Statistical Characterization of Cable Electrical Failure Temperatures Due to Fire, with Simulation of Failure Probabilities

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Abstract: Single-value failure temperatures for loss of electrical cable functionality due to fire have been the norm for Fire Probabilistic Risk Assessments (PRAs) since the publication of the landmark state-of-the-art report NUREG/CR-6850 / EPRI 1011989 in 2005. Electrical cable fire tests conducted by the USNRC since then have added a significant amount of failure data that can be used to examine the feasibility of now assigning probability distributions to these failure temperatures. This paper analyzes these data to develop probability distributions for different generic cable types (based on insulation). Then, building on recent work to investigate the sensitivity of fire phenomenological models to variations in input parameters, simulation techniques are employed to show potential refinement in predicting the probability of fire-induced electrical cable failure based on these temperature distributions. Results indicate the potential for relaxation in conservatism in Fire PRA through adoption of a probabilistic/statistical approach in conjunction with fire phenomenological modeling. Examples are presented along with suggestions for future enhancements.

Keywords: Cable Fires, Damage Temperatures, Electrical Failures, Simulation, Statistics, Probabilities

1. INTRODUCTION[1]

NUREG/CR-6850 / EPRI (Electric Power Research Institute) 1011989 provides generic screening criteria in terms of temperature for the assessment of ignition and damage potential to electrical cables of 205°C for thermoplastic (TP) and 330°C for thermoset (TS) insulation. [1] National Fire Protection Association (NFPA) 805 Frequently Asked Question (FAQ) 08-0053 [2] endorses the use of 247°C for the special case of Kerite-FR® cables, a TS-insulated cable whose failure behavior has been shown to more closely approach that of TP from the KATE-Fire series of cable fire tests. [3] Experimental programs conducted for the USNRC by Sandia National Laboratories (SNL) have confirmed these screening values while generating an abundance of data on the variability of cable failure temperatures. [3-5]

An initial evaluation of some of these failure data has been completed as part of a Master's Thesis from the University of Maryland. [6] My paper builds on this initial work to derive probability distributions for both TP and TS cable failure temperatures, then incorporates these into stochastic simulation using a simple fire model correlation to show how uncertainties in both input parameters and the fire model correlation itself can relax conservatism in cable failure probabilities. The simulation includes Kerite® cables based on a previous statistical analysis of mine. [7]

2. TEST DATA

Complete description of the Penlight facility employed by SNL to collect thermal response data for cables exposed to cylindrically uniform radiant heating during the CAROLFIRE, DESIREE-Fire and KATE-Fire test series can be found in NUREG/CR-6931. [4] Suffice it to say that, to record the most accurate measurements of the temperatures at which thermally-exposed cables experienced electrical failures, thermocouples were embedded as close as possible to the conductors beneath the cable jackets. Generally two temperatures were recorded for a wide variety of both TP and TS cables. With few exceptions, I retained data only from trials where electrical failure occurred prior to cable ignition for further analysis.

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1 This paper was prepared by an employee of the U.S. NRC. The views presented do not represent an official staff position.

Where the two temperatures were relatively close, I used their arithmetic average as the failure datum. Among the TP data, one datum was based on a single recording and one was excluded as an outlier, after discussion with the SNL experimenter, for being nearly 90°C higher than the next highest temperature. Among the TS data, four were based on a single recording, three of which were outliers by at least 115°C too high. Since these three had counterparts among other trials where two temperatures were recorded, well within the spread of the rest of the data, they were excluded as outliers. The remaining one was retained, as it was well within the spread of data. For one other trail, the two temperature recordings were nearly 60°C apart, with the lower already representing the maximum value for the data spread. Therefore, only this datum was retained. Table 1 presents all the data for both TP and TS cables from the CAROLFIRE and DESIREE-Fire tests.

A Kolmogorov-Smirnov statistical test for poolability of two sets of data confirmed that the CAROLFIRE and DESIREE-Fire TP failure temperatures could be assembled into one distribution for further analysis. The small number of DESIREE-Fire TS data made similar use of this test impractical for the two sets of TS data. However, based on visual inspection of the two sets, I decided that they could be combined for further analysis, especially since three of the six DESIREE-Fire data comprised the lowest temperatures and would, therefore, tend toward conservatism (lower failure temperature). Histograms for the combined TP and TS data were generated and, upon inspection, appeared to be amenable to characterization via a fit to the gamma distribution of the following form:

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

where x is the temperature in °C. The alpha (scale) and beta (shape) parameters were derived from the mean and variance of each data set, as shown among the statistics in Table 2 (which also includes the results from my previous analysis of the Kerite® data from the earlier paper).

Histograms for the test data and the corresponding gamma fits are provided in Figure 1 (the one for Kerite® is taken from my earlier paper). All three fits appear reasonable, given the variability in the test data, at least for the purpose of simulating distributed failure temperatures for each cable type.

3. SIMULATION

To demonstrate the use of these failure temperature distributions in stochastic simulation, I assume the following configuration: a target cable (if in a bundle, then at the very bottom and fully exposed) is located at the ceiling in an open tray 5 ft (1.52 m) directly above an electrical cabinet 7 ft (2.13 m) high with a cross-sectional area of $(3\ \text{ft})^2$ $[0.914\ \text{m}]^2$. A fire in the cabinet (nominally 1 ft [0.305 m] below the top) occurs with a characteristic heat release rate (HRR) as defined by either of the following from NUREG/CR-6850, Appendix E: (1) Case 2, fire in more than one bundle of qualified cable, with 75th and 98th %ile HRRs of 211 and 702 kW, respectively, and gamma distributed with parameters alpha = 0.7 and beta = 216; or (2) Case 4, fire in more than one bundle of unqualified cable, with 75th and 98th %ile HRRs of 232 and 464 kW, respectively, and gamma distributed with alpha = 2.6 and beta = 67.8.

Table 1: Failure Temperature Data Retained for Further Analysis

CAROLFIRE Trial	Cable Type	Failure Temp (^{o}C)	Notes	DESIREE-Fire Trial	Cable Type	Failure Temp (^{o}C)	Notes
T-8	TP	169		31-SOV1	TP	209.5	
P-8	TP	191		31-SOV2	TP	213	
T-4	TP	197.5		33-MOV2	TP	223.05	
T-63	TP	206.5		32-SwGr-C	TP	223.5	
P-19	TP	209		33-MOV1	TP	223.75	
T-6	TP	211		32-SwGr-T	TP	224.2	
T-5	TP	212		12-MOV1	TP	237.35	
T-21	TP	212.5		9-SOV2	TP	248.3	
P-15	TP	220		9-SOV1	TP	254.4	
P-14	TP	221		12-MOV2	TP	255.5	
P-7	TP	222		39-SOV2	TP	258.9	
T-65	TP	225	[2],[4]	10-SwGr-C	TP	259.05	
T-10	TP	228	[3]	11-LgCoil	TP	266.2	
T-29	TP	235.5		11-Valve	TP	267.5	
T-14	TP	237.5		10-SwGr-T	TP	267.65	
T-16	TP	240		30-MOV1	TP	291	
T-30	TP	249.5		30-MOV2	TP	291.45	
T-15	TP	256		28-SOV1	TP	293.55	
P-20	TP	270		28-SOV2	TP	301.5	
P-4	TP	273		29-SwGr-C	TP	304.45	
P-18	TP	288		29-SwGr-T	TP	311	
P-23	TP	295					
T-1	TS	394.5		24-SwGr-T	TS	369.6	
T-2	TS	401.5	[2]	25-MOV2	TS	379.1	
P-13	TS	409		23-SOV1	TS	389.8	
T-7	TS	413.5		42-SwGr-T	TS	404.765	
T-9	TS	415.5		23-SOV2	TS	416.95	
T-20	TS	417	[2]	25-MOV1	TS	426.7	[1]
T-11	TS	420					
P-17	TS	422	[2]				
T-12	TS	422.5					
T-27	TS	424.5					
T-28	TS	425.5					
T-13	TS	426.5					
T-24	TS	426.5					
T-23	TS	427					
T-19	TS	427.5					
P-21	TS	432					
P-6	TS	436					
P-9	TS	438					
T-17	TS	447.5	[2]				
P-25	TS	456					
P-3	TS	460					
P-22	TS	462					

[2] Although ignition occurred prior to electrical failure, the case met the criteria for inclusion.

[3] One of the two thermocouples failed, so this was based on one reading.

[4] The cables' small diameters necessitated use of just one thermocouple.

[1] Because of the nearly 60^{o}C difference between the two measurements, only the lower was used as this already represented the maximum.

Table 2: Statistics and Gamma Parameters for Cable Failure Temperatures (^{o}C)

Statistic		Cable Type		
		Thermoplastic	**Thermoset**	**Kerite®**
Mean		251.62	421.12	383.0
Median		249.5	423.5	400
Variance		915.79	479.70	2487.02
Standard Deviation		30.26	21.90	49.87
Minimum		209.5	369.6	247
Maximum		311	462	448
Count		37	28	40
Gamma Fit	**Alpha (scale)**	69.13	369.7	59.0
	Beta (shape)	3.64	1.14	6.49

To determine if the fire fails the cable, the following correlation for centerline temperature of a buoyant fire plume ($T_{p, c\text{-}l}$) from NUREG-1805 will be employed [8]:

$$T_{p, c\text{-}l} = T_a + 9.1(T_a [Q\chi_c]^2)^{1/3}/[(g\, c_p^{\,2}\, \rho_a^{\,2})^{1/3} (z - z_0)^{5/3}] \quad (2)$$

$$z_0 = 0.083Q^{2/5} - 1.02(4A_f/\pi)^{1/2} \quad (3)$$

where:

T_a = ambient temperature (^{o}K)
Q = total HRR (kW)
χ_c = convective heat release fraction (assumed constant at 0.7 for the simulation)
g = acceleration of gravity (9.81 m/s^2)
c_p = specific heat of air (assumed constant at 1.00 kJ/kg-^{o}K for the simulation)
ρ_a = ambient air density (assumed constant at 1.18 kg/m^3 for the simulation)
z = distance from the top of the fuel package to the ceiling (m)
z_0 = hypothetical virtual origin of the fuel package (m)
A_f = equivalent area of the fire source (m^2)

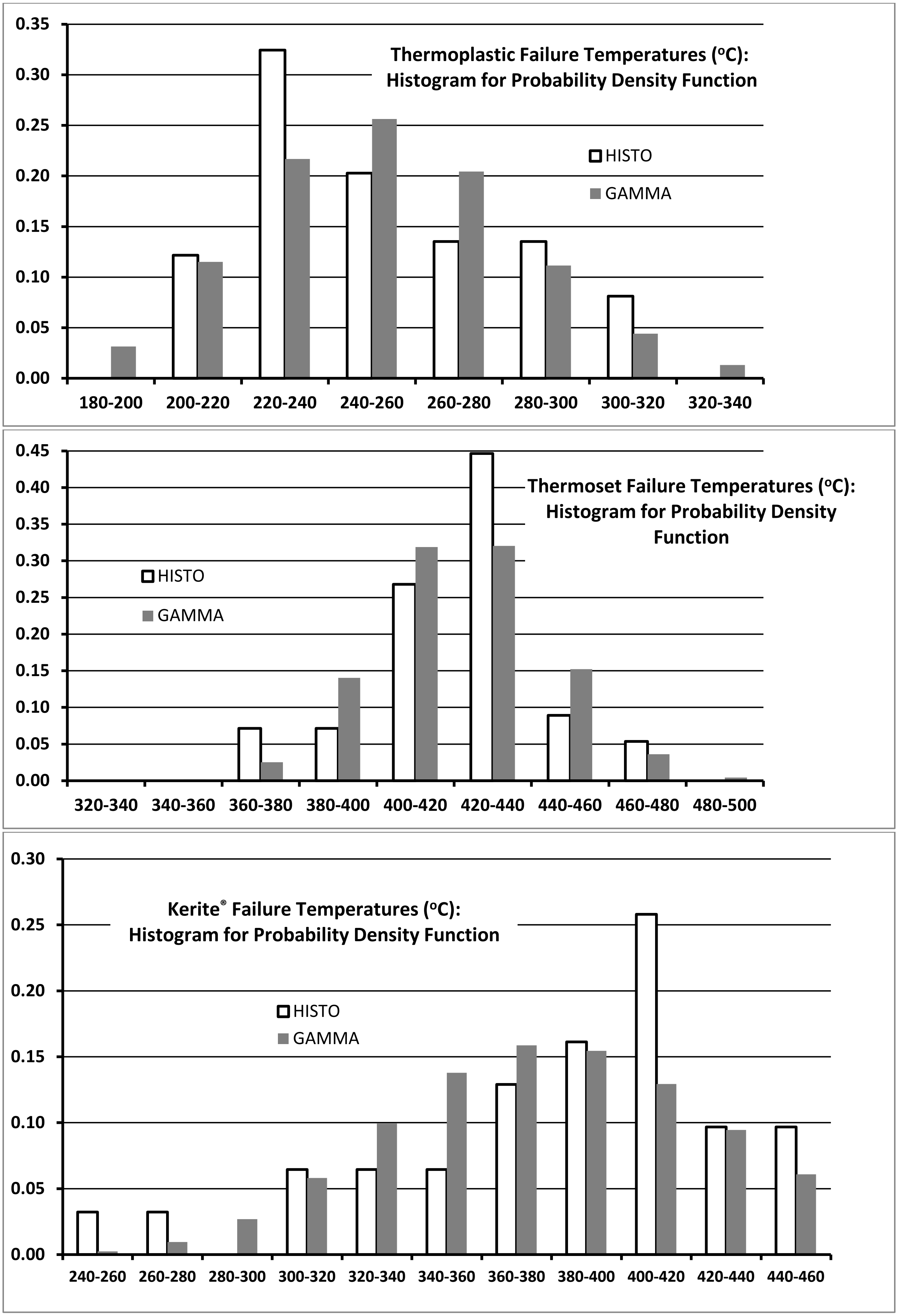
The following input parameters are assumed to be distributed:

(1) Q, as defined above for Case 2 and Case 4
(2) z, assumed to be 5 ft (1.52 m) + b(2 ft) [0.610 m], where b(2 ft) is the distance below the top of the cabinet, with b determined by a beta distribution with parameters $\alpha = 2$ and $\beta = 2$, such that it is symmetric about a value of 0.5 and constrained over the range from 0 to 1. (This limits the location of the fire to within 2 ft [0.610 m] below the top of the cabinet, symmetrically distributed about the nominal location of 1 ft [0.305 m] below the top of the cabinet.)
(3) A_f, assumed to be $(0.5\ ft)^2$ $[0.152\ m]^2$ + b'$(2\ ft)^2$ $[0.610\ m]^2$, where b'$(2\ ft)^2$ is the additional equivalent area of the fire source, with b' determined by a beta distribution with parameters $\alpha = 2$ and $\beta = 2$, such that it is symmetric about a value of 0.5 and constrained over the range from 0 to 1. (This limits the equivalent area of the fire to the range from $[0.5\ ft]^2$ to $[2.5\ ft]^2$, symmetrically distributed about a nominal equivalent area of $[1.5\ ft]^2$, given the cabinet's cross-sectional area of $[3\ ft^2]$).

Note that the form of the beta distribution for b and b' is as follows:

$$b^{(')}(x) = x^{\alpha-1}(1 - x)^{\beta-1}\Gamma[\alpha + \beta])/(\Gamma[\alpha]\Gamma[\beta]) \quad (4)$$

Figure 1. Histograms of Test Data and Gamma Distributional Fits for Three Cable Types



With all this input, one could perform a stochastic simulation that yields a distribution of the plume centerline temperature at the ceiling (location of the target cable). With each of the failure temperature distributions for the three cable types also simulated, the number of trials where the plume centerline temperature met or exceeded the failure temperature divided by the total number of trials yields the probability of electrical failure of the cable due to the postulated fire. The failure temperature distributions for each of the three cable types would each be modeled as gamma, with the corresponding alpha (shape) and beta (scale) parameter from Table 2. The difference between the simulated plume centerline and failure temperatures would be the metric, indicating failure for any non-negative value.

However, prior to running this simulation, I opted to add one more level of sophistication to the demonstration, namely the uncertainty on the plume centerline temperature rise (the "+9.1, etc.," term in the previous equation for $T_{p,\,c\text{-}l}$), given as follows in Table 4.1 of NUREG-1934 / EPRI 1023259. [9]

$$T_{p,\,c\text{-}l}\ (\text{distributed}) = [1 + 0.24N][T_{p,\,c\text{-}l}\ (\text{calculated})]/0.73 \tag{5}$$

The term N is the standard normally distributed number of standard deviations ($\sigma = 1$) where the mean (μ) = 0. From NUREG-1934, for $T_{p,\,c\text{-}l}$, the calculated value from the NUREG-1805 correlation is under-predicted by a factor of 0.73 and varies with a standard deviation of 24% (0.24). Note that, although NUREG-1934 states that there were insufficient data to pass a statistical test for normality, I still assume that the standard deviation of 24% follows a normal distribution, but with the limit on my simulation that no more than 1/0.24 = 4.17 standard deviations can result from the simulation, i.e., for any simulated value below -4.17 or above 4.17, this limit is imposed.

My final input to the simulation is the variable N, sampled from the standard normal distribution ($\mu = 0$, $\sigma = 1$). This incorporates the uncertainty on the correlation itself into the simulation. Using the software Oracle Crystal Ball® [10], which is compatible with Excel, I simulate the difference between the plume centerline and cable failure temperatures for each of the three cable types, i.e., (1) for thermoplastic, ($T_{p,\,c\text{-}l} - T_{fail,\,TP}$); (2) for thermoset, ($T_{p,\,c\text{-}l} - T_{fail,\,TS}$); and (3) for Kerite®, ($T_{p,\,c\text{-}l} - T_{fail,\,Ker}$). Note that this simulation is a first step toward addressing the following recommendation from the Advisory Committee on Reactor Safeguards (ACRS) regarding publication of NUREG-1934 [11]:

> "After NUREG-1934 is issued, the [NRC] staff should develop a separate case study to demonstrate how uncertainties are assessed and quantified in an integrated analysis of a typical nuclear power plant fire hazard and its consequential fire damage scenarios."

4. RESULTS

For both Case 2 and Case 4, 10,000 trials were run for each simulation, each calculating a plume center-line temperature and cable failure temperature for each of the three cable types. For each type, the difference between the plume center-line and failure temperatures was calculated. The results for the plume center-line temperature and each of the three temperature differences are tabulated in Table 3 and plotted in Figure 2.

For both Cases, the maximum (most positive) mean difference between the plume and failure temperatures occurs for the TP cable; the minimum (most negative) occurs for the TS; and the Kerite® is intermediate, but closer to the TS value. This seems reasonable, given the mean failure temperatures for the three types, with TP being the lowest (~252 °C), TS the highest (~421 °C), and Kerite® intermediate (~383°C), but much closer to the TS value. Furthermore, as expected, TP cable exhibits the highest failure probability in both Cases (0.49 in Case 2 and 0.69 in Case 4).

Table 3: Statistics for Failure Temperatures (^oC) and Probabilities from Simulations

Stats	Case 2 (75^{th} & 98^{th} %ile = 211 & 702 kW)				Case 4 (75^{th} & 98^{th} %ile = 232 & 464 kW)			
	$T_{p, c\text{-}l}$	$(T_{p, c\text{-}l} - T_{fail, TP})$	$(T_{p, c\text{-}l} - T_{fail, TS})$	$(T_{p, c\text{-}l} - T_{fail, Ker})$	$T_{p, c\text{-}l}$	$(T_{p, c\text{-}l} - T_{fail, TP})$	$(T_{p, c\text{-}l} - T_{fail, TS})$	$(T_{p, c\text{-}l} - T_{fail, Ker})$
Mean	371.4	119.8	-43.00	-14.6	398.7	146.7	-21.43	12.21
Median	215.6	-6.47	-52.92	-131.6	335.6	103.0	36.03	-23.84
Std Dev	518.6	535.4	646.9	542.1	263.3	293.5	473.5	304.2
5^{th} %ile	37.74	-339.9	-946.6	-506.5	118.1	-235.6	-878.0	-402.5
95^{th} %ile	1171.4	910.8	868.7	802.6	895.9	665.7	647.7	552.8
Fail Prob	n/a	0.49	0.45	0.33	n/a	0.69	0.55	0.46

However, there is somewhat of, at least at first, a seemingly unexpected trend between the failure probabilities of the TS and Kerite® cables. While both are lower than the TP failure probabilities (0.45 and 0.55 for Case 2 and Case 4, respectively, for TS; 0.33 and 0.46 for Case 2 and Case 4, respectively, for Kerite®), as expected, that for Kerite® is actually lower than that for TS, despite having the lower mean failure probability. This is the result of the difference between the distributional shapes for the failure temperatures. From Figure 1, note that the distribution for TS cable, while centered at the higher temperature, is also much "tighter," as further evidenced by its standard deviation in Table 2 being less than half of that for Kerite®. This translates into there being a greater portion of the Kerite® distribution at higher temperatures than the TS distribution. As a result, when modeled probabilistically, there is actually a greater likelihood of the failure temperature for a Kerite® cable exceeding that for a TS cable, therefore resulting in the lower failure probability from the simulation.

Another insightful trend can be observed within the two Cases. In Case 2, the failure probability for TS is only slightly lower than that for TP. In Case 4, this difference is more pronounced. This is the result of the difference between the distributional shapes of the input HRR curves for the two Cases, as shown in Figure 4 (from NUREG/CR-6850). Both Cases represent fires in electrical cabinets involving more than one bundle of cables, these cables being qualified in Case 2 vs. unqualified in Case 4. Case 2, with the lower mean HRR (~151 kW) has a much longer tail toward the higher HRRs, such that the probabilities of reaching these values are greater than for Case 4, despite the latter's slightly higher mean HRR (~176 kW). That is, the distribution for Case 4 is much "tighter" than for Case 2. Therefore, for a given higher temperature, in Case 2 there is a greater probability of the fire generating this temperature than in Case 4. This reduces the "benefit" (effectiveness) of the higher failure temperature of TS vs. TP. However, in Case 4, for a given higher temperature there is a lower probability of the fire generating this temperature than in Case 2. Thus, this increases the "benefit" (effectiveness) of the higher failure temperature of TS vs. TP. As a result, we see the observed trend where the difference between failure probabilities for TP and TS is more pronounced in Case 4 than in Case 2.

Figure 2: Case 2: Simulated Probability Density Functions

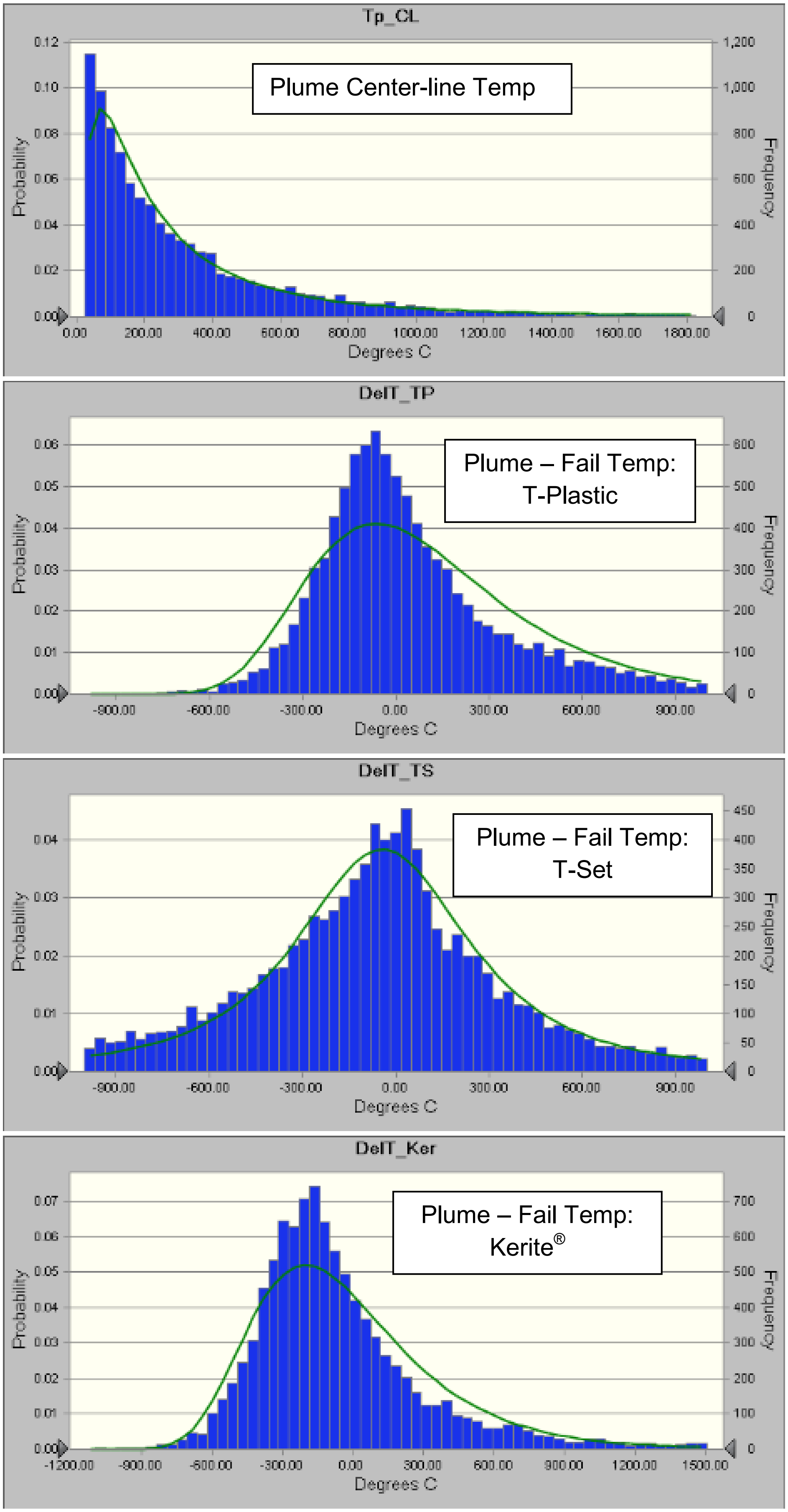


Figure 3: Case 4: Simulated Probability Density Functions

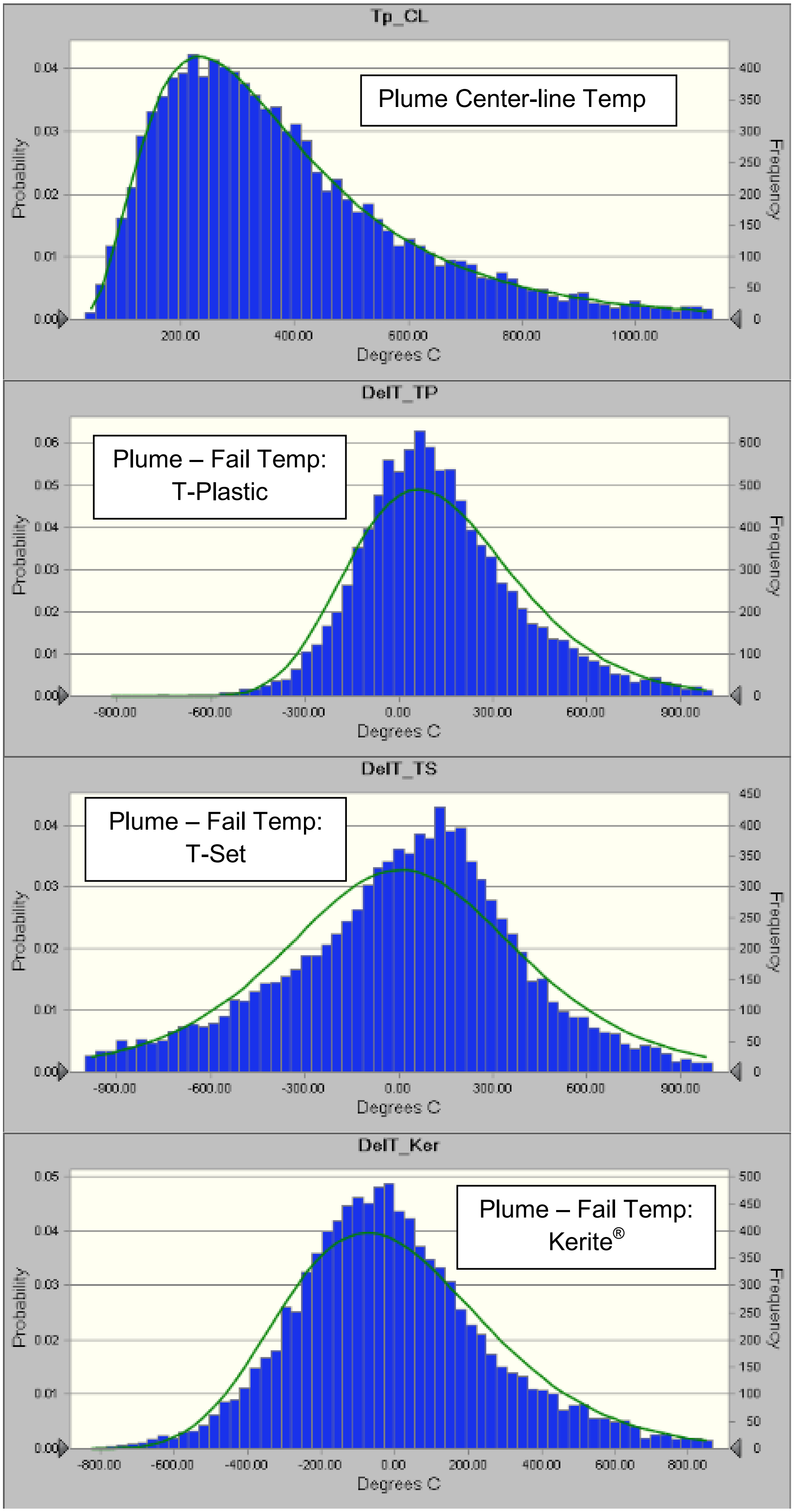
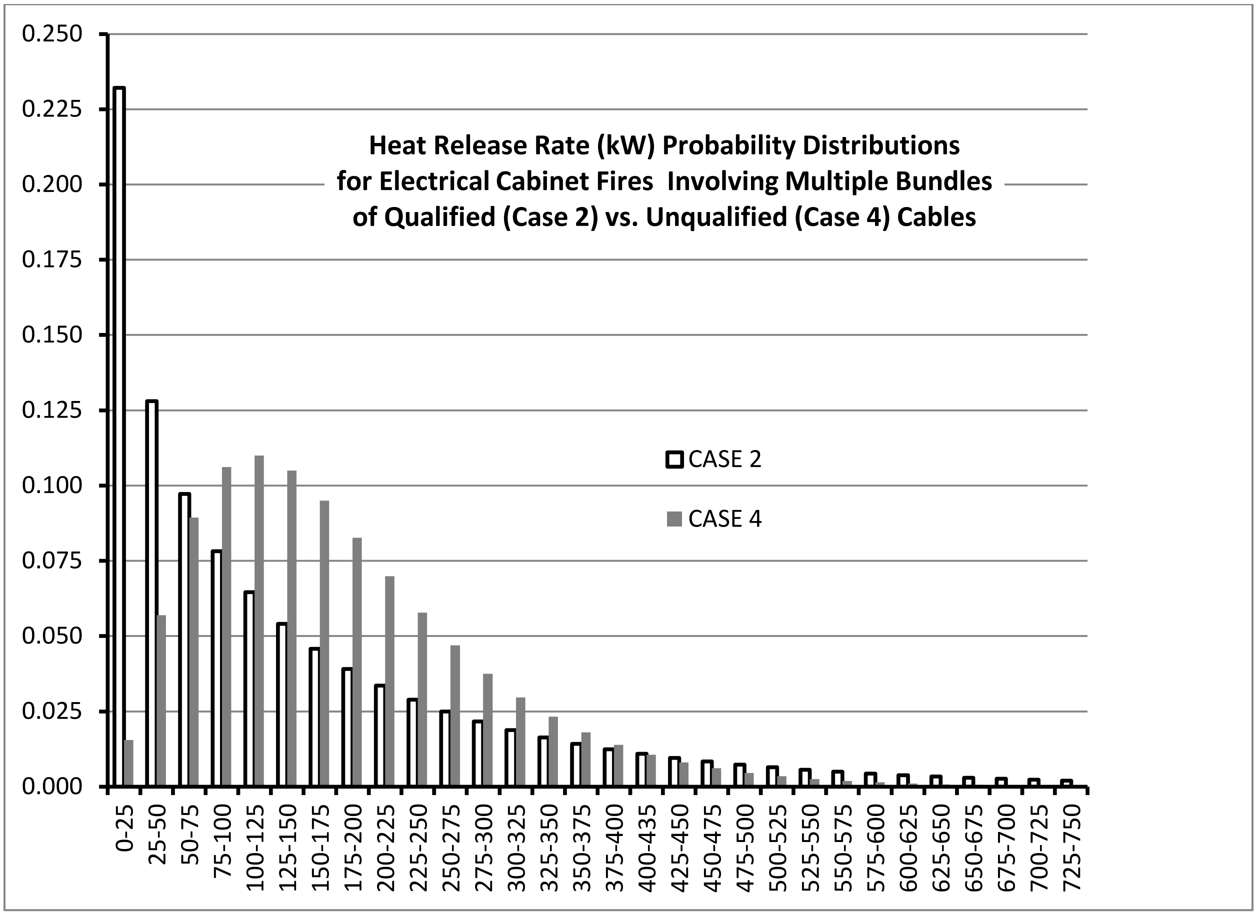


Figure 4: Input HRR Distributions for Case 2 vs. Case 4



5. INSIGHTS

NUREG/CR-6850 recommends using failure temperature thresholds of 205°C and 330°C for TP and TS cable, respectively, as screening values. FAQ 08-0053 recommends 247°C for Kerite-FR®, an older but most commonly used variety of Kerite® at nuclear power plants, again for screening. For the plume centerline temperature correlation employed here from NUREG-1805, even the mean HRRs for Case 2 and Case 4, which occur below the 75th %iles, yield point estimates of 335°C and 382°C (when the shift by the factor of 1/0.73 = 1.37, based on NUREG-1934, is included), which translate into a screening failure probability of 1.0 for all three cable types. When probability distributions on selected input parameters and the cable failure temperatures are employed, the simulation indicates reductions in this failure probability by factors ranging from 1/0.69 ≈ 1.4 to 1/0.33 ≈ 3.0, modest but not insignificant.

Consider that, in this demonstration, the simplest of the various fire models for calculating plume centerline temperature was employed, primarily for ease of demonstrating the advantages possible when probability distributions on the input parameters, especially cable failure temperatures, are used. As shown in Table 3 and Figures 2 and 3, the spread in predicted temperatures from this correlation is quite wide in both Case 2 and Case 4 (e.g., see the 5th and 95th %ile values in Table 3, as well as the standard deviations). This indicates that relatively small changes in the inputs can lead to large variation in the output.

From Table 4.1 in NUREG-1934, it is clear that use of one of the more sophisticated fire models for plume temperature rise, e.g., MAGIC [12] or FDS [13], should yield much "tighter" results (over-predictions by only 7% and 15 %, respectively, with standard deviations of only 7% and 11%, respectively). Of course, integrating these more complex models, especially FDS, into a framework with thousands of trials for simulation is more involved and time consuming than for the simple correlation used here. However, conceptually the approach is the same. Depending upon the results (reductions in cable failure probabilities), the effort may be worthwhile.

6. SUMMARY

The goal of this paper was two-fold. The first was to derive probability distributions for cable failure temperatures based on the most comprehensive experimental programs, namely those from CAROLFIRE and DESIREE-Fire, conducted to date. As a result, probability distributions for failure of both TP and TS cables have been developed, with one for Kerite® included from my similar, earlier analysis. Second, these new probability distributions were combined in a stochastic simulation that considered variable input parameters to characterize cable failure metrics and probabilities using a simple correlation for plume center-line temperature from NUREG-1805. This was done in the spirit of taking a first step toward addressing the recommendation from the ACRS regarding the follow-on to the publication of NUREG-1934:

> "After NUREG-1934 is issued, the [NRC] staff should develop a separate case study to demonstrate how uncertainties are assessed and quantified in an integrated analysis of a typical nuclear power plant fire hazard and its consequential fire damage scenarios."

The next step would be to refine the probability distributions for cable failure temperature (other "parsing" of the test data could be considered, such as categorization by type of TS or TP cable or exposure conditions) and/or develop simulation algorithms for the more sophisticated fire models, such as CFAST [14], MAGIC or FDS. Demonstrations for some of the examples of nuclear power plant fire scenarios in NUREG-1934 could be performed.

References

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ADDENDUM

An additionally distributed input parameter, the time for the fire to reach peak HRR in an electrical cabinet, can also be incorporated when using the more sophisticated fire models such as CFAST, MAGIC or FDS. Appendix G of NUREG/CR-6850 provides a table of 22 test results from electrical cabinet fire experiments reported in NUREG/CR-4527. [15] These times to reach peak HRR are reproduced in Table A-1 along with the statistics and the parameters for a gamma-fitted distribution. The histogram for the actual test data and the gamma fit is provided in Figure A-1. A reasonable fit is evident (alpha = 8.66, beta = 1.31).

These more sophisticated fire models allow a time-dependent HRR as input to represent fire growth to the peak HRR, often as a function of time-squared. The gamma distribution from the analysis of these test data would enable simulation of the time to reach the peak HRR value in this relationship.

Table A-1: Statistics and Gamma Parameters for Time to Peak HRR (min)

TEST	TIME TO PEAK HRR (min)	STATISTIC		
Test 21	4	Mean		11.36
ST2	6	Median		10.5
ST1	7	Variance		14.91
ST5	8	Standard Deviation		3.86
ST6	8	Minimum		4
Test 22	9	Maximum		18
ST10	10	Count		22
ST3	10	Gamma Fit	Alpha (scale)	8.66
ST8	10		Beta (shape)	1.31
ST9	10			
Test 23	10			
PCT1	11			
PCT6	11			
PCT2	12			
Test 24	12			
PCT3	13			
ST4	14			
PCT4a	16			
PCT4c	16			
PCT5	17			
ST11	18			
ST7	18			

Figure A-1: Histograms of Test Data and Gamma Distributional Fits for Time to Reach Peak HRR