the two distributions and assessing a "figure of merit' called the "p-statistic" to accept or reject the statistical hypothesis that the two distributions could be taken from the same data set (i.e., they are "poolable"). P-statistics > 0.1, typically, suggest poolability, and such values were obtained in the K-S two sample comparison [4].

Table 1
Summary of selected 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
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
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