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HEAT RELEASE RATES FOR NUCLEAR POWER PLANT ELECTRICAL ENCLOSURE FIRES

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ANS PSA 2017: Sept. 24-28, 2017; Pittsburgh

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BACKGROUND

- In 2005, NUREG/CR-6850 / EPRI (Electric Power Research Institute) 1011989 (*Fire PRA Methodology for Nuclear Power Facilities*) established default peak heat release rates (HRRs) and their distributions for electrical enclosure fires
  - In 2012, EPRI 1022993, *Evaluation of Peak Heat Release Rates in Electrical Cabinet Fires,* 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."
- 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.
  - 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.

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CABLE TYPES

- "Qualified" cable has passed the IEEE-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 can be deformed and/or liquefied when heated, then cooled down to solid form. These "melt."
  - TS jacketing cannot be deformed or liquefied, have better mechanical properties, are stiffer and can withstand higher temperatures for longer times. These "char."
- 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

- 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)

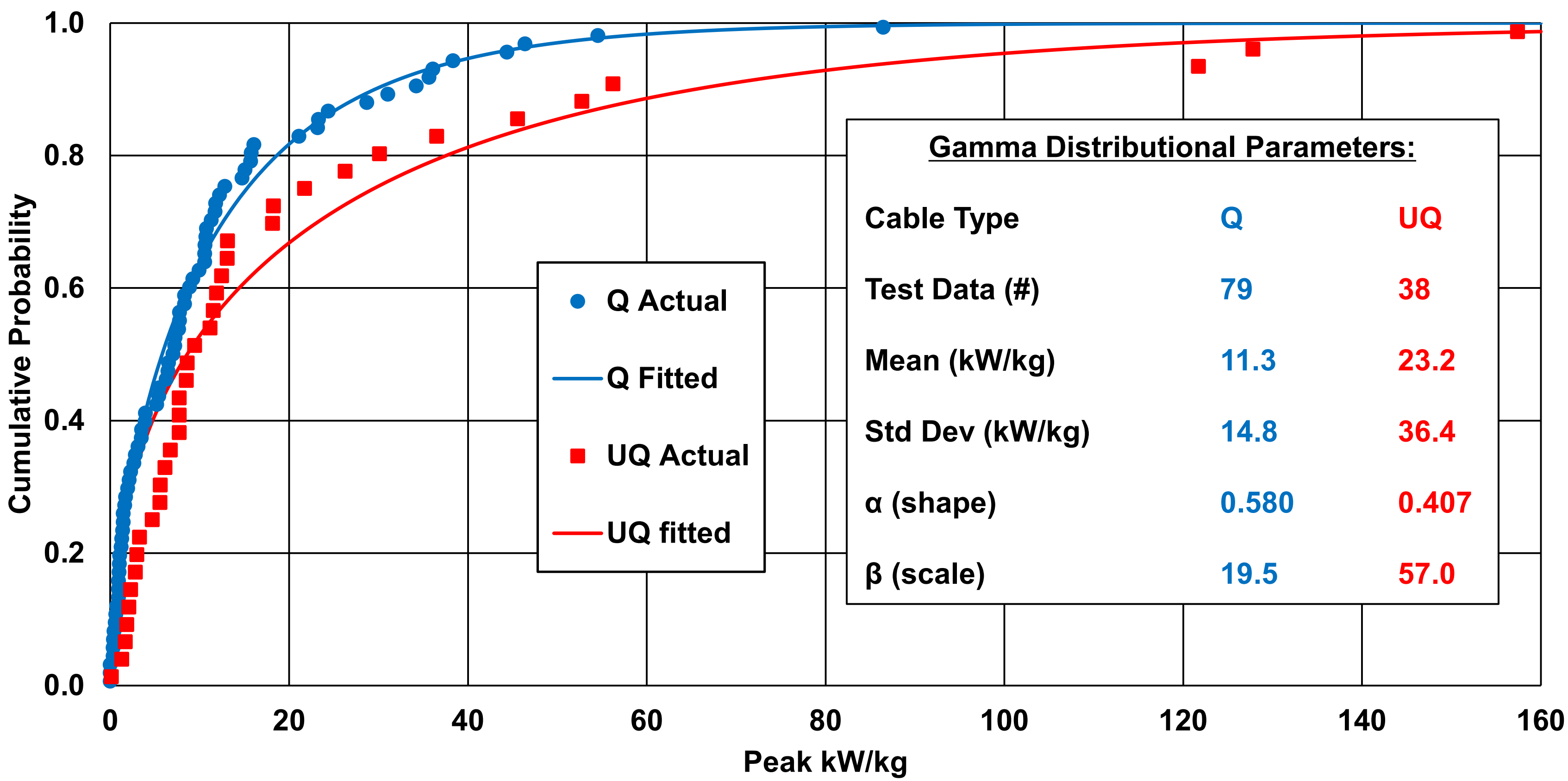
Test #	Enclosure Type	Ignition HRR (kW)	Pre-heat HRR (KW)	Fuel Mass (kg)	Cable Type	Door Position	Peak HRR (kW)	Total energy release (MJ)
22B	1	0.7	16	2.87	Q	Closed	11.3	17
96	6	5.5	21	5.37	UQ	Closed	33	47
Etc.	1-8	0.7-35	0-26	0.73-11.8	Q/UQ	Open/ Closed	0-577	3-152

- 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.

HRR/MASS AS METRIC

- 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.
  - 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.

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).
      - 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.

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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 affect the HRRs, so many tests included change in door position during a single or across multiple tests.
  - Mostly 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.
  - Still, supplementary analysis for peak HRR per fuel mass at least suggests a difference based on door position.
    - 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 34% for UQ).

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EFFECT OF DOOR POSITION? (2)

- 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.
- Compare two tests with equivalent cable type and fuel mass with high peak HRRs, i.e., 216 kW vs. 577 kW, both for 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 (98^{th} %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 98^{th} %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.