Statistical Characterization of Heat Release Rates from Electrical Enclosure Fires for Nuclear Power Plant Applications[1]

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Abstract: 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. HRRs are an integral part of the fire phenomenological modeling phase of a fire PRA, which consists of identifying fire scenarios which can damage equipment or hinder human actions necessary to prevent core damage. Fire ignition frequency, fire growth and propagation, fire detection and suppression, and mitigating equipment and actions to prevent core damage in the event fire damage still occurred are all parts of a fire PRA. The fire growth and propagation phase incorporates fire phenomenological modeling where HRRs have a key effect. 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. Unlike NUREG/CR-6850, where five different distributions are provided, or NUREG-2178, which now provides 31, the peak HRRs for electrical enclosure fires can be characterized by only two distributions. These distributions depend only on the type of cable, namely qualified vs. unqualified, for which the mean peak HRR per unit mass is 11.3 and 23.2 kW/kg, respectively, essentially a factor of two difference. Two-sided, 90^{th} percentile confidence bounds are 0.091 to 41.15 kW/kg for qualified cables, and 0.027 to 95.93 kW/kg for unqualified cables. From the mean (~70^{th} percentile) upward, the peak HRR/kg for unqualified cables is roughly twice that that for qualified, increasing slightly with higher percentile, an expected phenomenological trend. Simulations using variable fuel loadings are performed to demonstrate how the results from this analysis may be used for nuclear power plant applications.

Keywords: Electrical Enclosures, Cable Fires, Heat Release Rates, Fire Modeling, Nuclear Power Plants

1. INTRODUCTION

[1] The views expressed herein are strictly the authors' personal ones and do not necessarily represent any opinion or position by the U.S. Nuclear Regulatory Commission.

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 to support fire probabilistic risk assessments (PRAs), 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, 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.[2]

2. 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

[2] The authors recognize that other combustible materials (e.g., circuit breakers, circuit cards) will normally be present within an electrical enclosure. Traditionally, assessment of HRRs for electrical cabinet fires in the nuclear power industry focus solely on the combustible content from cables (insulation) as this typically dominates any contribution from non-cable materials. This assumption was maintained throughout the HELEN-FIRE program and remains in effect for the analysis presented here.

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 1 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, where mass is specifically only for the insulation material, not the metallic conductors. **(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 (e.g., *http://www.physics.csbsju.edu/stats/KS-test.n.plot_form.html*) 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 1. 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***
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***

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)*
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***
41B	3	20	0	***5***	Q	Open	***232***	141	***46.400***
30	1	18	0	***1.32***	Q	Closed	***72***	59	***54.545***
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***

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)*
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***
52	4	5.5	0	***2.17***	UQ	Open	***122***	61	***56.221***
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:

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

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 $A_{twigs}/A_{log} = \sqrt{n}$. For a relatively equivalent combustible composition, 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 2. 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.

<u>TABLE 2</u>. 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	0.633	0.526
10-20	15	8	0.190	0.211
20-30	5	2	0.063	0.053
30-40	5	2	0.063	0.053
40-50	2	1	0.025	0.026
50-60	1	2	0.013	0.053
60+	1	3	0.013	0.079
Total	79	38	1	1
Mean (kW/kg)	11.296	23.233		
Std dev (kW/kg)	14.834	36.405		
Gamma Dist. alpha	0.580	0.407		
Gamma Dist. beta	19.480	57.046		

	Peak HRR/Unit Mass (kW/kg)		**Ratio UQ/Q**
Fractile (%ile)	**Q**	**UQ**	
0.005 (0.5%)	1.720E-03	9.511E-05	**0.055**
0.010 (1.0%)	5.685E-03	5.217E-04	**0.092**
0.020 (2.0%)	1.879E-02	2.861E-03	**0.152**
0.025 (2.5%)	2.762E-02	4.949E-03	**0.179**
0.050 (5.0%)	9.147E-02	2.715E-02	**0.30**
0.250 (25.0%)	1.537	1.438	**0.94**
0.500 (50.0%)	5.798	8.602	**1.48**
0.750 (75.0%)	15.262	29.457	**1.93**
0.950 (95.0%)	41.150	95.930	**2.33**

Range (kW/Kg)	Count (Q)	Count (UQ)	Q Fraction	UQ Fraction
0.975 (97.5%)	53.054	128.161	**2.42**	
0.980 (98.0%)	56.942	138.807	**2.44**	
0.990 (99.0%)	69.159	172.528	**2.49**	
0.995 (99.5%)	81.542	207.036	**2.54**	

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.

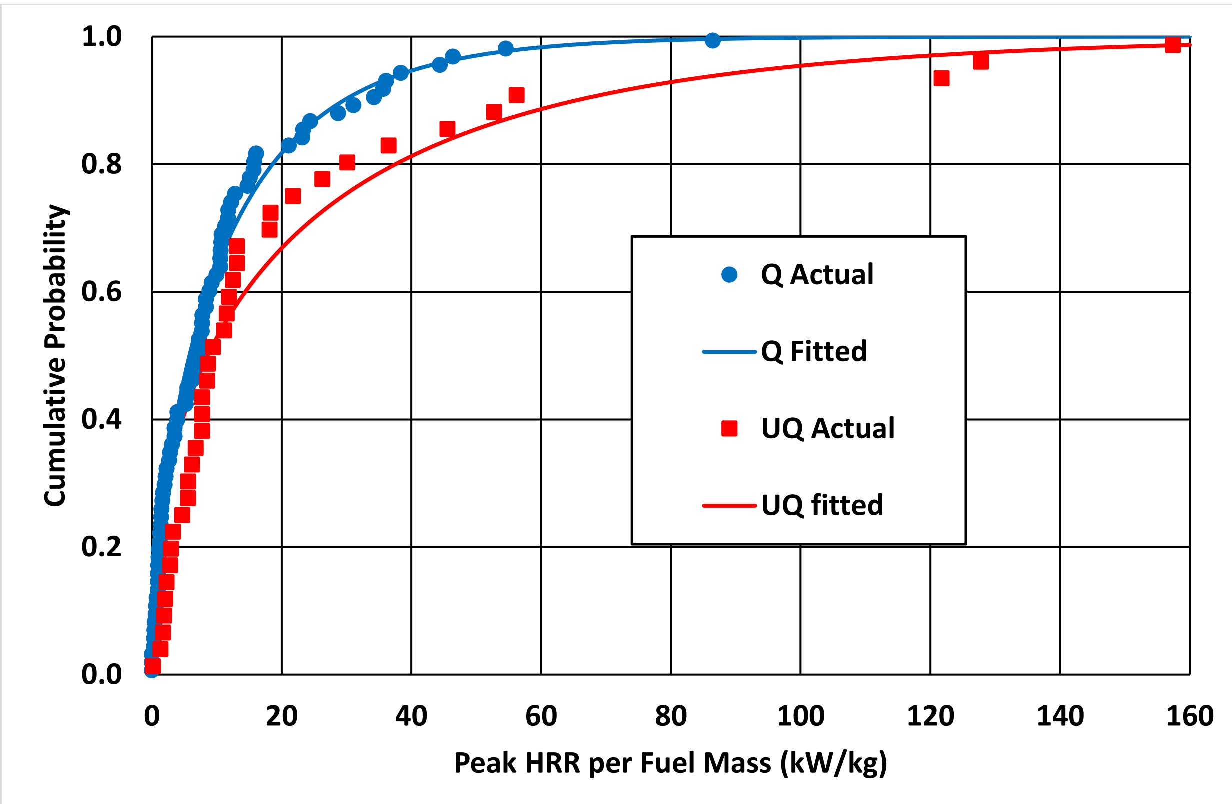

FIGURE 1. Cumulative Distribution Functions of Test Data and Gamma Distributional Fits for Both Qualified (Q) and Unqualified (UQ) Cables

3. PHENOMENOLOGY

From NUREG/CR-6850, and confirmed for the cable types tested as reported in 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).[3] 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.

[3] As demonstrated during the Fire Performance of Electric Cables (FIPEC) program, performance of cables can exhibit a wide variety of results for flame spread and HRR [15]. The types of cables cited in NUREG/CR-7010 were selected to be representative of the variety utilized in U.S. commercial nuclear power plants.

Additionally, consider two electrical enclosures loaded with equal amounts of Q and UQ cables, 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.[4]

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 3, 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 3. 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		

[4] The authors recognize that burning within an electrical enclosure will be a combination of both horizontal and vertical fire propagation. This comparison uses data only for horizontal configurations. Nonetheless, since only the relative, not absolute, burning rates are relevant for the comparison, it seems reasonable to assume that the ratios would remain at least approximately equivalent for vertical burning as for horizontal, as the composition of the combustibles remains the same.

Cable		HRR per Unit Area (kW/m^2) [Imposed Flux = 50 kW/m^2]
Number	Type	
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 2). 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.

3.1 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 1 are regrouped by door position within each cable class, the results are as shown in Table 4.

TABLE 4. 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	0	0	2
60+	0	1	1	2
Total	66	13	22	16
Mean (kW/kg)	9.784	18.973	17.483	31.138
Std Dev(kW/kg)	11.641	24.899	27.257	45.977

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 2, there is some reduction in the mean ratios for each cable type for the closed door position (13% for Q and 25% for UQ) and increase for the open door position (94% for Q and 34% 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).

4. 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 5, 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 5. 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	11.3	15.2	57.4	15.4
	All UQ	23.2	29.5	138.0	37.2
	50/50 split	17.3	23.0	79.2	21.4
5 kg (11 lb)	All Q	56.6	76.0	287.2	76.9
	All UQ	116.1	147.5	690.1	186.0
	50/50 split	86.7	114.8	396.0	107.2
10 kg (22 lb)	All Q	113.1	152.1	574.4	153.7
	All UQ	232.3	294.9	1380.1	371.9
	50/50 split	173.4	229.6	791.9	214.3

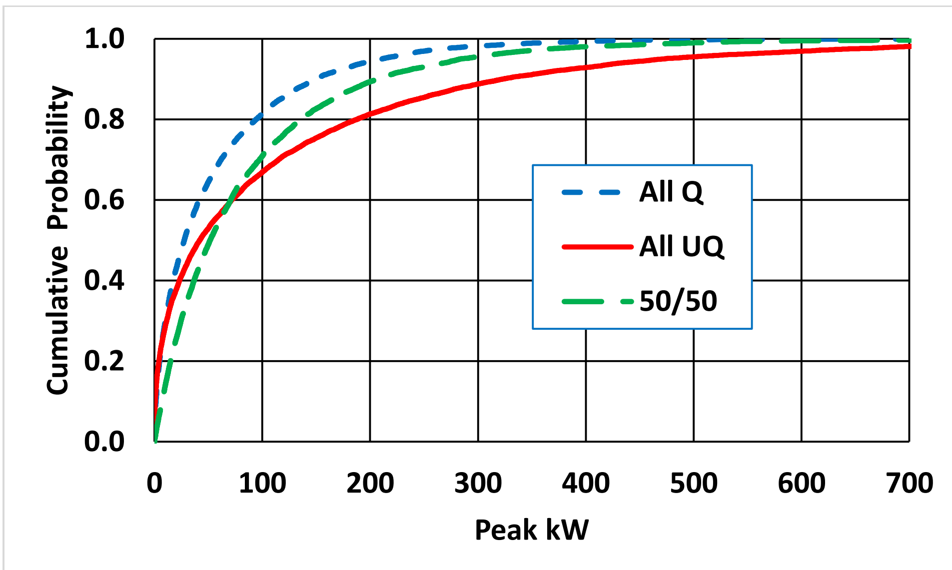

FIGURE 2. Cumulative Distribution Functions for Simulation of Peak HRR for Nominal 5-kg Fuel Mass for All Qualified (Q), All Unqualified (UQ) and Nominal 50/50 Split of Cables

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 11.3 kW for a nominal 1-kg loading of all Q to a maximum (98th percentile) of 1380.1 kW for a nominal 10-kg loading of all UQ, a factor of ~120. 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.

5. 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 1, 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 98^{th} 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.

ACKNOWLEDGMENT

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APPENDIX I
SENSITIVITY STUDY ON POTENTIAL EFFECT OF DOOR POSITION

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 3.1, for the closed groupings, this implied a reduction for the closed door position of 13% for Q and 25% for UQ, and increase for the open door position of 94% for Q and 34% for UQ). The results are shown in the table 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 6. 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%)	5.798	5.022	5.726	9.738	9.747	8.602	6.473	6.547	11.529	13.070
Mean	11.296	9.784	9.784	18.973	18.973	23.233	17.483	17.483	31.138	31.138
0.75 (75 %)	15.262	13.219	13.447	25.632	25.636	29.457	22.167	22.224	39.481	40.560
0.98 (98 %)	56.942	49.323	44.917	95.636	95.579	138.807	104.455	103.945	186.041	175.666
	Statistics and Gamma Distributional Parameters									
Mean	11.296		9.784		21.633	23.233		17.483		29.466
Std Dev	14.834		11.641		25.911	36.405		27.257		47.085
Gamma alpha	0.580		0.707		0.697	0.407		0.411		0.392
Gamma beta	19.480		13.849		31.034	57.046		42.495		75.237

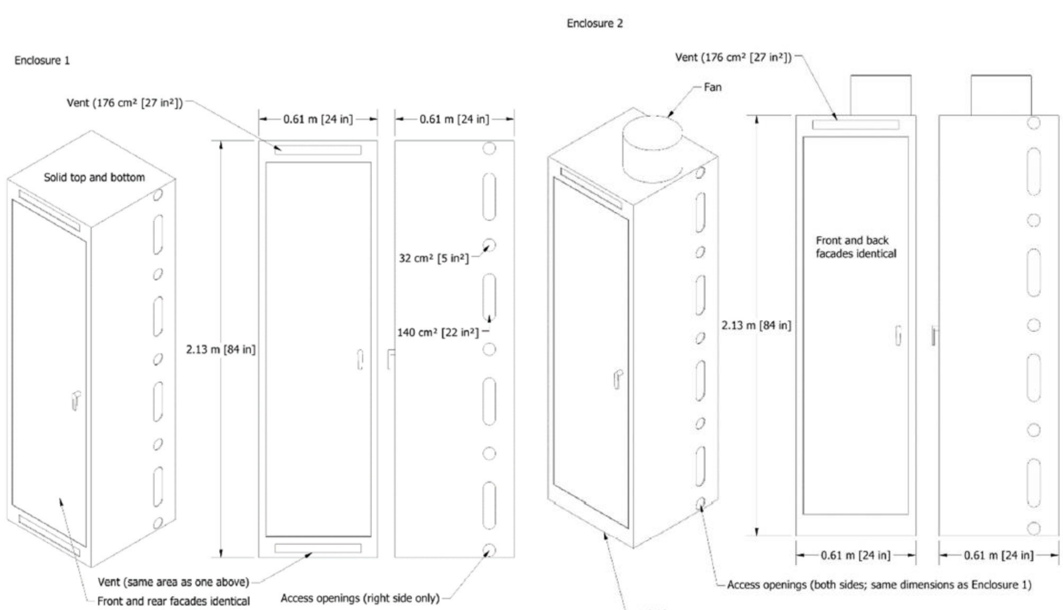
The largest relative variation occurs at the 50th percentile for Q in the closed groupings, where the peak HRR per fuel mass metric for the reduced overall distribution is ~12% lower than the corresponding value from the gamma distribution fit to the closed grouping (5.022 vs. 5.726 kW/kg). The largest absolute variation occurs at the 98th percentile for UQ in the open groupings, where the peak HRR per fuel mass metric for the increased overall distribution is ~10 kW/kg higher than the corresponding value from the gamma distribution fit to the open grouping (186.041 vs. 175.666 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 10 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.

APPENDIX II
OVERVIEW OF THE HELEN-FIRE TEST PROGRAM
(AS EXTRACTED FROM NUREG/CR-7197 [13])

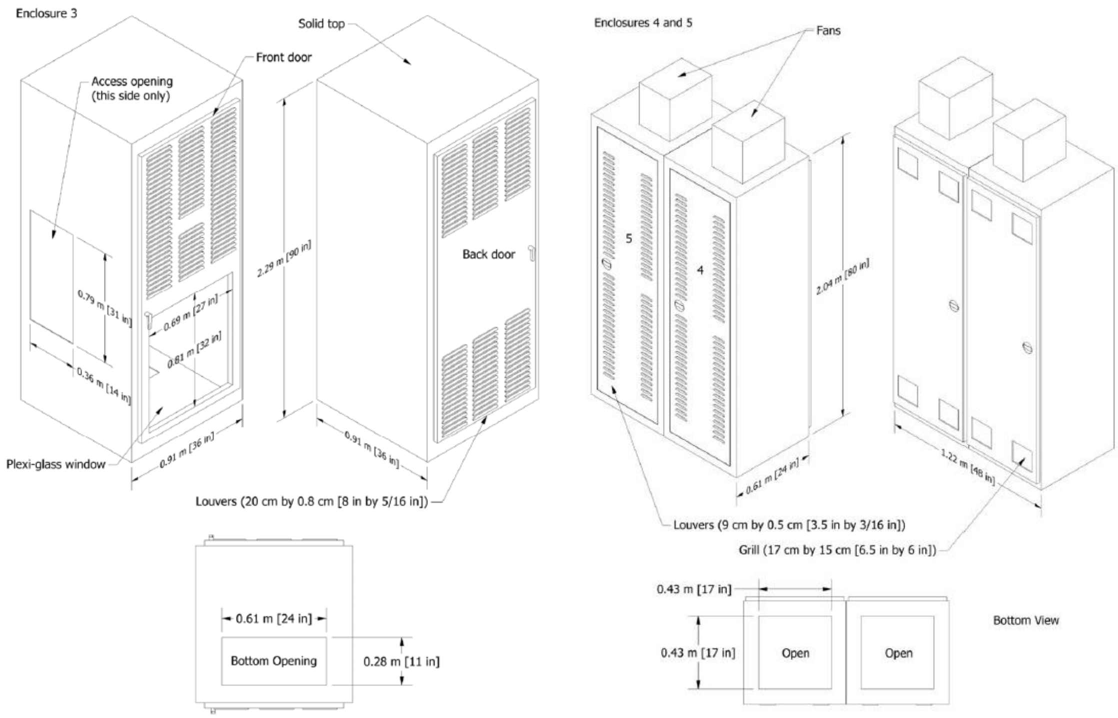
To better quantify the heat release rate (HRR) and burning behavior of electrical enclosures, 112 full-scale experiments were conducted at the Chesapeake Bay Detachment of the Naval Research Laboratory [Maryland, USA]. Eight electrical enclosures were acquired from Bellefonte Nuclear Generating Station, a plant owned by the Tennessee Valley Authority located in Hollywood, Alabama [Figures 3-8]. The enclosures were installed in the early 1980s, but the plant was never operated. The enclosures were originally low voltage control cabinets, but in the experiments they were reconfigured with various amounts and types of electrical cable to represent other kinds of enclosures that would be found in a typical plant [Figure 9 and Table 7] … An oxygen consumption calorimeter was built on site to measure the HRR of the fire as a function of time. Of particular interest is the peak HRR, the time to peak, and the total energy released. Thermocouples were positioned at various heights within the enclosures to monitor internal temperatures.

The … Chesapeake Bay Detachment of the Naval Research Laboratory … has a large-scale calorimeter that is nominally 6.1 m by 6.1 m (20 ft by 20 ft), designed to measure the HRR of fires ranging from *approximately 100 kW to 10 MW. However, its instruments are not sensitive enough to measure accurately the HRR of the small fires that were expected in many of the enclosure experiments. For this reason, a smaller calorimeter (see Figure 10) was built to fit underneath the large hood (see Figure 11). The smaller hood was 2.4 m by 2.4 m (8 ft by 8 ft), and 2.4 m (8 ft) off the floor. Its 46 cm (18 in) duct was instrumented with a Rosemount Annubar® to measure the volume flow, four thermocouples to measure the gas temperature, and a gas extraction tube to measure the oxygen concentration of the exhaust gases. The instruments were located approximately 4 m (13 ft) from the vertical centerline of the hood … Three types of ignition sources were used in the experiments: cartridge heaters, line burners, and pans of liquid fuel. A cartridge heater is a surrogate for an over-heated electrical component or cable. The line burner is a surrogate for a small fire that could result from an over-heated wire or component. The pan fire is a surrogate for a relatively large fire whose origin is difficult to specify exactly, but most likely due to an event such as a high energy arc fault or similar malfunction resulting in the ignition of a relatively large amount of combustible material.*

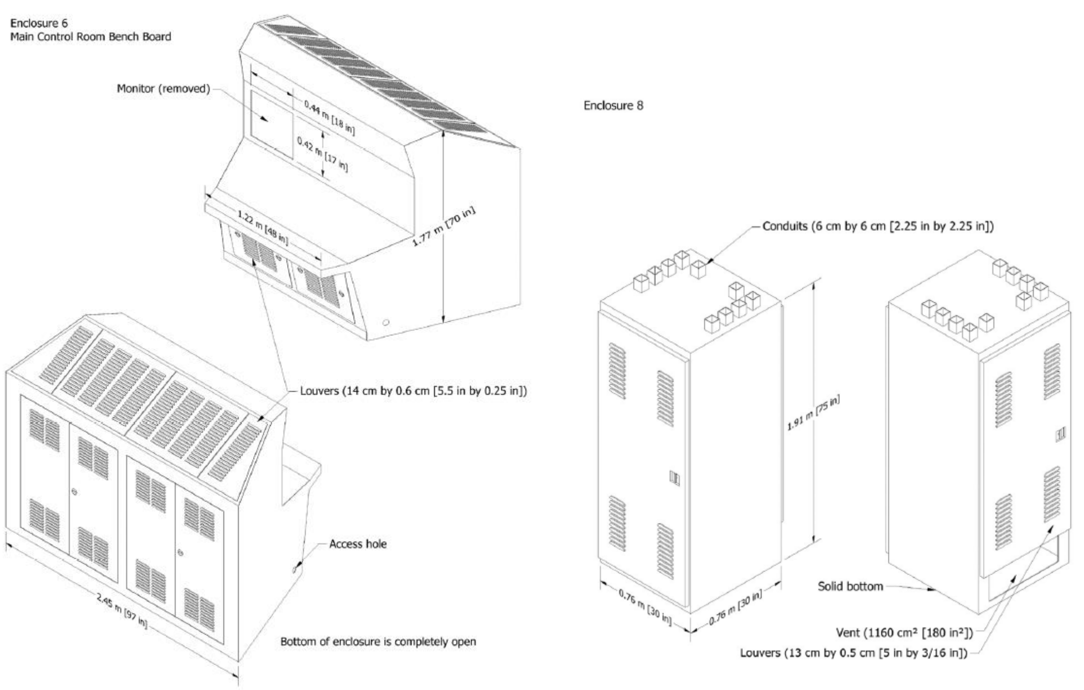
The experiments were conducted from late October of 2013 through early March of 2014 … The facility was not heated, and temperatures ranged from approximately 0°C (32°F) to 20°C (68°F). Typically, electrical enclosures are operated at 32°C (90°F), but in the experiments, the enclosures were not powered. For some experiments, a pan of ethanol or acetone was placed at the base of the enclosure away from the combustibles to raise the interior enclosure temperature. These same pans of alcohol were sometimes used to ignite the combustibles directly … The propane line burner was typically positioned within a bundle of cable as if it were just another cable. Wire was used to hold the burner firmly in place. The exact placement of the burner varied from test to test, and there was no particular emphasis on a "standard" ignition system. Rather, the burner position and HRR were varied as would be expected in actual fire events. The cables and wiring were not installed in a particularly systematic way either. Typically, bundles of cables would be hung using wires on either the left or right side of the enclosure, as had been observed in enclosures found on the plant visits. Sometimes the cables and/or individual conductors would be tightly bundled using plastic wire or "zip ties," and at other times they would be left to hang in no particular arrangement. It was observed that "loose" or non-bundled cables or wires led to higher HRRs, even though bundling was necessary to accumulate enough combustible mass in the vicinity of the igniter to facilitate fire spread. The total combustible mass refers to the mass of cable jacketing and insulation material derived from the measured length of cable multiplied by the mass of non-metallic materials per unit length …



<u>FIGURES 3-4</u>. Enclosure Types 1 and 2 Tested in HELEN-FIRE



FIGURES 5-6. Enclosure Types 3 through 5 Tested in HELEN-FIRE

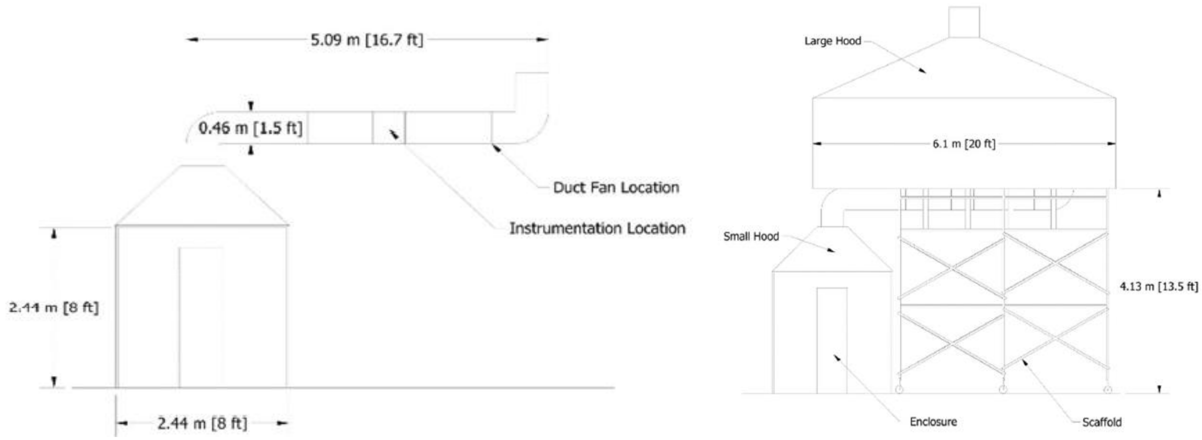


FIGURES 7-8. Enclosure Types 6 through 8 Tested in HELEN-FIRE
(Type 7 not shown, as it is very similar to Type 6)

FIGURE 9. Photos of Electrical Cables Tested in HELEN-FIRE

TABLE 7. Properties of Electrical Cables Tested in HELEN-FIRE

Insulation Material	Jacket Material	Class.	Conductors	Diameter (mm)	Jacket Thickness (mm)	Insulator Thickness (mm)	Mass per Length (kg/m)	Copper Mass Fraction	Jacket Mass Fraction	Insulation Mass Fraction	Filler Mass Fraction
Tefzel®		TP	7	10.2	0.76	0.45	0.29	0.74	0.08	0.15	0.02
PE	PVC	TP	7	14.0	1.54	0.27	0.37	0.59	0.24	0.15	0.01
SR	Aramid Braid	TS	7	14.5	1.21	1.10	0.35	0.62	0.08	0.31	0.01
XLPE	CSPE	TS	12	12.7	1.46	1.18	0.25	0.37	0.33	0.29	0.01
PVC	PVC	TP	12	11.3	1.15	0.54	0.19	0.56	0.03	0.40	0.00
XLPE	CSPE	TS	2	7.8	1.64	0.92	0.11	0.24	0.58	0.15	0.00
PE	PVC	TP	1	6.3	1.35	1.41	0.06	0.38	0.40	0.07	0.15
XLP	CPE	TS	3	17.1	3.06	1.74	0.44	0.52	0.33	0.13	0.02
SIS	TS	TS	1	3.6	0.00	1.25	0.03	0.65	0.00	0.35	0.00
Unknown	Unknown	Unknown	1	6.8	0.98	2.34	0.08	0.41	0.37	0.21	0.01
Unknown	Unknown	Unknown	1	4.7	N/A	1.74	0.05	0.63	0.00	0.37	0.00
XLPE	No Jacket	TS	1	4.0	N/A	1.98	0.04	0.73	0.00	0.27	0.00
SR	Aramid Braid	TS	1	3.64	0.44	1.47	0.02	0.46	0.13	0.41	0.00
XLPE	CSPE	TS	2	8.6	2.60	1.48	0.11	0.31	0.46	0.13	0.10
XLPE	CSPE	TS	4	16.9	2.86	1.48	0.38	0.19	0.53	0.07	0.20
XLPE	CSPE	TS	6	18.4	2.86	1.48	0.46	0.24	0.55	0.09	0.12
XLPE	CSPE	TS	8	19.8	2.86	1.48	0.55	0.29	0.53	0.11	0.07
XLPE	CSPE	TS	10	23.4	3.65	1.48	0.77	0.24	0.63	0.08	0.05
TPE	TPE	TP	3	13.5	2.08	1.19	0.12	0.29	0.50	0.15	0.06
Unknown	Unknown	Unknown	40	1.2	N/A	N/A	0.08	--	--	--	--
Unknown	Unknown	Unknown	352	36.1	N/A	N/A	2.86	--	--	--	--
PVC	PVC	TP	3	10.2	01.80	0.76	0.17	0.47	0.33	0.18	0.03
EP	TS	TS	1	5.9	0	2.10	0.08	0.60	0.40	0.00	0.00



<u>FIGURES 10-11</u>. Schematic Diagram of Small Calorimeter, with Location beneath the Large Hood

APPENDIX III
ALIGNMENT WITH HRR DISTRIBUTIONS FROM RACHELLE-FIRE [10]

In the spirit of NUREG/CR-6850, the NRC Office of Nuclear Regulatory Research (RES) and Electric Power Research Institute (EPRI) developed a new set of HRR distributions from electrical enclosure fires by reviewing not only the results from HELEN-FIRE, but also those from the previous series of tests used to develop the original NUREG/CR-6850 default HRRs as well as the methods in EPRI 1022993. The results of this effort were published in NUREG-2178 (EPRI 3002005578), *<u>R</u>efining <u>a</u>nd <u>C</u>haracterizing <u>H</u>eat Release Rates from <u>El</u>ectrica<u>l</u> <u>E</u>nclosures during <u>Fire</u>* (RACHELLE-FIRE) in 2015. [10] Using an elicitation process via an ad hoc working group in a manner intended to parallel that employed to develop the original HRR distributions for NUREG/CR-6850, a panel of NRC-RES, EPRI, nuclear industry and contractor staff developed 31 HRR distributions for various electrical enclosure classes and functional groups, considering three levels of fuel loading: default (presumed to be conservative), low and very low. Details and descriptions of these categories and the elicitation approach are beyond the scope of this Addendum, which examines only the results in light of the distributions based on HRR per fuel mass developed in the main body of the paper. The goal is to determine whether the RACHELLE-FIRE distributions would predict results consistent with those from the analysis of the HELEN-FIRE data.

As shown in the Table below, RACHELLE-FIRE reports 31 HRR distributions via the gamma parameters α and β (from which the mean can be calculated as the product) and the 75th and 98th %iles (non-italicized columns). From these, the corresponding fuel masses (combustible loadings) that would generate each of these values (mean, 75th and 98th %iles) were "back-calculated" using the HRR/mass (kW/kg) for the corresponding three %iles as derived from the gamma distributions in the main body of this paper for qualified (assumed to correspond to TS) and unqualified cables (assumed to correspond to TP). (Note that "qualification" is not a function of whether or not a cable is classified as TS or TP. This is based on performance in the IEEE 383 or 1202 flame spread tests… Nonetheless, since most TS cables are "qualified" and many TP are not, this designation is applied here.) These are shown in the *italicized* columns labeled "Load." Finally, for each row entry, the average and standard deviation of the three loads were calculated, as shown in the ***bold italicized*** last two columns.

Three trends should be noted if using the RACHELLE-FIRE distributions for predictive purposes. First, for every entry (other than 4c, where TS and TP are combined), the average load for UQ (TP) would always be lower than that for Q (TP). If one were comparing equivalent electrical enclosures where the fuel mass per enclosure class/function group would be expected to be the same regardless of the cable class, this trend suggests that (1) the HRRs for UQ (TP) cables could be systematically underestimated or (2) the HRRs for

Q (TS) cables could be systematically overestimated.[5] One possible reason for this derives from a statement in RACHELLE-FIRE itself, whereby the panel cites that "[w]ithin a given enclosure group, the TS/QTP [qualified thermoplastic]/SIS [Switchboard Wire or XLPE-Insulated Conductor] and unqualified TP peak HRR distributions generally have the same value for the 98th percentile (with the exception of 4a – large/open/default) … [i]n general, the working group established the same 98th percentile peak HRR value for both cable types (with the exception of large open enclosures)." However, the group also noted that "[w]ithin a given enclosure group, the 75th percentile value for the TS/QTP/SIS type is generally one-half the value assigned for the 75th percentile in the corresponding unqualified TP type," which is consistent with the trend seen for qualified vs. unqualified cables based on HRR/mass, given equal fuel mass.[6] With such constraints on the distributional range and shape, it is not surprising that a systematic variation may have occurred.

The second trend is highlighted by the shaded entries in the table. These represent cases where the standard deviation is at least 25% (and in a few cases 50%) of the value of the average, indicating wide variability in the "back-calculated" fuel masses. This likely results from the construction (or constraining) of the gamma distributions for these entries, each of which may be worth re-examination for consistency. Finally, note the minimum and maximum "back-calculated" average fuel masses, 0.45 and 8.40 kg. While the maximum is fairly consistent with the maximum examined in the main body of the paper (10 kg), the minimum is over half as low as the 1-kg minimum examined in the main body. Yet the range of postulated HRRs by the working group, from the 12-kW means for the 4b Medium and 4c Small Enclosures to the 1000-kW 98th %ile for the 4a Large Enclosure with UQ (TP) cables (default), is comparable to that from the simulated results in the main body of the paper (11.3 kW to 1380.1 kW). Therefore, one would expect the "back-calculated" fuel masses to show consistency within each category (first trend) and among the gamma distribution %iles (second trend).

Unlike the analysis done in the main body of the paper solely based on the HELEN-FIRE data, the panel reconsidered much of the data from the earlier tests that resulted in the allegedly "too conservative" HRRs in NUREG/CR-6850 and the non-endorsed method from EPRI 1022993. Data from HELEN-FIRE were considered on a selective basis, not *in toto*. Is the justification for reconsidering the non-HELEN-FIRE data, questioned in the earlier efforts, supported by the working group judgment? The degree of subjectivity that may have entered into the development of the RACHELLE-FIRE HRR distributions, given the apparent success from analyzing solely the HELEN-FIRE data, suggests re-examination of the RACHELLE-FIRE HRR distributions.

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5 Or a combination of both.

6 Note that not only the analysis of the HELEN-FIRE data, but also the phenomenological arguments in the main body of this paper, indicate this ratio of approximately two for unqualified vs. qualified HRRs is not only maintained, but also increases, with higher percentiles of the HRR distributions, contrary to the constraint imposed in RACHELLE-FIRE.

Encl. Class/ Func. Group	Vent	Fuel	Alpha	Beta	*Mean*	***Load-Mn (kg)***	**75%**	**98%**	***Load-75 (kg)***	***Load-98 (kg)***	***Avg (kg)***	***StDv (kg)***
1 - SWGR and Load Centers	**closed**	**Q (TS)**	0.32	79	*25.28*	*2.24*	30	170	*1.97*	*2.99*	***2.40***	***0.53***
		UQ (TP)	0.99	44	*43.56*	*1.88*	60	170	*2.04*	*1.22*	***1.71***	***0.43***
2 - MCCs and Battery Chargers	**closed**	**Q (TS)**	0.36	57	*20.52*	*1.82*	25	130	*1.64*	*2.28*	***1.91***	***0.33***
		UQ (TP)	1.21	30	*36.30*	*1.56*	50	130	*1.70*	*0.94*	***1.40***	***0.41***
3 - Power Inverters	**closed**	**Q (TS)**	0.23	111	*25.53*	*2.26*	25	200	*1.64*	*3.51*	***2.47***	***0.95***
		UQ (TP)	0.52	73	*37.96*	*1.63*	50	200	*1.70*	*1.44*	***1.59***	***0.13***
4a - Large Enclosures >1.42 m^3 [50 ft^3] (default)	**closed**	**Q (TS)**	0.23	223	*51.29*	*4.54*	50	400	*3.28*	*7.02*	***4.95***	***1.91***
		UQ (TP)	0.52	145	*75.40*	*3.25*	100	400	*3.39*	*2.88*	***3.17***	***0.26***
	open	**Q (TS)**	0.26	365	*94.90*	*8.40*	100	700	*6.55*	*12.29*	***9.08***	***2.93***
		UQ (TP)	0.38	428	*162.64*	*7.00*	200	1000	*6.79*	*7.20*	***7.00***	***0.21***
4a - Large Enclosures >1.42 m^3 [50 ft^3] (low)	**closed**	**Q (TS)**	0.23	25	*5.75*	*0.51*	25	200	*1.64*	*3.51*	***1.89***	***1.52***
		UQ (TP)	0.52	50	*26.00*	*1.12*	50	200	*1.70*	*1.44*	***1.42***	***0.29***
	open	**Q (TS)**	0.26	50	*13.00*	*1.15*	50	350	*3.28*	*6.15*	***3.52***	***2.51***
		UQ (TP)	0.38	100	*38.00*	*1.64*	100	500	*3.39*	*3.60*	***2.88***	***1.08***
4a - Large Enclosures >1.42 m^3 [50 ft^3] (very low)	**closed**	**Q (TS)**	0.38	15	*5.70*	*0.50*	15	75	*0.98*	*1.32*	***0.93***	***0.41***
		UQ (TP)	0.88	25	*22.00*	*0.95*	25	75	*0.85*	*0.54*	***0.78***	***0.21***
	open	**Q (TS)**	0.38	15	*5.70*	*0.50*	15	75	*0.98*	*1.32*	***0.93***	***0.41***
		UQ (TP)	0.88	25	*22.00*	*0.95*	25	75	*0.85*	*0.54*	***0.78***	***0.21***
4b - Medium Enclosures ≤1.42 m^3 [50 ft^3] (default)	**closed**	**Q (TS)**	0.23	111	*25.53*	*2.26*	25	200	*1.64*	*3.51*	***2.47***	***0.95***
		UQ (TP)	0.52	73	*37.96*	*1.63*	50	200	*1.70*	*1.44*	***1.59***	***0.13***
	open	**Q (TS)**	0.23	182	*41.86*	*3.70*	40	325	*2.62*	*5.71*	***4.01***	***1.57***
		UQ (TP)	0.51	119	*60.69*	*2.61*	80	325	*2.72*	*2.34*	***2.56***	***0.19***
4b - Medium Enclosures ≤1.42 m^3 [50 ft^3] (low)	**closed**	**Q (TS)**	0.27	51	*13.77*	*1.22*	15	100	*0.98*	*1.76*	***1.32***	***0.40***
		UQ (TP)	0.52	36	*18.72*	*0.81*	25	100	*0.85*	*0.72*	***0.79***	***0.07***
	open	**Q (TS)**	0.19	92	*17.48*	*1.55*	15	150	*0.98*	*2.63*	***1.72***	***0.84***
		UQ (TP)	0.30	72	*21.60*	*0.93*	25	150	*0.85*	*1.08*	***0.95***	***0.12***
4b - Medium Enclosures ≤1.42 m^3 [50 ft^3] (very low)	**closed**	**Q (TS)**	0.88	12	*10.56*	*0.93*	15	45	*0.98*	*0.79*	***0.90***	***0.10***
		UQ (TP)	0.88	12	*10.56*	*0.45*	15	45	*0.51*	*0.32*	***0.43***	***0.10***
	open	**Q (TS)**	0.88	12	*10.56*	*0.93*	15	45	*0.98*	*0.79*	***0.90***	***0.10***
		UQ (TP)	0.88	12	*10.56*	*0.45*	15	45	*0.51*	*0.32*	***0.43***	***0.10***
4c - Small Enclosures >0.34 m^3 [12 ft^3]	**n/a**	**TS/TP***	0.88	12	*10.56*	*0.61*	15	45	*0.67*	*0.46*	***0.58***	***0.11***
* For these, the average corresponding HRR/load for Q and UQ was used: 0.5 x [HRR(Q)+HRR(UQ)]					min	*0.45*			*0.51*	*0.32*	***0.43***	
					max	*8.40*			*6.79*	*12.29*	***9.08***	

Light Grey - StDv > 25% of Avg
Dark Grey - StDv > 50% of Avg

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HEAT RELEASE RATES FOR NUCLEAR POWER PLANT ELECTRICAL ENCLOSURE FIRES

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BACKGROUND (1)

- Since publication of NUREG/CR-6850 / EPRI (Electric Power Research Institute) 1011989 in 2005 (*Fire PRA Methodology for Nuclear Power Facilities*), the nuclear industry has sought to re-evaluate the default peak heat release rates (HRRs) and their distributions for electrical enclosure fires, which are typically used as fire modeling inputs to support fire probabilistic risk assessments (PRAs), considering them too conservative.
  - EPRI 1022993 (with Science Applications International Corporation [SAIC]), *Evaluation of Peak Heat Release Rates in Electrical Cabinet Fires,* in 2012 offered an analytical method built on existing test results.
  - US NRC did not endorse, citing a need for "… significant additional data … to develop improved guidance on electrical cabinet HRR … [which] are unlikely to be found in available literature."

BACKGROUND (2)

- NRC, in conjunction with the National Institute of Standards and Technology (NIST), in 2013-14 tested representative nuclear power plant electrical enclosure fires to establish more realistic peak HRRs.
  - Eight electrical enclosures from a never operated plant were tested and then reconfigured with varying amounts and types of electrical cables to represent typical configurations at nuclear power plants.
  - Each enclosure was situated beneath a mid-scale calorimeter designed to measure HRRs from ~100 kW to 10 MW, further located beneath a large hood to measure exhaust volume flow, gas temperature and oxygen concentration.
  - NUREG/CR-7197, *Heat Release Rates of Electrical Enclosure Fires (HELEN-FIRE)*, published in 2015.

OUTLINE

- Statistically analyze HELEN-FIRE test results to develop two probabilistic distributions for peak HRR per unit mass of fuel that refine the values from NUREG/CR-6850 and provide a simple way to estimate peak HRRs from electrical enclosure fires for fire PRA.
- Additionally, perform simple simulations for variable fuel loadings to demonstrate the use in nuclear power plant applications.

CABLE TYPES (1)

- "Qualified" cable has passed the IEEE (Institute of Electrical and Electronics Engineers)-383 flame spread test and corresponds to cables with thermoset (TS) insulation. "Unqualified" has not and corresponds to cables with thermoplastic (TP) insulation.
  - TP jacketing materials for conductors consist of polymers that can be deformed and/or liquefied when heated, then cooled down to solid form. These "melt."
  - TS jacketing utilizes polymers which cannot be deformed or liquefied, have better mechanical properties, are stiffer and can withstand higher temperatures for longer times. These "char."

CABLE TYPES (2)

- Temperature where fire-induced electrical failure occurs is higher for TS than TP cables.
- Flame spread across TP cables is roughly triple that across TS cables.
- TP cable exhibits HRRs per unit area roughly twice that of TP.
  - Expected peak HRRs for qualified (i.e., mainly TS) cables should be less than for unqualified (i.e., mainly TP) cables.

HELEN-FIRE TESTS (1)

- Key variables per enclosure type:
  - Ignition HRR (kW)
  - Pre-heat HRR (if applied to "warm up" cables, kW)
  - Fuel mass (kg)
  - Cable type (Qualified [Q] vs. Unqualified [UQ])
  - Cabinet door position (open vs. closed)
  - Peak HRR (kW)
  - Total energy release (MJ)

Test #	Enclosure Type	Ignition HRR (kW)	Pre-heat HRR (KW)	Fuel Mass (kg)	Cable Type	Door Position	Peak HRR (kW)	Total energy release (MJ)
22B	1	0.7	16	2.87	Q	Closed	11.3	17
96	6	5.5	21	5.37	UQ	Closed	33	47
Etc.	1-8	0.7-35	0-26	0.73-11.8	Q/UQ	Open/ Closed	0-577	3-152

HELEN-FIRE TESTS (2)

- 117 tests with recorded fuel mass.
- Several iterations of Kolmogorov-Smirnov (K-S) pairwise comparisons for poolability of data sets were performed against the various parameters.
- Most practical and statistically meaningful metric determined to be peak HRR per fuel mass (combustible loading), i.e., kW/kg, from shaded columns in previous slide.
  - Sorted into two groups: Q vs. UQ cables.

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HRR/MASS AS METRIC

- Logical metric given similar composition – batches of cables with reasonably equivalent radii (r) contained in metal enclosures.
  - HRR is proportional to exposed surface area (A)
    - For cylindrical cables of length h with homogeneous mass density ρ, HRR is proportional to the mass (M):
      - $M = \rho \pi r^2 h \rightarrow h = M/\rho \pi r^2$
      - $A = 2\pi r h = 2M/\rho r$
    - Since radius and density are approximately constant, the proportionality with M dominates.

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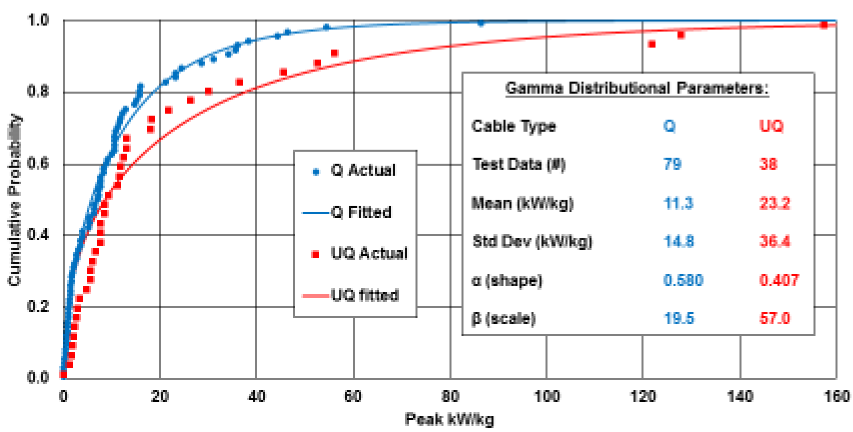
PEAK HRR/MASS DISTRIBUTIONS



PHENOMENOLOGY (1)

- From analysis, the UQ peak HRR/kg from mean (~70th %ile) upward is roughly twice that of Q. Expected, due to (1):
  - TP lengthwise burning rate (corresponding to UQ) is triple that for TS (corresponding to Q).
    - As cylindrical cable burns, expect rate of fire propagation along surface (axially lengthwise) to dominate over "downward" rate (radially inward). 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 HELEN-FIRE test cables were not completely exposed, 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.

PHENOMENOLOGY (2)

- From analysis, the UQ peak HRR/kg from mean (~70th %ile) upward is roughly twice that of Q. Expected, due to (2):
  - For two electrical enclosures with equal amounts of Q and UQ cable, equal physical dimensions and installed in an equivalent manner, if peak HRR occurs when entire exposed cable surface is burning, ratio of the peak HRRs should be roughly equal to HRR per unit area (q') ratio for each type.
    - NUREG/CR-7010 (*Cable Heat Release, Ignition and Spread in Horizontal Trays*) recommends HRRs per unit area from 100 to 200 kW/m^2 for TS and from 200 to 300 kW/m^2 for TP cables, with point estimates at 150 and 250 kW/m^2, respectively.
    - The ratio q'(UQ)/q'(Q) would extend from 1 (lowest q'[UQ] = 200 divided by highest q'[Q] = 200) to 3 (highest q'[UQ] = 300 divided by lowest q'[Q] = 100), with a mean ratio of 250/150 = 1.67 ≈ 2.

PHENOMENOLOGY (3)

- From analysis, the UQ peak HRR/kg from mean (~70th %ile) upward is roughly twice that of Q. Expected, due to (3):
  - NUREG/CR-7010 HRRs per unit area are on a fixed heat flux of 50 kW/m^2. For nine TS cables, the average = 107.7 kW/m^2. For the one TP cable it is 184 kW/m^2. An estimate of the ratio for UQ (TP) vs. Q (TS) becomes 184/107.7 = 1.7.
  - Because UQ release heat more rapidly than Q cables, heat flux inside a UQ-filled enclosure is expected to be somewhat higher than for one that is Q-filled, given equal loadings, suggesting a higher ratio of the peak HRRs per unit area.
    - An upper bound estimate is obtained using the HRR per unit area for same 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 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.

PHENOMENOLOGY (4)

- Three simplistic estimates are consistent with the analytical results from the HELEN-FIRE data, i.e., a mean ratio of q'(UQ)/q'(Q) ≈ 2 for equal fuel mass.
  - The analysis directly compares HELEN-FIRE test data; most, if not all, of the fires were too small to consume more O_2 than available via in-leakage or openings.
    - There is no attempt to extract additional effects from the data, such as (1) oxygen-limited combustion due to robustly secured/sealed enclosures, or restricted or fuel-limited conditions; (2) tightly-bundled cabling. Nor did recorded HRRs distinguish how much of the available fuel was consumed.

EFFECT OF DOOR POSITION? (1)

- Door position (open vs. closed) was expected to significantly affect the HRRs, so many tests included change in door position during a single or across multiple tests.
  - In all but a few cases, the effect was nominal or occurred after the peak HRR had already been reached; therefore, one could not assess the role of ventilation from this set of data.
    - For example, a test described as door-closed had another large opening or the door was opened during the test.
  - Nonetheless, supplementary analysis for peak HRR per fuel mass at least suggests a difference based on reported door position.

EFFECT OF DOOR POSITION? (2)

- When regrouped by door position, most of the peak HRR per fuel mass ratios remain in the lower ranges independent from door position. However, there is some reduction in the mean ratios for each cable type for the closed door position (13% for Q and 25% for UQ) and increase for the open door position (94% for Q and 25% 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.

EFFECT OF DOOR POSITION? (3)

- Compare two tests with equivalent cable type and fuel mass with high peak HRRs, i.e., Test #68 (peak HRR = 216 kW, UQ cable) to Test #83 (577 kW, UQ cable).
  - To the extent that closed door position serves as a surrogate for a "tightly-sealed" enclosure, reduction of up to roughly a factor of two for peak HRR per fuel mass may be appropriate.

SIMULATION (1)

- Perform simple simulations for each cable class and a composite consisting of an equal split of classes:
  - Fuel mass per-unit (kg) was assumed to be uniformly distributed from 0.5 to 1.5 kg, with mean = 1.0 kg, thereby enabling simple scaling to any combustible loading.
    - For the composite case, the nominal loading of half Q and half UQ cables was assumed to vary uniformly from 25% Q/75% UQ to 75% Q/25% UQ.
    - 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.
  - Ten thousand trials were run for each of the three 1-kg cases, including illustrative scaling for nominal loadings of 5 and 10 kg.

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SIMULATION (2)

Fuel Mass	Cable Class(es)	Mean (kW)	75th %ile (kW)	98th %ile (kW)	Std Dev (kW)
1 kg (2.2 lb)	All Q	11.3	15.2	57.4	15.4
	All UQ	23.2	29.5	138.0	37.2
	50/50 split	17.3	23.0	79.2	21.4
5 kg (11 lb) [scaled]	All Q	56.6	76.0	287.2	76.9
	All UQ	116.1	147.5	690.1	186.0
	50/50 split	86.7	114.8	396.0	107.2
10 kg (22 lb) [scaled]	All Q	113.1	152.1	574.4	153.7
	All UQ	232.3	294.9	1380.1	371.9
	50/50 split	173.4	229.6	791.9	214.3

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SIMULATION (3)

- The approximate 2:1 ratio for UQ vs Q HRR (given equal fuel mass) is evident for the mean and two upper %iles.
- HRRs range from a low (mean) of 11.3 kW for a nominal 1-kg loading of all Q to a maximum (98th %ile) of 1380.1 kW for a nominal 10-kg loading of all UQ, factor of ~120.
  - From 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 %ile for a vertical cabinet with UQ cables, open doors and fire in multiple bundles (a factor of ~20).

SIMULATION (4)

- This suggests a 1-kg loading may be somewhat unrealistic as a minimum or such a low loading, if not unrealistic, was possibly dismissed in NUREG/CR-6850.
  - Nonetheless, alignment with the HRRs from NUREG/CR-6850 remains possible for higher loadings.
- Considering that fires are often detected and extinguished before reaching peak HRR potential, or fuel within an enclosure is not configured to support total consumption, it may be easier to understand why operating experience might not reflect common occurrence of large thermal fires, as often contended.

CONCLUSION

- Considerable effort to analytically lower the default HRRs from NUREG/CR-6850 for use in bounding fire modeling and fire PRA has proven unsuccessful.
- Statistical analysis of a set of definitive tests (HELEN-FIRE), combined with supporting phenomenological arguments, yields a simplified approach to develop "realistic" or "representative" peak HRR distributions for electrical enclosure fires at nuclear power plants.
  - It requires only a reasonable estimate of the fuel mass (combustible loading) and split of cable class (Q and UQ) prior to fire modeling.
  - Only two distributions for peak HRR per fuel mass greatly simplifies the amount of analyses needed for fire PRAs.