Statistical Characterization of Heat Release Rates from Electrical Enclosure Fires for Nuclear Power Plant Applications

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Since the publication of NUREG/CR-6850 / EPRI 1011989 in 2005, the US nuclear industry has sought to re-evaluate the default peak heat release rates (HRRs) for electrical enclosure fires typically used as fire modeling inputs to support fire probabilistic risk assessments (PRAs), considering them too conservative. A major effort by the Electric Power Research Institute and Science Applications International Corporation in 2012 was not endorsed by the US Nuclear Regulatory Commission (NRC) for use in risk-informed, regulatory applications. Subsequently the NRC, in conjunction with the National Institute of Standards and Technology, conducted a series of tests for representative nuclear power plant electrical enclosure fires designed to definitively establish more realistic peak HRRs for these often important contributors to fire risk. The results from these tests are statistically analyzed to develop two probabilistic distributions for peak HRR per unit mass of fuel that refine the values from NUREG/CR-6850, thereby providing a fairly simple means by which to estimate peak HRRs from electrical enclosure fires for fire modeling in support of fire PRA. Simulations using variable fuel loadings are performed to demonstrate how the results from this analysis may be used for nuclear power plant applications.

I. INTRODUCTION[a]

Since the publication of NUREG/CR-6850 / EPRI (Electric Power Research Institute) 1011989 in 2005, the nuclear industry has sought to re-evaluate the default peak heat release rates (HRRs) and their distributions for electrical enclosure fires, considering them too conservative.[1] These were based on analyst judgment using test results from Sandia National Laboratories[2,3] in the late 1980s and the Technical Research Centre of Finland[4,5] in the mid-1990s. Eschewing further experiments, EPRI and Science Applications International Corporation (SAIC) published EPRI 1022993 in 2012,[6] which built on these test results and additional ones from the Technical Research Centre of Finland[7] in 2003 and Melis, et al.,[8] in 2004. The result was a statistical/probabilistic-based model yielding adjusted, and presumably more realistic, HRRs from electrical enclosure fires as a function of parameters such as cable qualification, volumetric fuel density, and ventilation. However, in a letter to the Nuclear Energy Institute (NEI) in 2012, the NRC chose not to endorse EPRI 1022993 for use in risk-informed, regulatory applications, citing a need for "… significant additional data … to develop improved guidance on electrical cabinet HRR … [which] are unlikely to be found in available literature."[9] An effort to modify the HRR information in NUREG/CR-6850 (EPRI 1011989) by NRC-RES (Office of Nuclear Regulatory Research) has been completed (NUREG-2178).[10] This paper provides an alternative to this based exclusively on the test results from the NRC-RES program.

The testing program, discussed in Section 2 (below), utilized both "qualified" and "unqualified" cables. A "qualified" cable is typically one that has passed the IEEE (Institute of Electrical and Electronics Engineers)-383 flame spread test.[11] These correspond closely to cables with thermoset (TS) and thermoplastic (TP) insulation, respectively. Cable 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. As a result, the temperature at which fire-induced electrical failure occurs is higher for TS than TP cables, i.e., given a certain exposure temperature,

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[a] This paper was prepared by employees of the U.S. NRC. The views presented do not represent an official staff position.

one would expect the TP cable to fail electrically more readily than the TS. In addition, flame spread rate across TP cables has been found to be roughly three times greater than that across TS cables; the former also exhibits HRRs per unit area roughly twice that of the latter.[12] Therefore, one would expect peak HRRs for electrical enclosures with qualified (i.e., mainly TS) cables to be less than those for enclosures with unqualified (i.e., mainly TP) cables, and this has been demonstrated as discussed below.

II. HELEN-FIRE TEST DATA

In 2013-2014, the NRC contracted with the National Institute of Standards and Technology (NIST) to complete a series of over 100 tests at the Chesapeake Bay Detachment of the Naval Research Laboratory to measure HRRs from electrical enclosure fires, the HELEN-FIRE program (Heat Release Rates of Electrical Enclosure Fires).[13] Eight electrical enclosures from the Bellefonte Nuclear Generating Station, a plant owned by the Tennessee Valley Authority but never operated, were obtained, tested, and then reconfigured with varying amounts and types of electrical cables to represent expected configurations typical at nuclear power plants. Detailed descriptions of the tests and results are available in NUREG/CR-7197. Only a summary is presented here, since the focus of this paper is the analysis of the test results therein.

Electrical enclosures were situated beneath an oxygen consumption calorimeter hood designed to measure the HRR of fires from approximately 100 kW to 10 MW. This calorimeter, 2.4 m by 2.4 m (8 ft by 8 ft) and 2.4 m (8 ft) off the floor, was located beneath the large hood at the facility and instrumented to measure volume flow, gas temperature and oxygen concentration of the exhaust gases. Eight different configurations of electrical enclosures were tested as typical of the types found at nuclear power plants. Table I shows the results for 117 of the tests in the first nine columns. Excluded are tests where the fuel mass, which became a key parameter in this analysis, was not recorded. There were many variables among the tests, as characterized by the various columns, summarized as follows from the detailed descriptions in Reference 13. **(1) Test**—Test ID from [13]. **(2) Encl.**—Cabinet ID from [13]. Eight different types of enclosures were used in the experiments. **(3) Ignition HRR**—HRR of the ignition source in kW. Three types of ignition sources were used in the experiments: cartridge heaters, line burners, and pans of liquid fuel. **(4) Preheat HRR**—HRR of the heater to preheat the enclosure in kW. A variety of heaters were used to pre-heat the interior of the enclosures prior to or at the beginning of each experiment. **(5) Fuel Mass**—Total mass of the cables installed in the enclosure in kg. **(6) Cable Class**—The cables were classified as either qualified (Q) or unqualified (UQ) based on performance in a flame spread test (IEEE 383). **(7) Door Position**—The doors of the enclosure were either open or closed. **(8) Peak HRR**—Maximum HRR of the enclosure contents (cables) recorded during the test in kW. Note that the HRRs of the ignition source and the heater to preheat the enclosure were subtracted from the measured HRR. **(9) Total Energy Release**—Total heat released in the test in MJ. This is equal to the area under the HRR versus time curve. **(10) Peak HRR/Mass (kW/kg)**—Peak HRR divided by fuel mass in kW/kg (developed for this paper).

Examination of the results from the tests immediately indicated that there was high variability in the peak HRRs with limited control of any potential variables that would be relevant for predictive purposes when applied to actual electrical enclosure fires at nuclear power plants. For example, neither ignition HRR nor preheat HRR would be a parameter relevant to actual enclosure fires during operation. Cable class and door position, the distinction for which “closed” vs. “open” was questionable (see Section 3 below), offered only binary differentiation. As a result, the only quantifiable control variable against which a correlation (regression) might be obtained for peak HRR was fuel mass, but this proved not to be feasible.

At this point, rather than discard the test results or default to a subjective, opinion-based approach [10], the authors took a different tack. Since HRR is known to be dependent on fuel mass (recognizing there is variability depending upon fuel configuration and the degree to which fuel is consumed, discussed further in Section 3), they explored the efficacy of a distributional analysis for a derived metric, that being peak HRR per fuel mass as shown below by the ***bold italicized*** columns. The fuel mass would be a quantifiable parameter for actual electrical enclosure fires at nuclear power plants. Furthermore, the fact that the potential influencing variables, other than fuel mass, were not rigorously controlled somewhat parallels what might be expected in actual conditions for electrical enclosures at a nuclear power plant, where wide variation would be expected. Therefore, the HELEN-FIRE results, at least for this selected metric, could be reasonably representative and reproducible for use in fire phenomenological modeling in PRA applications.

Several iterations of Kolmogorov-Smirnov (K-S) pairwise comparisons for poolability of data sets using the calculated peak HRR per fuel mass (combustible loading), i.e., kW/kg, were performed, e.g., preheat vs. none, closed vs. open door, until cable class proved to be the most practical and statistically meaningful characteristic. The data are sorted into two groups, Q (unshaded) and UQ cables (shaded) in ascending order of peak HRR/mass.

TABLE I. HELEN-FIRE Test Results Sorted by Peak HRR per Unit Mass and Cable Class

Test	**Encl.**	**Ignition HRR (kW)**	**Preheat HRR (kW)**	***Fuel Mass (kg)***	**Cable Class**	**Door Position**	***Peak HRR (kW)***	**Total Energy Release (MJ)**	***Peak HRR/Mass (kW/kg)***
17	4	0.7	0	***2.7***	Q	Open	***0***	0	***0.000***
15B	5	0.7	0	***3.23***	Q	Closed	***0***	7	***0.000***
86A	7	5	0	***1.96***	Q	Open	***0***	15	***0.000***
26	1	0.7	0	***3.03***	Q	Closed	***1***	0	***0.330***
27A	1	0.7	14	***2.99***	Q	Closed	***1***	9	***0.334***
50	4	22	0	***2.65***	Q	Closed	***1***	21	***0.377***
61	1	0.8	19	***11.84***	Q	Closed	***5***	29	***0.422***
27B	1	0.7	14	***2.99***	Q	Closed	***1.7***	9	***0.569***
70	1	1.6	0	***3.11***	Q	Closed	***2***	1	***0.643***
62	1	1.6	19	***4.1***	Q	Closed	***3***	33	***0.732***
36A	2	4	0	***2.71***	Q	Closed	***2.5***	4	***0.923***
15A	5	0.7	0	***3.23***	Q	Open	***3***	7	***0.929***
19	5	0.7	0	***3.23***	Q	Closed	***3***	7	***0.929***
64	8	0.8	11	***6.05***	Q	Closed	***6***	13	***0.992***
85	7	0.8	0	***1.96***	Q	Closed	***2***	2	***1.020***
16	5	0.7	0	***1.89***	Q	Open	***2***	2	***1.058***
65	8	0.8	11	***5.7***	Q	Closed	***7***	15	***1.228***
25	1	0.7	0	***3.11***	Q	Closed	***4***	5	***1.286***
73	4	1.6	22	***2.88***	Q	Closed	***4***	26	***1.389***
91	7	1.6	20	***2.07***	Q	Closed	***3***	26	***1.449***
36B	2	4	0	***2.71***	Q	Closed	***4***	4	***1.476***
28A	1	0.7	16	***2.87***	Q	Closed	***4.7***	17	***1.638***
45	5	5.5	22	***2.88***	Q	Closed	***5***	34	***1.736***
74	5	1.6	20	***2.56***	Q	Closed	***5***	28	***1.953***
21	4	0.7	0	***1.89***	Q	Closed	***4***	3	***2.116***
22	4	0.7	0	***1.76***	Q	Closed	***4***	4	***2.273***
20	5	0.7	0	***1.89***	Q	Closed	***5***	9	***2.646***
102	6	23	0	***3.56***	Q	Open	***10***	17	***2.809***
76	5	22	0	***2.88***	Q	Closed	***9***	25	***3.125***
28C	1	0.7	16	***2.87***	Q	Closed	***10***	17	***3.484***
90	7	0.8	16	***3.41***	Q	Closed	***12***	33	***3.519***
77A	5	5.5	24	***2.56***	Q	Closed	***10***	53	***3.906***
28B	1	0.7	16	***2.87***	Q	Closed	***11.3***	17	***3.937***
75	5	5.5	26	***2.88***	Q	Closed	***15***	57	***5.208***
100	6	5.5	0	***6.24***	Q	Closed	***34***	42	***5.449***

Test	**Encl.**	**Ignition HRR (kW)**	**Preheat HRR (kW)**	***Fuel Mass (kg)***	**Cable Class**	**Door Position**	***Peak HRR (kW)***	**Total Energy Release (MJ)**	***Peak HRR/Mass (kW/kg)***
24	5	0.7	0	***0.73***	Q	Closed	***4***	4	***5.479***
43	4	16	0	***2.88***	Q	Closed	***18***	21	***6.250***
37	2	54	0	***5.41***	Q	Closed	***35***	27	***6.470***
79A	4	5.5	0	***6.12***	Q	Closed	***40***	63	***6.536***
77B	5	5.5	24	***2.56***	Q	Closed	***18***	53	***7.031***
80A	4	5.5	19	***2.77***	Q	Closed	***20***	92	***7.220***
92	7	5.5	20	***2.07***	Q	Closed	***15***	37	***7.246***
32A	4	5.5	25	***0.73***	Q	Closed	***5.6***	35	***7.671***
94	7	5.5	0	***4.78***	Q	Closed	***37***	23	***7.741***
63	1	5.5	19	***11.84***	Q	Closed	***92***	156	***7.770***
46	4	19	0	***5.41***	Q	Closed	***45***	68	***8.318***
81	5	30	0	***2.88***	Q	Closed	***24***	48	***8.333***
87	7	0.8	21	***3.27***	Q	Closed	***29***	35	***8.869***
49	4	19	0	***5.41***	Q	Closed	***50***	76	***9.242***
107	1	5.5	19	***5.53***	Q	Open	***55***	51	***9.946***
39	8	25	0	***5.68***	Q	Closed	***60***	65	***10.563***
101	6	20	0	***6.24***	Q	Closed	***66***	70	***10.577***
79B	4	5.5	0	***6.12***	Q	Closed	***65***	63	***10.621***
109	8	5.5	19	***5.98***	Q	Closed	***64***	61	***10.702***
44	5	5.5	0	***2.88***	Q	Closed	***31***	32	***10.764***
84	7	0.8	20	***3.27***	Q	Open	***37***	51	***11.315***
78A	5	5.5	0	***2.56***	Q	Closed	***30***	27	***11.719***
42	4	5.5	0	***2.88***	Q	Closed	***34***	35	***11.806***
86B	7	5	0	***1.96***	Q	Open	***24***	15	***12.245***
35	8	27	0	***11.37***	Q	Closed	***146***	153	***12.841***
47	4	19	0	***2.71***	Q	Closed	***40***	49	***14.760***
32B	4	5.5	25	***0.73***	Q	Closed	***11***	35	***15.068***
111A	5	5.5	20	***3.12***	Q	Closed	***49***	120	***15.705***
98	6	20	0	***7.67***	Q	Closed	***121***	126	***15.776***
48	4	19	0	***5.41***	Q	Open	***87***	89	***16.081***
78B	5	5.5	0	***2.56***	Q	Closed	***54***	27	***21.094***
108	1	5.5	0	***1.38***	Q	Closed	***32***	15	***23.188***
51	4	30	0	***1.33***	Q	Open	***31***	34	***23.308***
41A	3	20	0	***5***	Q	Closed	***122***	141	***24.400***
34	5	35	0	***1.22***	Q	Closed	***35***	46	***28.689***
29	1	18	0	***2.64***	Q	Closed	***82***	76	***31.061***
33	5	25	0	***1.46***	Q	Closed	***50***	40	***34.247***
38	2	20	0	***4.74***	Q	Closed	***169***	95	***35.654***
80B	4	5.5	19	***2.77***	Q	Open	***100***	92	***36.101***
31	4	5.5	22	***0.73***	Q	Closed	***28***	45	***38.356***
71	1	5.5	0	***3.11***	Q	Closed	***138***	99	***44.373***

Test	**Encl.**	**Ignition HRR (kW)**	**Preheat HRR (kW)**	***Fuel Mass (kg)***	**Cable Class**	**Door Position**	***Peak HRR (kW)***	**Total Energy Release (MJ)**	***Peak HRR/Mass (kW/kg)***
41B	3	20	0	***5***	Q	Open	***232***	141	***46.400***
30	1	18	0	***1.32***	Q	Closed	***72***	59	***54.545***
52	4	5.5	0	***2.17***	Q	Open	***122***	61	***56.221***
111B	5	5.5	20	***3.1***	Q	Open	***268***	120	***86.452***
82A	1	1.6	19	***7.39***	UQ	Closed	***1***	112	***0.135***
99	6	5.5	0	***2.3***	UQ	Open	***3***	7	***1.304***
18	4	0.7	0	***1.76***	UQ	Open	***3***	3	***1.705***
97A	6	5.5	0	***4.87***	UQ	Closed	***9***	120	***1.848***
110A	4	5.5	24	***3.36***	UQ	Closed	***7***	32	***2.083***
59A	5	0.8	0	***2.33***	UQ	Open	***5.3***	14	***2.275***
69	8	1.6	13	***3.53***	UQ	Closed	***10***	22	***2.833***
57	5	0.8	24	***1.68***	UQ	Closed	***5***	26	***2.976***
110B	4	5.5	24	***3.36***	UQ	Open	***11***	32	***3.274***
56	5	0.8	22	***1.7***	UQ	Closed	***8***	16	***4.706***
106A	1	5.5	0	***3.05***	UQ	Closed	***17***	25	***5.574***
95	7	5.5	0	***5.37***	UQ	Closed	***30***	27	***5.587***
96	6	5.5	21	***5.37***	UQ	Closed	***33***	47	***6.145***
55	4	10	0	***3.12***	UQ	Closed	***21***	26	***6.731***
67A	4	5.5	0	***3.36***	UQ	Closed	***26***	21	***7.738***
66A	4	5.5	24	***3.36***	UQ	Closed	***26***	57	***7.738***
66B	4	5.5	24	***3.36***	UQ	Open	***26***	57	***7.738***
82B	1	1.6	19	***7.39***	UQ	Open	***63***	112	***8.525***
67B	4	5.5	0	***3.36***	UQ	Open	***29***	21	***8.631***
59B	5	0.8	0	***2.33***	UQ	Open	***22***	14	***9.442***
58	5	0.8	21	***2.33***	UQ	Closed	***26***	36	***11.159***
23	5	0.7	0	***1.56***	UQ	Open	***18***	12	***11.538***
60	1	0.8	19	***7.39***	UQ	Closed	***88***	96	***11.908***
106B	1	5.5	0	***3.05***	UQ	Open	***38***	25	***12.459***
112	4	5.5	0	***1.68***	UQ	Open	***22***	12	***13.095***
105	1	5.5	0	***6.1***	UQ	Closed	***80***	25	***13.115***
93	7	5.5	0	***3.25***	UQ	Closed	***59***	27	***18.154***
97B	6	5.5	0	***4.87***	UQ	Closed	***89***	120	***18.275***
89	7	0.8	0	***1.15***	UQ	Closed	***25***	10	***21.739***
53A	4	5.5	0	***2.17***	UQ	Closed	***57***	60	***26.267***
54	4	2.2	0	***3.12***	UQ	Open	***94***	41	***30.128***
103	6	5.5	0	***1.15***	UQ	Closed	***42***	50	***36.522***
68	1	0.8	0	***4.74***	UQ	Closed	***216***	121	***45.570***
104	1	0.8	24	***4.74***	UQ	Open	***250***	141	***52.743***
83	1	0.8	0	***4.74***	UQ	Open	***577***	152	***121.730***
88	7	0.8	0	***1.15***	UQ	Closed	***147***	18	***127.826***
53B	4	5.5	0	***0.54***	UQ	Open	***85***	60	***157.407***

HRR/mass is a logical metric for the HELEN-FIRE test results, given the similarity of combustible composition – batches of cables with reasonably equivalent radii (r) contained in metal enclosures. In addition, for comparable levels of burning, HRR is known to be proportional to exposed surface area (A) which, for cylindrical cables of length h with homogeneous mass density ρ, can be shown to be proportional to the mass (M) as follows:

$M = \rho\pi r^2 h \rightarrow h = M/\rho\pi r^2$
$A = 2\pi rh = 2M/\rho r$

Since radius and density are approximately constant, the proportionality with M dominates.

Some may contend that mass is not a reliable indicator of HRR, but this stems from differences in the composition of the combustibles. For equal masses of one "log" (with mass M and radius R) and a number n of "twigs" (each with mass m and radius r), both of the same density (ρ) and length (h), the ratio of HRRs is proportional to the ratio of exposed surface areas, i.e., $A_{twigs}/A_{log} = (2nm/\rho r)/(2M/\rho R) = nmR/Mr$. For equal masses, $M = nm \rightarrow \rho\pi R^2 h = n\rho\pi r^2 h \rightarrow R/r = \sqrt{n}$. Therefore, the ratio of surface areas (and HRRs) becomes $A_{twigs}/A_{log} = \sqrt{n}$. As any camper knows, it is much easier to light a bunch of twigs than a log; and, once lit, that corresponds to a higher HRR for the twigs vs. the log for equal masses. Since HELEN-FIRE tested "twigs," it is reasonable to assume a relatively equivalent combustible composition, such that HRR should be proportional to exposed surface area and, therefore, to mass as shown above. HRR/mass is a logical choice as a characteristic metric.

Graphs for each of the data sets (peak HRR/mass, Q and UQ) were developed and, upon inspection (subsequently confirmed via χ^2 goodness-of-fit tests), fit to the gamma distribution of the following form:

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

where x is the peak HRR/mass in kW/kg. The alpha (scale) and beta (shape) parameters were derived from the mean and standard deviation of each data set, as shown among the statistics in Table II. The cumulative distribution functions with both the actual and gamma-fitted data are shown in Figure 1. The choice of the gamma distribution was based not only on the relatively good fit to the experimental data, but also given precedence for its use in fire PRA applications, in particular for both the original and recently updated fire ignition frequencies as well as the original and more recent RES HRR distributions.[1,10,14] It is quite familiar to fire PRA analysts for its flexibility and relative ease of use, especially when Bayesian updating of generic by plant-specific data is performed, a widely-used statistical method for all nuclear power plant PRAs.

TABLE II. Actual and Fitted Data for Qualified (Q) and Unqualified (UQ) Cables

Range (kW/Kg)	Count (Q)	Count (UQ)	Q Fraction	UQ Fraction
0-10	50	20	0.625	0.541
10-20	15	8	0.188	0.216
20-30	5	2	0.063	0.054
30-40	5	2	0.063	0.054
40-50	2	1	0.025	0.027
50-60	2	1	0.025	0.027
60+	1	3	0.013	0.081
Total	80	37	1	1
Mean (kW/kg)	11.858	22.341		
Std dev (kW/kg)	15.572	36.484		
Gamma alpha	0.580	0.375		
Gamma beta	20.450	59.581		

Range (kW/Kg)	Count (Q)	Count (UQ)	Q Fraction	UQ Fraction
	Peak HRR/Unit Mass (kW/kg)		Ratio UQ/Q	
Fractile (%ile)	Q	UQ		
0.005 (0.5%)	1.804E-03	3.178E-05	**0.018**	
0.010 (1.0%)	5.964E-03	2.018E-04	**0.034**	
0.020 (2.0%)	1.972E-02	1.282E-03	**0.065**	
0.025 (2.5%)	2.898E-02	2.324E-03	**0.080**	
0.050 (5.0%)	9.598E-02	1.476E-02	**0.15**	
0.250 (25.0%)	1.614	1.094	**0.68**	
0.500 (50.0%)	6.086	7.497	**1.23**	
0.750 (75.0%)	16.020	27.690	**1.73**	
0.950 (95.0%)	43.197	94.909	**2.20**	
0.975 (97.5%)	55.693	127.963	**2.30**	
0.980 (98.0%)	59.776	138.912	**2.32**	
0.990 (99.0%)	72.600	173.662	**2.39**	
0.995 (99.5%)	85.600	209.308	**2.45**	

Evident from the statistical analysis is that from the mean (~70th percentile) upward, the UQ peak HRR/kg is roughly twice that of Q, increasing slightly with higher percentile. Phenomenologically, that is to be expected, as discussed in the next section.

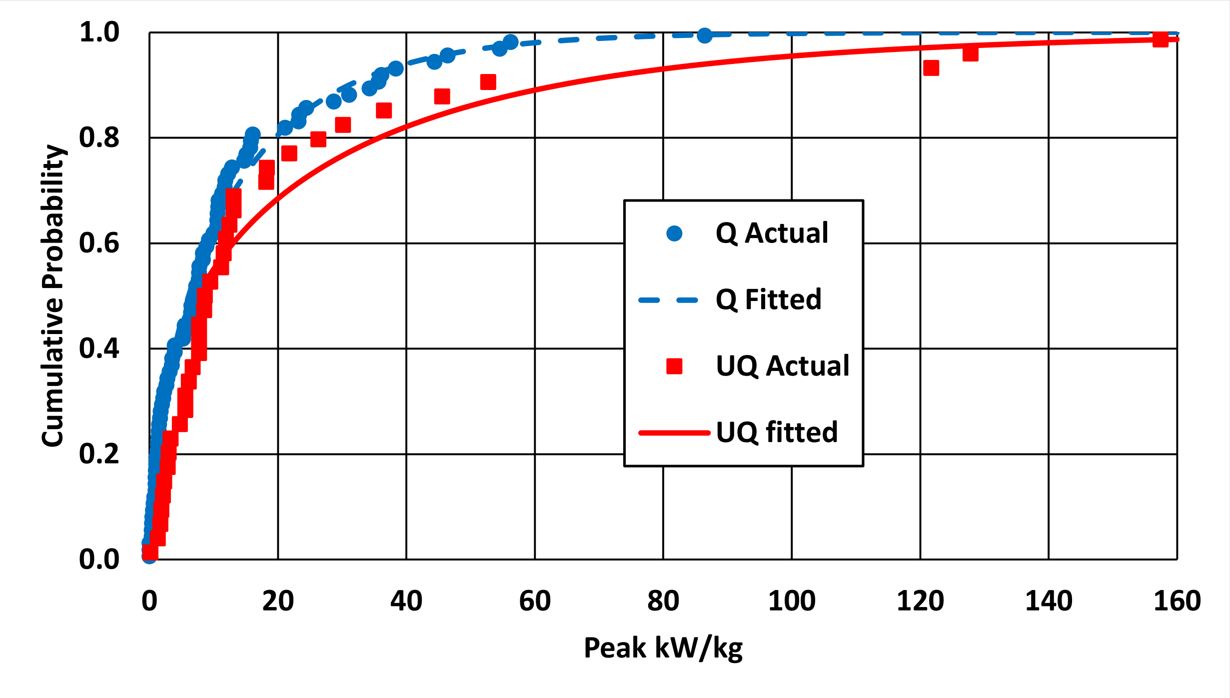

FIGURE 1. Cumulative Distribution Functions of Test Data and Gamma Distributional Fits for Both Qualified (Q) and Unqualified (UQ) Cables

III. PHENOMENOLOGY

From NUREG/CR-6850, and confirmed by NUREG/CR-7010, Volume 1,[12] the lengthwise burning rate for TP cable (assumed to correspond to UQ) is triple that for TS (assumed to correspond to Q). As a cable of cylindrical cross-section burns, one would expect the rate of fire propagation along the surface in the axial (lengthwise) direction to dominate over the rate at which fire burns "downward" (inward) in the radial direction. Therefore, the ratio of HRRs for UQ vs. Q should be roughly a factor of three, at least for individual cables with completely exposed surfaces. Given that the cables in the HELEN-FIRE tests were likely not completely exposed, the observed ratio (for a given fuel mass) of roughly a factor of two over much of the distributions seems reasonable when compared to the theoretical value of three.

Additionally, consider two electrical enclosures loaded with equal amounts of Q and UQ cable, each type of the same physical dimensions and installed in an equivalent manner. If the peak HRR occurs when the entire exposed cable surface is burning, the ratio of the peak HRRs should be approximately equal to the ratio of the HRR per unit area (q") for each type. NUREG/CR-7010, Volume 1, recommends HRRs per unit area ranging from 100 to 200 kW/m^2 for TS ("qualified") cables and from 200 to 300 kW/m^2 for TP cables ("unqualified"), with point estimates at 150 and 250 kW/m^2, respectively. Considering the ranges, the ratio q"(UQ)/q"(Q) would extend from a low of 1 (lowest q"[UQ] = 200 divided by highest q"[Q] = 200) to 3 (highest q"[UQ] = 300 divided by lowest q"[Q] = 100). The ratio for the means would be 250/150 = 1.67.

Note that the HRRs per unit area recommended in NUREG/CR-7010 are based on test data obtained for cable specimens exposed to a fixed heat flux of 50 kW/m^2. Table III, extracted from Table 6-1 of NUREG/CR-7010, Volume 1, provides the recorded HRRs per unit area for cables tested in the cone calorimeter experiments. For the single TP cable listed, the recorded HRR per unit area at an imposed flux of 50 kW/m^2 is 184 kW/m^2. An estimate for the ratio of peak HRRs for UQ (TP) vs. Q (TS) becomes 184/107.7 = 1.7, using the average for the TS cables. However, UQ cables release heat more rapidly than Q cables. Therefore, the heat flux inside an enclosure filled with the former is expected to be somewhat higher than for the latter given equal loadings. Consequently, the ratio of the peak HRRs is expected to be somewhat higher than this ratio of HRR per unit area. An upper bound estimate on this effect can be obtained using the HRR per unit area for the TP cable at an imposed flux of 75 kW/m^2, namely 266 kW/m^2. The result is 266/107.7 = 2.5. Given this estimated range for the ratio from 1.7 to 2.5, the roughly factor of two ratio for peak HRR per fuel mass for UQ vs. Q cables is consistent.

TABLE III. Measured HRRs from Cone Calorimeter Experiments[12]

Cable		HRR per Unit Area (kW/m^2) [Imposed Flux = 50 kW/m^2]
Number	**Type**	
11	**TS**	90
16	**TS**	130
23	**TS**	92
43	**TS**	70
46	**TS**	61
219	**TS**	140
220	**TS**	143
367	**TS**	107
700	**TS**	136
TS Average		107.7
701	**TP**	184 (@50 kW/m^2) 266 (@ 75 kW/m^2)
The results for cable numbers 270 and 271 are excluded since these differed somewhat from the rest of the TS cables, being from the same manufacturer. Cable 270 was a triaxial cable with cross-linked polyethylene insulation and chloro-sulfonated polyethylene jacket. Cable 271 was a power and control cable. Although both were technically classified as TS, the observed relatively high HRR was more indicative of thermoplastic burning.		

These simplistic estimates seem reasonably consistent with the analytical results from the HELEN-FIRE data showing a mean ratio of q"(UQ)/q"(Q) ≈ 2 for equal fuel mass (see Table II). It is important to note that this analysis makes a direct comparison of the data obtained from the HELEN-FIRE tests, which typically included sufficient ventilation characteristics for the recorded HRRs, i.e., most, if not all, of the fires were not large enough to consume more oxygen than was available via enclosure leakage or openings. Further, this analysis does not attempt to extract additional effects from the data set, such as (1) oxygen-limited combustion as a result of robustly secured or sealed enclosures, or restricted or fuel-limited conditions; (2) tightly-bundled cabling. It is also worth noting that the recorded HRRs did not distinguish whether all of the available fuel was actually consumed during the test; the mass lost simply was not recorded.

III.A. Potential Effect of Door Position

Many of the tests included a change in the enclosure door position either during a single test or across multiple tests in order to observe its effect. However, in all but a few cases, the effect was either nominal or occurred after the peak HRR had already been reached; therefore, it was not possible to assess the role of ventilation from this set of data. For example, in several instances, a test was described as door-closed but there was either another large opening in the enclosure or the door was opened at some point during the test. Nonetheless, supplementary analysis of the data for peak HRR per fuel mass (combustible loading, kW/kg) at least suggests a difference based on reported door position.

When the data in Table I are regrouped by door position within each cable class, the results are as shown in Table IV.

TABLE IV. Ranges and Statistics for Peak HRR per Fuel Mass Based on Reported Door Position

Range (kW/kg)	Count (Q)		Count (UQ)	
	Closed	Open	Closed	Open
0-10	44	6	12	8
10-20	12	3	5	3
20-30	4	1	2	0
30-40	4	1	1	1
40-50	1	1	1	0
50-60	1	1	0	1
60+	0	1	1	2
Total	66	14	22	15
Mean (kW/kg)	9.784	21.633	17.483	29.466
Std Dev(kW/kg)	11.641	25.911	27.257	47.085

The majority of the peak HRR per fuel mass ratios remain in the lower ranges independent from door position. However, compared to the results from Table II, there is some reduction in the mean ratios for each cable type for the closed door position (~20%) and increase for the open door position (~80% for Q and 30% for UQ). This at least suggests a trend of up to roughly a factor of two difference in the peak HRR per fuel mass as a function of door position. Consistent with this is a comparison of two tests with equivalent cable type and fuel mass which yielded high peak HRRs, namely Test #68 (peak HRR = 216 kW, UQ cable) to Test #83 (577 kW, UQ cable). This suggests that a reduction again of roughly a factor of two in a particular peak HRR might be appropriate between an open and closed door position. To the extent that the closed door position from the HELEN-FIRE tests might serve as a surrogate if an enclosure is confirmed to be tightly sealed, a reduction of up to roughly a factor of two for peak HRR per fuel mass may be appropriate.

The method discussed in Section 4 (below) is intended to represent a baseline for analysts seeking to estimate the peak HRR for a fire in an electrical enclosure typically found in a nuclear power plant and containing primarily Q or

UQ cabling. If an analyst has reason to suspect that a fire within a particular enclosure would be expected to exhibit a fuel- or oxygen-limited condition as discussed above, steps could be taken to adjust the values appropriately in order to reasonably account for these effects. Similarly, if an analyst is unable to calculate or approximate the mass of fuel within a particular enclosure by way of physical inspection, a comparison to the catalog of images and data obtained during the HELEN-FIRE tests could serve as a surrogate or starting point for estimating the mass of available fuel.

Physical inspection so as to estimate the combustible loading within an electrical enclosure can be performed whenever an opportunity arises, or intentionally during an outage whenever the enclosures are de-energized. Enclosures, of course de-energized, may be open during power operation due to maintenance, at which time visual inspection of the contents can be made (or a photograph taken). Based on an estimate of the volume occupied by the combustibles and knowledge of the mass density, a reasonable approximation to the combustible mass is practical (within a factor of two at low loadings and even tighter at higher ones). Given the various uncertainties involved not only in fire phenomenological modeling but also in PRA itself, such estimates are well within any margin of error that would affect the PRA results. Furthermore, while there may be hundreds of electrical enclosures at a plant, they are limited to a relatively small number of different types such that obtaining mass loading estimates for a few of each type should suffice for the majority of enclosures within that type. It is instructive to note that both NUREG/CR-6850 and NUREG-2178 (other than the default condition) also require knowledge of the electrical enclosure contents when selecting the appropriate distribution for peak HRR, the former being based on number of cable bundles and the latter, other than the default condition, depending upon whether the fuel loading is "low" or "very low." That is, at some point in time, the interior of the enclosure needs to have been visually examined (or photographed).

IV. SIMULATION

To demonstrate the use of these two new peak HRR/fuel mass distributions, simple simulations for each cable class and a composite nominally consisting of an equal split were performed. Fuel mass on a per-unit (kg) basis was assumed to follow a uniform distribution ranging from 0.5 to 1.5 kg, with a mean of 1.0 kg. An on-line random number generator (http://appincredible.com/online/random-number-generator/) employing a Monte-Carlo, pseudo algorithm yields 10,000 random deviates for this uniform distribution as input into a Microsoft EXCEL® worksheet. This results can be simply scaled to any combustible loading via direct multiplication. For the composite case, the nominal loading of half Q and half UQ cables was assumed to vary uniformly as well, ranging from 25% Q/75% UQ to 75% Q/25% UQ, and subjected to a parallel simulation. The composite peak HRR per fuel mass when both Q and UQ cables are present is assumed to be the weighted sum of the corresponding values for each cable type. This is based on a separate analysis of the HELEN-FIRE test results for both Q and UQ cables confirming that the times to peak HRR are essentially the same for both types, i.e., around the 12 minutes recommended in NUREG/CR-6850. Therefore, the peak HRRs for both cable types should be reached at approximately the same time, such that a summation approach seems reasonable.

The results from the simulations for each of the three cases are shown in Table V, including illustrative scaling for nominal loadings of 5 and 10 kg. Figure 2 illustrates the trends for the 5 kg case. Note that there is the additional variation for the composite case due to the simulation of the split between the two cable types such that its probability curve does not always lie between the other two cases.

TABLE V. Simulation Results for Pairings of Fuel Mass and Cable Class

Fuel Mass	Cable Class(es)	Mean (kW)	75th %ile (kW)	98th %ile (kW)	Std Dev (kW)
1 kg (2.2 lb)	**All Q**	11.9	16.0	60.3	16.1
	All UQ	22.3	27.6	137.6	37.2
	50/50 split	17.2	22.6	79.4	21.6
5 kg (11 lb)	**All Q**	59.4	79.8	301.5	80.7
	All UQ	111.6	137.8	687.8	185.9
	50/50 split	85.9	113.2	396.8	107.8
10 kg (22 lb)	**All Q**	118.8	159.7	603.0	161.4
	All UQ	223.1	275.6	1375.6	371.7
	50/50 split	171.7	226.3	793.6	215.7

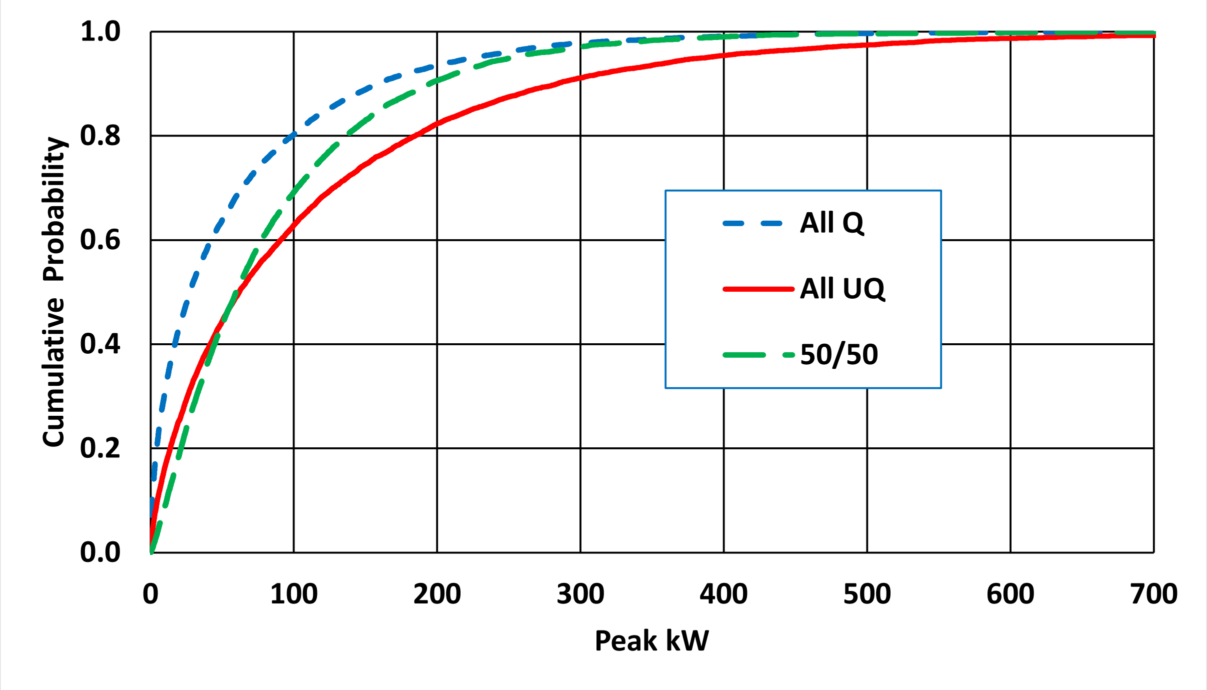

FIGURE 2. Cumulative Distribution Functions for Simulation of Peak HRR for Nominal 5-kg Fuel Mass for All Qualified (Q), All Unqualified (UQ) and Nominal 50/50 Split of Cables

The approximate 2:1 ratio for UQ vs Q HRR (given equal fuel mass) is evident for the mean and two upper percentiles. They range from a low (mean) of 11.9 kW for a nominal 1-kg loading of all Q to a maximum (98th percentile) of 1375.6 kW for a nominal 10-kg loading of all UQ, a factor of ~115. From Table G-1 of NUREG/CR-6850, a slightly tighter range is evident, from a low of 49.8 kW, the mean for a vertical cabinet with Q cable, fire limited to one bundle, to a maximum of 1002 kW, the 98th percentile or a vertical cabinet with UQ cables, open doors and fire in multiple bundles (a factor of ~20). This suggests that the 1-kg loading may be somewhat unrealistic as a minimum or that such a low loading, if not unrealistic, was possibly dismissed during the development of NUREG/CR-6850. Alignment with the HRRs from NUREG/CR-6850 remains possible for higher loadings. Considering that fires are often detected and extinguished prior to reaching their peak HRR potential, or the fuel within an enclosure is not configured in a manner conducive to supporting total consumption, it is perhaps easier to understand why plant operating experience might not reflect a common occurrence of large thermal fires.

V. CONCLUSION

There has been considerable effort on the part of the nuclear industry to *a priori* lower the default HRRs from NUREG/CR-6850 for use in bounding fire modeling and fire probabilistic risk assessment (PRA). A set of definitive tests (HELEN-FIRE) was designed to resolve this contention. Statistical analysis of the HELEN-FIRE test data, combined with phenomenological arguments supporting the results, indicate that a simplified approach to developing “realistic” or “representative” peak HRR distributions for fires in electrical enclosures is now available, requiring only that a reasonable estimate of the fuel mass (combustible loading) and split of cable class (Q and UQ) be made prior to fire modeling. The fact that there now need be only two distributions for peak HRR per fuel mass can simplify the amount of analyses needed to support fire PRAs.

Comparison of the potential effect of using this approach vs. others, such as those from NUREG/CR-6850 or NUREG-2178, cannot be performed directly unless a specific fire scenario is examined. NUREG/CR-6850 provides five distributions for peak HRR, none of which employs a quantifiable parameter other than single vs. multiple cable bundles. NUREG-2178 provides 31 distributions based on type of electrical enclosure and enclosure volume, the only potentially quantifiable parameter other than the pseudo-quantitative designations of “default,” “low” and “very low” fuel loading options. As neither method incorporates even a rough estimate of the combustible loading inside an electrical enclosure, any direct comparison is moot. Nonetheless, it suffices to say that, if a fire model of an electrical enclosure using the approach advocated here, i.e., quantifiable based on fuel loading, were compared to that from one of the other methods, it could result in a lower, equivalent or greater peak HRR depending upon which of the categories from the other approaches was assumed vs. the actual fuel loading that our approach would employ.

As a final note, caution should still be exercised when applying these distributions to ensure that they are not extrapolated too far beyond the range on which they were based, namely fuel mass up to ~12 kg. As indicated in Table I, no test involved a mass greater than 11.84 kg (Tests 61 and 63). Nonetheless, as this already represents a substantial loading and generates relatively high 98th percentile peak HRRs, often used for bounding estimates, it is expected that sufficient damage to electrical enclosures would already have occurred to threaten core damage in fire PRA applications, rendering extrapolation beyond this limit moot.

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APPENDIX

As a sensitivity study on the potential effect of door position, the results from adjusting the two distributions for qualified (Q) and unqualified (UQ) cables were compared, via scaling based on the ratio of the means for the closed and open groupings for each to the means for the overall distributions, to gamma distributions fit to the closed and open groupings in the same manner as for the overall groupings. As mentioned in Section III.a, for the closed groupings, this implied a reduction of ~20% for both Q and UQ and, for the open groupings, an increase of ~80% for Q and ~30% for UQ. The results are shown in Table A.I below. The various columns are as follows:

(U)Q (All) = kW/kg based on primary gamma distribution for cable type
(U)Q (All) Reduced = kW/kg based on adjusting (U)Q (All) by ratio of means of (U)Q (Closed) to (U)Q (All)
(U)Q (Closed) = kW/kg based on gamma distribution using only closed door position data
(U)Q (All) Increased = kW/kg based on adjusting (U)Q (All) by ratio of means of (U)Q (Open) to (U)Q (All)
(U)Q (Open) = kW/kg based on gamma distribution using only open door position data

TABLE A.I. Results from Sensitivity Study on Potential Effect of Door Position

Fractile (%ile)	Peak HRR per Unit Mass (kW/kg)									
	Q (All)	Q (All) - Reduced	Q (Closed)	Q (All) - Increased	Q (Open)	UQ (All)	UQ (All) - Reduced	UQ (Closed)	UQ (All) - Increased	UQ (Open)
0.50 (50.0%)	6.086	5.022	5.726	11.103	12.560	7.497	5.867	6.547	9.888	10.426
Mean	11.858	9.784	9.784	21.633	21.633	22.341	17.483	17.483	29.466	29.466
0.75 (75 %)	16.020	13.219	13.447	29.227	29.707	27.690	21.668	22.224	36.520	36.977
0.98 (98 %)	59.776	49.323	44.917	109.052	99.939	138.912	108.706	103.945	183.214	179.406
	Statistics and Gamma Distributional Parameters									
Mean	11.858		9.784		21.633	22.341		17.483		29.466
Std Dev	15.572		11.641		25.911	36.484		27.257		47.085
Gamma alpha	0.580		0.707		0.697	0.375		0.411		0.392
Gamma beta	20.450		13.849		31.034	59.581		42.495		75.237

For the closed groupings, the largest relative variation occurs at the 50th percentile for Q, where the peak HRR per fuel mass metric for the reduced overall distribution is ~12% lower than the corresponding value from the gamma distribution fit to the closed grouping (5.022 vs. 5.726 kW/kg). The largest absolute variation occurs at the 98th percentile for Q, where the peak HRR per fuel mass metric for the increased overall distribution is ~9 kW/kg higher than the corresponding value from the gamma distribution fit to the closed grouping (109.052 vs. 99.939 kW/kg). The remaining variations are less. By definition of the scaling, the means are the same. At the 75th percentiles, the adjusted values are practically the same as those obtained from the additional gamma fits. At the 98th percentiles, the adjusted values are slightly higher, but by no more than ~10% (Q [all] – Reduced vs. Q [Closed], 49.323 vs. 44.917 kW/kg) and the 9 kW/kg previously cited. This suggests that the simple use of just two distributions, with scaling adjustments if desired to address the potential effect of door position as a surrogate if an enclosure is confirmed to be tightly sealed, is quite practical.

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