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TIME TO REACH PEAK HEAT RELEASE RATE: Nuclear Plant Electrical Enclosure Fires

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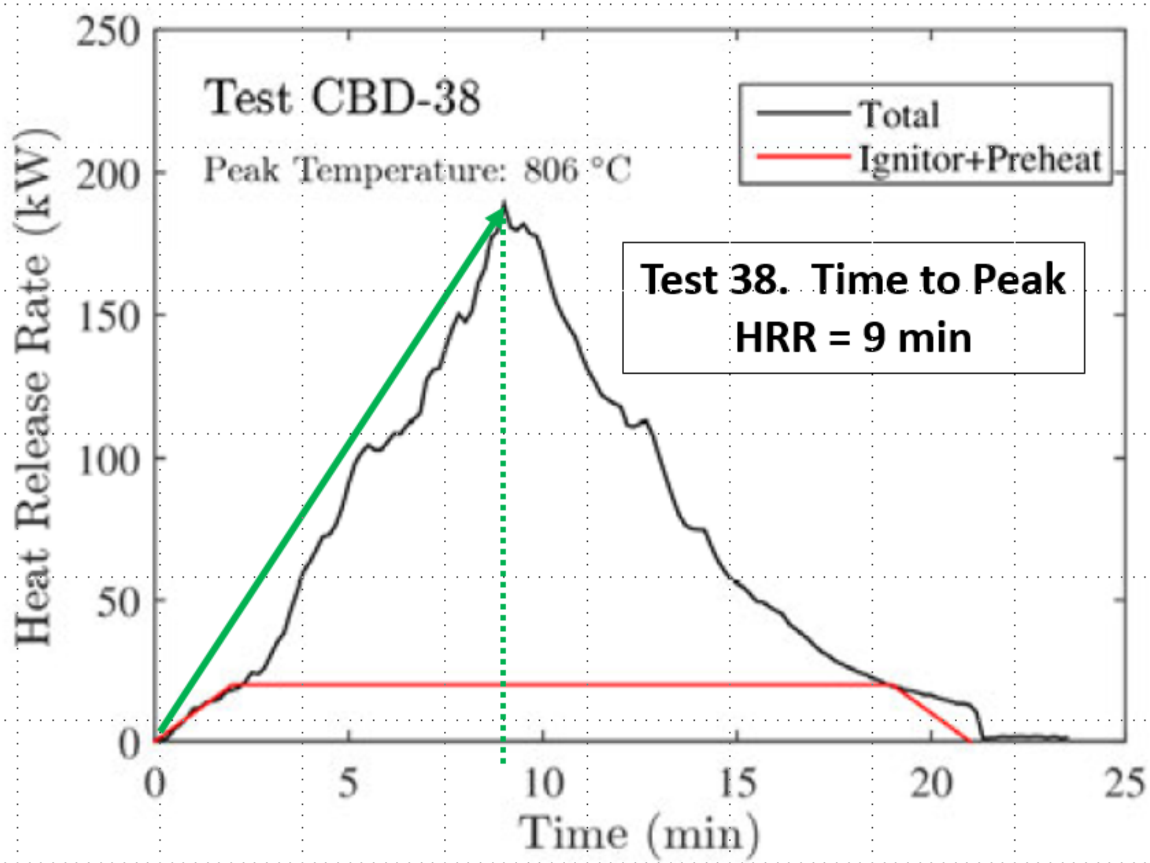
BACKGROUND

- Current Guidance (NUREG/CR-6850) – Assume average of 12 min between fire start and attainment of peak heat release rate (HRR) for nuclear plant electrical enclosure fires
  - First Enhancement – Based on 22 test data from NUREG/CR-6850, gamma distribute times to reach peak HRR with scale (α) and shape (β) parameters of 8.66 and 1.31, with mean = 11.4 min (Gallucci, PSAM12, Hawaii [2014])
  - New Enhancement – This paper, based on 114 electrical enclosure fire tests by NRC and National Institute for Standards and Technology (NIST) from NUREG/CR-7197 (*Heat Release Rates of Electrical Enclosure Fires [HELEN-FIRE*]), 2016, for IEEE-383 qualified and unqualified cables (surrogates for thermoset [char when heated] and thermoplastic [melt when heated])

HRR vs. TIME – HELEN-FIRE EXAMPLE



Plots generated for 114 tests, from which times to reach peak HRR have been extracted as shown. Both qualified (83) and unqualified (31) sets of cables subjected to ignition source, some with pre-heating, some with enclosure doors "open" vs. "closed" (but not in the sense of a fire being "oxygen limited").

STATISTICAL RESULTS

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

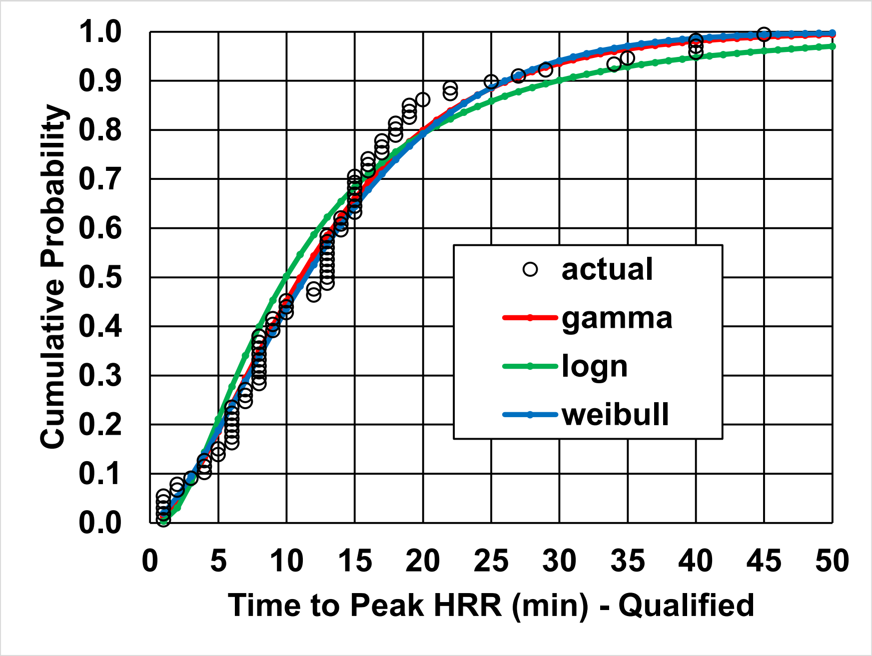
Little variation

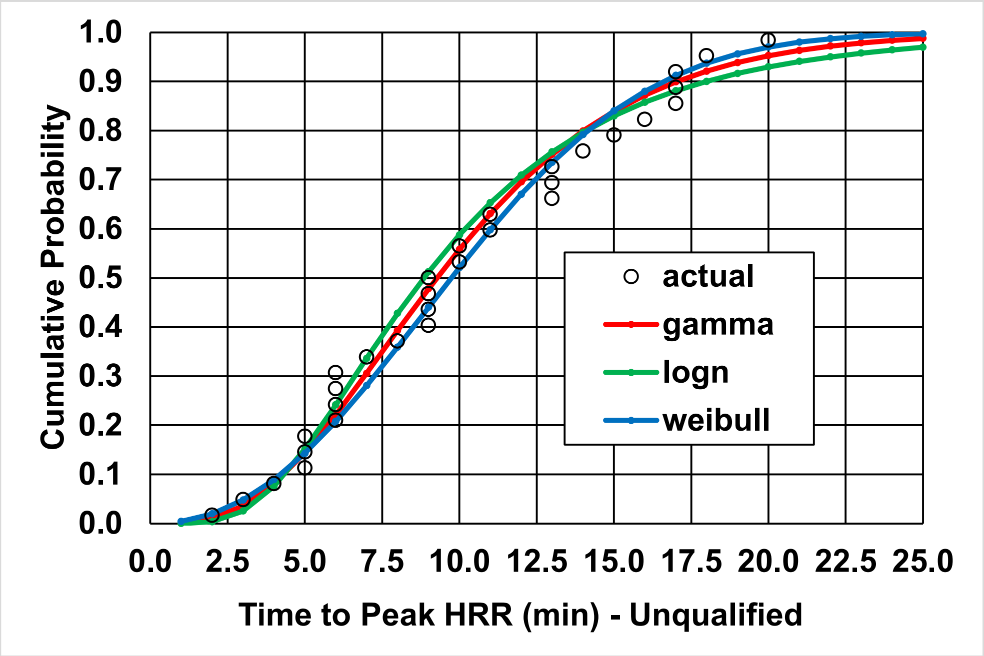
EFFECT ON NON-SUPPRESSION PROBABILITY (NSP)

- Despite little variation among test groupings, peak HRRs are reached slightly more quickly for UQ than Q cables, as expected
- Kolmogorov-Smirnov data poolability test supports use of "All" group
  - Comparing among Q, UQ and All using the mean times to reach peak HRR and NSP for electrical fires from NUREG-2169 (2014):
    - Ratio of NSP for Q vs. that for UQ is 27% lower due to the 3.2-min difference.
    - Ratio of NSP for Q vs. that for All is 8% lower due to the 0.9-min difference.
    - Ratio of NSP for UQ vs. that for All is 26% higher due to the 2.3 min difference.
  - Some relaxation in NSP possible based on type of cable insulation

TIME TO PEAK HRR DISTRIBUTIONS (1)

- Compare distributional fits for gamma, lognormal and Weibull via Mathematica® for Q and UQ groups



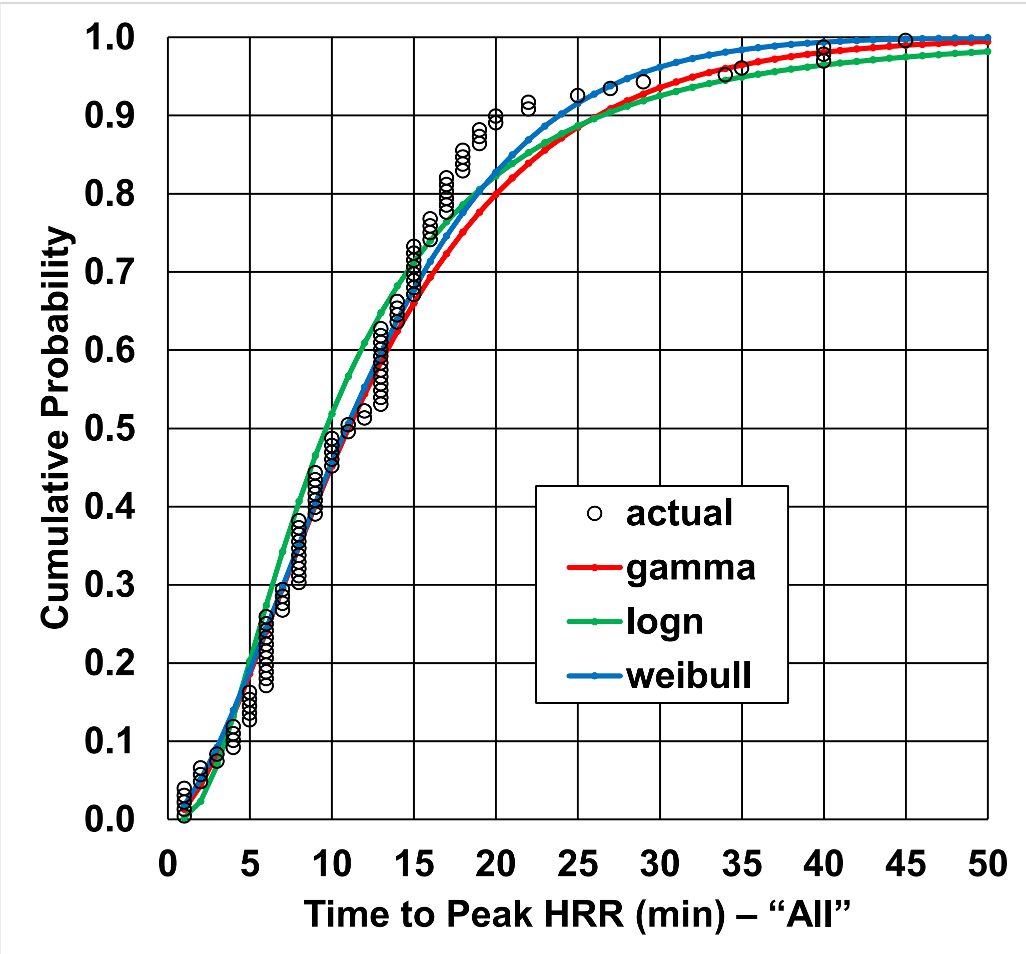


TIME TO PEAK HRR DISTRIBUTIONS (2)

- Q cables – No difference between gamma and Weibull fits; some difference noticeable for lognormal fit
- UQ cables – Gamma fit is intermediate between lognormal and Weibull, with Weibull showing largest variation
- Choose gamma distribution for both, as well as “All” group

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

TIME TO PEAK HRR DISTRIBUTIONS (3)



The gamma appears to be a reasonable choice to characterize the time to reach peak HRR for both Q and UQ cables, with the parameters shown, including those for All cables, for which the gamma is also a reasonable representation:

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

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

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

SIMULATIONS FOR EFFECT ON NSP (1)

- Stochastically simulate NSPs for electrical enclosure fires that would result for a range of response times
- Assume lognormal distribution for response time with a median of 10 min and error factor of 1.5, implying a mean of 10.31 min:
  - $f(\tau) = \frac{e^{(-[\ln \tau - \mu]^2/2\sigma^2)}}{\tau\sigma\sqrt{2\pi}}$
  - $\mu = 2.30; \ \sigma = 0.246$
  - Consider six cases:
    - First three cases assume detection at time zero (when the fire starts), with 10, 20 and 30 min to failure after the peak HRR has been reached.
    - Second trio parallels the first, except now assume detection does not occur immediately when the fire starts, but at the halfway point between time zero and the time at which the peak HRR is reached.

SIMULATIONS FOR EFFECT ON NSP (2)

- For each case, NSP is calculated for 10,000 samples based on NUREG-2169 exponential NSP for electrical fires with mean suppression rate = 0.0975/min, assumed to be normally distributed with 90%, two sided confidence bounds of $\pm$0.0120 min ($\mu = 0.0975, \sigma = 0.00729$)

Case	Time to Failure after Peak (min)	Time when Detected (min)	NSP (with minimum value of 0.001, imposed during simulation)				
			5^{th} %ile	Median	Mean	95^{th} %ile	Std Dev
1.1	10	0 (Fire starts)	0.0588	0.367	0.405	0.917	0.256
1.2	20		0.219	0.139	0.156	0.348	0.106
1.3	30		0.00801	0.0523	0.0595	0.135	0.0415
2.1	10	Halfway to peak	0.235	0.598	0.606	1.000	0.234
2.2	20		0.0872	0.225	0.237	0.428	0.108
2.3	30		0.0316	0.0849	0.0902	0.166	0.0430

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SIMULATIONS FOR EFFECT ON NSP (3)

- As expected, when the time to detection is delayed (Case 2 trio), the NSP is higher than its corresponding Case 1 since there is less time available to suppress the fire.
  - Within each trio, the NSP decreases with increasing time to failure after the peak HRR is reached since more time becomes available to suppress.
- Next, compare a probabilistic vs. deterministic approach based on the simulated mean times to reach peak HRR and the NUREG/CR-6850 point estimate of 12 min (half of that, 6 min, for Case 2 trio).

PROBABILISTIC vs. DETERMINISTIC - NSP

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

In all cases, the ratio for the simulated mean NSP to that calculated from the NUREG/CR-6850 point estimate is higher by approximately 30% when the fire is detected at its start and 10% when the fire is detected halfway between its start and the time at which it reaches its peak HRR. <u>This suggests that the NUREG/CR-6850 approach is somewhat non-conservative because it yields lower NSPs by ~10% to 30%.</u> This point estimation could be adjusted by just increasing the calculated NSP by 10% to 30% or subtracting 1 to 3 min, respectively, from the time available for suppression prior to calculating the NSP.

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SUMMARY

- The assumption of an average growth time to peak HRR of 12 minutes from NUREG/CR-6850 was based on 22 tests and was subsequently shown to follow a gamma distribution with alpha (scale) and beta (shape) parameters of 8.66 and 1.31 (Gallucci, PSAM 12, 2014).
- More recent experiments by the NRC and NIST in the HELEN-FIRE program expanded the number of applicable tests to 114, from which the author developed probabilistic distributions with mean times to peak HRR of 13.3 min (qualified cables) and 10.1 min (unqualified), with a mean of 12.4 min when all data are combined.
- This confirms that the original NUREG/CR-6850 value of 12 min was quite reasonable as a point estimate.

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CONCLUSION

- Time to reach peak HRR for each cable type remains well represented by gamma distributions for Q, UQ and All cables.
- A probabilistic vs. deterministic approach using the mean times to reach peak HRR from simulations for All cables yields average NSPs 30% and 10% higher than the 12-min point estimate when the fire is assumed to be detected at its start and halfway between start and when its HRR peaks.
- This suggests that the NUREG/CR-6850 point estimate of 12 min yields somewhat non-conservative results for the time for electrical enclosure fires to reach peak HRR.
  - Adopting a probabilistic approach enables more realistic modeling of this particular fire phenomenon (growth time).