RISK-BASED SCHEDULAR JUSTIFICATION FOR THE HEMYC® ONE-HOUR RATED ELECTRICAL RACEWAY FIRE BARRIER SYSTEM

The HEMYC® one-hour rated electrical raceway fire barrier system (ERFBS) was tested via the time-temperature curve from the ASTM-E119 standard test method (Ref. 1). It exhibited failures starting at approximately 15 min into the test. At the end of 60 min, several failures had occurred, although some locations remained intact. The following analysis will be based on two assumptions:

1. The probability of failure of a HEMYC® ERFBS when subjected to the ASTM-E119 curve ranges from 0 at 10 min or less to 1 at 60 min or more.

2. The HEMYC® ERFBS failure can be characterized as a function of either the temperature "T" at time "t" from the ASTM-E119 curve or the area "A" at time "t" under the ASTM-E119 curve, whichever is more severe. That is, we can develop a probability of failure "P" for the HEMYC® ERFBS that is a function of either temperature "T" or area "A," following the time-dependent behavior of "T" and "A" from the ASTM-E119 curve.[a]

To simplify the calculations, we first linearize the ASTM-E119 curve by dividing it into three line segments connecting the following points:

Time (min)	Temp (°C)[b]
0	0
6.5	680
30	840
60	920

Next we develop a linear equation for the temperature as a function of time along each segment of the form:

$$T = \frac{(t - t_1)(T_2 - T_1)}{t_2 - t_1} + T_1$$

where (t_1, T_1) and (t_2, T_2) are the time-temperature coordinates at the lower and upper ends of each segment, respectively. With the function T = f(t) defined for each segment, it is straightforward calculus to integrate the area under the curve from 0 through t, giving us a corresponding area function A = g(t). These calculations are automated in the attached Microsoft Excel® spreadsheets.

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[a] The area under the ASTM-E119 curve (A) is the product of temperature (T) and time (t). NUREG-1805 (Iqbal, N., and M. Salley, *Fire Dynamics Tools (FDT^s)*, USNRC, December 2004) indicates that heat release rate (Q) is usually proportional to $T^{1.0\rightarrow2.0}$. The total heat released is Q x t, which is proportional to $T^{1.0\rightarrow2.0}$ x t. If one postulates that the probability of failure (P) for the HEMYC® ERFBS is a function of heat released (or heat absorbed by the HEMYC® ERFBS), it follows that P is maximized by assuming it to be a function of A, where A is always ≤ $T^{1.0\rightarrow2.0}$ x t. Thus, for a particular time on the ASTM E-119 curve, a lesser value (A = T x t), rather than a greater value ($T^{1.0\rightarrow2.0}$ x t), is assumed to yield the same P value, meaning that P as a function of A will be a bounding assumption.

[b] The ASTM-E119 curve actually begins at an ambient 20 °C at time zero, so the "Temp" here can be viewed as "above ambient." It will be lost in the noise level of the calculations.

Based on the above two assumptions, we postulate that the threshold for HEMYC® ERFBS failure is T = 703.83 ºC and A = 4870 min-ºC, since these are the corresponding values at t = 10 min from the ASTM-E119 curve. (For simplicity, we drop the time and temperature units from all subsequent text, with the understanding that time is always in minutes and temperature always in ºC.) As a first approximation, we assume that the HEMYC® ERFBS failure probability "P" varies linearly with t for the range of values that result from the ASTM-E119 curve through t = 60. This yields the following equations:[c]

Temperature → $$P(T) = \frac{T - 703.83}{920 - 703.83}$$

Area → $$P(A) = \frac{A - 4870}{46470 - 4870}$$

The linear variation of P with T and A is evident in the Microsoft Excel® attachment.

1. EMERGENCY DIESEL GENERATOR ROOM FIRE

It is evident that the HEMYC® ERFBS will not fail under these assumptions for T < 703.83. Temperatures in areas of nuclear power plants where a HEMYC® ERFBS is typically installed do not approach this failure threshold. Thus, we do not expect to experience HEMYC® ERFBS failures as a result of only the temperatures attained in nuclear power plant fires. However, nuclear power plant fires can expose a HEMYC® ERFBS to sufficiently high temperatures for long enough times such that the threshold A = 4870 could be exceeded. The attached curve from a CFAST® (**C**onsolidated Model of **F**ire Growth **a**nd **S**moke **T**ransport, Ref. 2) simulation bounds a similar CFAST® simulation of a nuclear plant Emergency Diesel Generator (EDG) room fire. It shows a rapid initial temperature rise to ~390 ºC in ~ 7.5 min, with a final temperature of ~440 ºC reached after one hour. If we linearize this time-temperature curve in a manner similar to that for the ASTM-E119 fire, as follows:

Time (min)	Temp (°C)
0	0
7.5	390
60	440

we calculate that the threshold value A = 4870 is reached at t ≈ 16, with A reaching 23250 at t = 60. At the latter value, P(A) = 0.442 (see Microsoft Excel® attachment).

Assume a typical, older nuclear plant using a HEMYC® ERFBS for safe shutdown (SSD) cables in their EDG room protects against a diesel oil fire with fast-acting smoke detection and pre-action/deluge sprinkler suppression. From the Fire Protection (FP) Significance Determination Process (SDP), Table A4.1, the fire frequencies of components that might be found in a typical EDG room are as follows: (1) for "Cables," 1.6E-5/y (low loading) to 0.0014/yr (high loading); (2) per "General Electrical Cabinet," 6.0E-5/y; and (3) per "Diesel Generator," 5.6E-4/y (Ref. 3). We assume for our EDG room that there is a medium loading of cables, two general electrical cabinets and one EDG. The fire frequency becomes 4.8E-4/y + 2 x 6.0E-5/y + 0.0056/y = 0.0062/y.

[c] At t = 60 on the ASTM-E119 curve, T = 920 and A = 46470. In these equations, 703.83 < T < 920 and 4870 < A < 46470.

The recommended fire severity characteristics from Table A4.1 are "Self-Ignited Cable Fires," "Small Electrical Fires" and "Engines and Heaters;" and the recommended manual fire suppression curves are "Cable Fires," "Electrical Fires" and "All (Fire) Events." Referring to the corresponding tables (2.3.1 and 2.7.1), we find the 95^{th} %ile fire for "Small Electrical Fires" (assumed to be representative of "Self-Ignited Cable Fires") and "Engines and Heater" fires to be 200 kW; the manual non-suppression probabilities for "Cable Fires" dropping below 0.10 after 13 min; the manual non-suppression probabilities for "Electrical Fires" dropping below 0.10 after 20 min; and the manual non-suppression probabilities for "All (Fire) Events" not dropping below 0.10 until 30 min. For the sake of a bounding analysis, we choose more severe categories from each table to represent our diesel oil fire, namely "Indoor Oil-Filled Transformer" and "Turbine-Generator" (T-G) fires, respectively. We assume each can serve as a surrogate for a diesel oil fire in the EDG room severe enough to generate the time-temperature characteristics needed to fail the HEMYC® ERFBS.

The FP SDP recommends a severity factor of 0.1 for the 95^{th} %ile fire. Furthermore, if we assume that the HEMYC® ERFBS damage fails any enclosed cables, it is likely that no more than the equivalent of an automatic steam-drive train would remain available to mitigate core damage, especially should this older plant self-induce an SBO given a fire-initiated transient. This mitigating capability could be attributed to equipment in the area unaffected by the fire, since actual fires are not expected to be area-wide or to affect other manual actions taken by operators, even if those actions are not in procedures. The corresponding screening value for conditional core damage probability (CCDP) is 0.1. Thus, collecting the probabilities from the FP SDP, we can express the core damage frequency (CDF) as 0.0062/y x 0.1 x 0.1 x P(A) x PNS = 6.2E-5/y x P(A) x PNS, where PNS is the non-suppression probability. For CDF < 1E-6/y, we require P(A) x PNS < 0.016.

The Microsoft Excel® attachment shows P(A) as a function of t for the EDG oil fire. Rapid detection from the smoke detectors would be expected, such that the pre-action/deluge sprinkler system would deliver water within a minute of detection. Even without suppression, no HEMYC® ERFBS damage is expected until ~ 16 min after the fire starts. From the FP SDP, Table A8.2, the non-suppression probability for this sprinkler system is essentially zero, since the time-to-damage exceeds the time-to-suppression by at least 10 min. However, since the FP SDP recommends a 0.05 unavailability for a deluge system, we expect that 5% of the time suppression will be by manual means, namely the plant fire brigade. The manual non-suppression probability for "T-G" fires is given in Table 2.7.1 as follows:

$$PNS = e^{-0.021\Delta t}$$

where Δt is the difference between time-to-damage and time-to-detection. Since rapid detection has been assumed, we can approximate Δt with t, namely the time since ignition of our diesel oil fire, i.e.,

$$PNS = e^{-0.021t}$$

This has to be multiplied by the unavailability of automatic suppression, yielding:

$$PNS = 0.05e^{-0.021t}$$

These values are calculated in the Microsoft Excel® attachment.

Now, for given values of t for our EDG oil fire, we can readily calculate P(A) x PNS, as shown in the Microsoft Excel® attachment. This product rises continuously from 0 at t ≈ 16 to a maximum of 0.00627 at t = 60. Thus, it satisfies our criterion that P(A) x PNS be < 0.016 for the CDF to be < 1E-6/y. The maximum CDF is 6.2E-5/yr x 0.00627 = 3.9E-7/y.

SENSITIVITY CASE

As a sensitivity case, we assumed that P(T) and P(A) inversely varied quadratically and quartically to represent the situation where the probability of HEMYC® ERFBS failure is expected to exhibit a rapid initial rise, followed by a more gradual increase. The equations are as follows:

$$P(T) = \left(\frac{T - 703.83}{920 - 703.83}\right)^x$$

$$P(A) = \left(\frac{A - 4870}{46470 - 4870}\right)^x$$

where x = 0.5 for the quadratic case and 0.25 for the quartic case. Following a parallel approach as in the linear model, we calculate the following maxima for P(A) x PNS and corresponding maximum CDFs, as shown in the Microsoft Excel® attachment:

Quadratic: P(A) x PNS ≈ 0.0105 at t ≈ 40 → CDF ≈ 6.5E-7/y

Quartic: P(A) x PNS ≈ 0.0162 at t ≈ 27.5 → CDF ≈ 1.0E-6/y

Thus, even under these very conservative bounding assumptions, we essentially satisfy our criterion that P(A) x PNS be < 0.016 for the CDF to be < 1E-6/y.[d]

2. ELECTRICAL SWITCHGEAR ROOM FIRE

The attached curve from a CFAST® simulation of a nuclear plant Electrical Switchgear room fire shows a rapid initial temperature rise to ~300 ºC in ~ 3.5 min, followed by an exponential-type decrease due to oxygen depletion. For our purposes, we assume no oxygen depletion, such that the fire continues at the 300 ºC temperature out to t = 60. If we linearize this time-temperature curve in a manner similar to that for the ASTM-E119 fire, as follows:

Time (min)	Temp (°C)
0	0
3.5	300
60	300

we calculate that the threshold value A = 4870 is reached at t ≈ 18, with A reaching 23250 at t = 60. At the latter value, P(A) = 0.303 (see Microsoft Excel® attachment).

[d] For the quartic case, the CDF is at the 1E-6/y threshold value.

Assume a typical, older nuclear plant using HEMYC® ERFBS for SSD cables in their Electrical Switchgear room protects against an electrical fire, including a high-energy arcing fault switchgear fire, with fast-acting smoke detection and pre-action/deluge sprinkler suppression. From the FP SDP, Table A4.1, the fire frequencies of components that might be found in a typical Electrical Switchgear room are as follows: (1) for "Cables," 1.6E-5/y (low loading) to 0.0014/yr (high loading); and (2) per "Switchgear Cabinet," 5.5E-5/y (small electrical fire) and 4.7E-6/y (energetic fault), or a total of 6.0E-5/y. We assume for our Electrical Switchgear room that there is a high loading of cables and 25 electrical switchgear. The fire frequency becomes 0.0014/y + 25 x 6.0E-5/y = 0.0029/y.

The recommended fire severity characteristics from Table A4.1 are "Self-Ignited Cable Fires," "Small Electrical Fires" and "Energetic Faults;" and the recommended manual fire suppression curves are "Cable Fires," "Electrical Fires" and "Energetic Faults." Referring to the corresponding tables (2.3.1 and 2.7.1), we find the 95th %ile fire for "Small Electrical Fires" (assumed to be representative of "Self-Ignited Cable Fires") to be 200 kW; the 95th %ile for "Large Electrical Fires" (assumed to be representative of an energetic fault) to be 650 kW; the manual non-suppression probabilities for "Cable Fires" dropping below 0.10 after 13 min; the manual non-suppression probabilities for "Electrical Fires" dropping below 0.10 after 20 min; and the manual non-suppression probabilities for "Energetic Arcing Fault" fires not dropping below 0.10 until 45 min. For the sake of a bounding analysis, we choose the more severe categories from each table to represent our Electrical Switchgear room fire, namely "Large Electrical Fires" and "Energetic Arcing Fault" fires, respectively. We assume each can serve as a surrogate for an Electrical Switchgear room fire severe enough to generate the time-temperature characteristics needed to fail the HEMYC® ERFBS.

The FP SDP recommends a severity factor of 0.1 for the 95th %ile fire. Furthermore, if we assume that the HEMYC® ERFBS damage fails any enclosed cables, it is likely that no more than the equivalent of an automatic steam-drive train would remain available to mitigate core damage, especially should this older plant self-induce an SBO given a fire-initiated transient. This mitigating capability could be attributed to equipment in the area unaffected by the fire, since actual fires are not expected to be area-wide or to affect other manual actions taken by operators, even if those actions are not in procedures. The corresponding screening value for CCDP is 0.1. Thus, collecting the probabilities from the FP SDP, we can express the CDF as 0.0029/y x 0.1 x 0.1 x P(A) x PNS = 2.9E-5/y x P(A) x PNS, where PNS is the non-suppression probability. For CDF < 1E-6/y, we require P(A) x PNS < 0.034.

The Microsoft Excel® attachment shows P(A) as a function of t for the Electrical Switchgear room fire. Rapid detection from the smoke detectors would be expected, such that the pre-action/deluge system would deliver water within a minute of detection. Even without suppression, no HEMYC® ERFBS damage is expected until ~ 18 min after the fire starts. From the FP SDP, Table A8.2, the non-suppression probability for this sprinkler system is essentially zero, since the time-to-damage exceeds the time-to-suppression by at least 10 min. However, since the FP SDP recommends a 0.05 unavailability for a sprinkler system, we expect that 5% of the time suppression will be by manual means, namely the plant fire brigade. The manual non-suppression probability for "Energetic Arcing Fault" fires is given in Table 2.7.1 as follows:

$$PNS = e^{-0.051\Delta t}$$

where Δt is the difference between time-to-damage and time-to-detection. Since rapid detection has been assumed, we can approximate Δt with t, namely the time since ignition of our electrical fire, i.e.,

$$PNS = e^{-0.051t}$$

This has to be multiplied by the unavailability of automatic suppression, yielding:

$$PNS = 0.05e^{-0.051t}$$

These values are calculated in the Microsoft Excel® attachment.

Now, for given values of t for our Electrical Switchgear room fire, we can readily calculate P(A) x PNS, as shown in the Microsoft Excel® attachment. This product rises from 0 at t ≈ 18 to a maximum of 0.00104 at t ≈ 37.5. Thus, it satisfies our criterion that P(A) x PNS be < 0.034 for the CDF to be < 1E-6/y. The maximum CDF is 2.9E-5/yr x 0.00104 = 3.0E-8/y.

SENSITIVITY CASE

As a sensitivity case, we assumed that P(T) and P(A) inversely varied quadratically and quartically to represent the situation where the probability of HEMYC® ERFBS failure is expected to exhibit a rapid initial rise, followed by a more gradual increase. The equations are as follows:

$$P(T) = \left(\frac{T - 703.83}{920 - 703.83}\right)^x$$

$$P(A) = \left(\frac{A - 4870}{46470 - 4870}\right)^x$$

where x = 0.5 for the quadratic case and 0.25 for the quartic case. Following a parallel approach as in the linear model, we calculate the following maxima for P(A) x PNS and corresponding maximum CDFs, as shown in the Microsoft Excel® attachment:

Quadratic: P(A) x PNS ≈ 0.00322 at t ≈ 27.5 → CDF ≈ 9.3E-8/y

Quartic: P(A) x PNS ≈ 0.00674 at t ≈ 22.5 → CDF ≈ 2.0E-7/y

Thus, even under these very conservative bounding assumptions, we satisfy our criterion that P(A) x PNS be < 0.034 for the CDF to be < 1E-6/y.

3. MAKE-UP PUMP ROOM FIRE

The attached curve from a CFAST® simulation of a nuclear plant Make-up (MU) Pump room fire shows a rapid initial temperature rise to ~180 ºC in ~ 1.0 min, with a final temperature of ~235 ºC reached after one hour. If we linearize this time-temperature curve in a manner similar to that for the ASTM-E119 fire, as follows:

Time (min)	Temp (°C)
0	0
1.0	180

60	235

we calculate that the threshold value A = 4870 is reached at t ≈ 26, with A reaching 12332.5 at t = 60. At the latter value, P(A) = 0.179 (see Microsoft Excel® attachment).

Assume a typical, older nuclear plant using a HEMYC® ERFBS for safe shutdown (SSD) cables in their MU Pump room protects against a pump fire with fast-acting smoke detection and pre-action/deluge sprinkler suppression. From the FP SDP, Table A4.1, the fire frequencies of components that might be found in a typical MU Pump room are as follows: (1) for "Cables," 1.6E-5/y (low loading) to 0.0014/yr (high loading); (2) per "General Electrical Cabinet," 6.0E-5/y; and (3) per "Other Pump (> 100 HP)," 5.0E-5/y (large electrical fire) and 5.0E-5/y (oil fire), or a total of 1.0E-4/y. We assume for our MU Pump room that there is a low loading of cables, two general electrical cabinets, and six pumps. The fire frequency becomes 1.6E-5/y + 2 x 6.0E-5/y+ 6 x 1.0E-4/y = 7.4E-4/y.

The recommended fire severity characteristics from Table A4.1 are "Self-Ignited Cable Fires," "Small Electrical Fires," "Large Electrical Fires" and "Oil Fires;" and the recommended manual fire suppression curves are "Cable Fires," "Electrical Fires" and "All (Fire) Events." Referring to the corresponding tables (2.3.1 and 2.7.1), we find the 95th %ile fire for "Small Electrical Fires" (assumed to be representative of "Self-Ignited Cable Fires") to be 200 kW; the 95th %ile for "Large Electrical Fires" to be 650 kW; the 95th %ile for "Indoor Oil-Filled Transformer" fires to be 2 MW; the manual non-suppression probabilities for "Cable Fires" dropping below 0.10 after 13 min; the manual non-suppression probabilities for "Electrical Fires" dropping below 0.10 after 20 min; and the manual non-suppression probabilities for "All (Fire) Events" not dropping below 0.10 until 33 min. For the sake of a bounding analysis, we choose the more severe categories from each table to represent our Electrical Switchgear room fire, namely "Large Electrical Fires" and "All (Fire) Events," respectively.[e] We assume each can serve as a surrogate for a MU Pump room fire severe enough to generate the time-temperature characteristics needed to fail the HEMYC® ERFBS.

The FP SDP recommends a severity factor of 0.1 for the 95th %ile fire. Furthermore, if we assume that the HEMYC® ERFBS damage fails any enclosed cables, it is likely that no more than the equivalent of an automatic steam-drive train would remain available to mitigate core damage, especially should this older plant self-induce an SBO given a fire-initiated transient. This mitigating capability could be attributed to equipment in the area unaffected by the fire, since actual fires are not expected to be area-wide or to affect other manual actions taken by operators, even if those actions are not in procedures. The corresponding screening value for CCDP is 0.1. Thus, collecting the probabilities from the FP SDP, we can express the CDF as 7.4E-4/y x 0.1 x 0.1 x P(A) x PNS = 7.4E-6/y x P(A) x PNS, where PNS is the non-suppression probability. For CDF < 1E-6/y, we require P(A) x PNS < 0.14.

The Microsoft Excel® attachment shows P(A) as a function of t for the MU Pump room fire. Rapid detection from the smoke detectors would be expected, such that the pre-action/deluge system would deliver water within a minute of detection. Even without suppression, no HEMYC® ERFBS damage is expected until ~ 26 min after the fire starts. From the FP SDP,

[e] Although the "Indoor Oil-Filled Transformer" fire exhibits the highest 95th %ile fire at 2 MW, we choose the "Large Electrical Fire" as characteristic for the MU Pump room since the oil supply would presumably be more limited and the ignition source less energetic than those for the transformer fire. Also, the analysis for the EDG room fire would bound this since it assumed a higher ignition frequency, the more severe "Indoor Oil-Filled Transformer" fire, and manual non-suppression probabilities from the more severe "T-G" fire.

Table A8.2, the non-suppression probability for this sprinkler system is essentially zero, since the time-to-damage exceeds the time-to-suppression by at least 10 min. However, since the FP SDP recommends a 0.05 unavailability for a sprinkler system, we expect that 5% of the time suppression will be by manual means, namely the plant fire brigade. The manual non-suppression probability for “All (Fire) Events” is given in Table 2.7.1 as follows:

$$PNS = e^{-0.069\Delta t}$$

where Δt is the difference between time-to-damage and time-to-detection. Since rapid detection has been assumed, we can approximate Δt with t, namely the time since ignition of our pump fire, i.e.,

$$PNS = e^{-0.069t}$$

This has to be multiplied by the unavailability of automatic suppression, yielding:

$$PNS = 0.05e^{-0.069t}$$

These values are calculated in the Microsoft Excel® attachment.

Now, for given values of t for our MU Pump room fire, we can readily calculate P(A) x PNS, as shown in the Microsoft Excel® attachment. This product rises from 0 at t ≈ 26 to a maximum of 2.24E-4 at t ≈ 40. Thus, it satisfies our criterion that P(A) x PNS be < 0.14 for the CDF to be < 1E-6/y. The maximum CDF is 7.4E-6/yr x 2.24E-4 = 1.7E-9/y.

SENSITIVITY CASE

As a sensitivity case, we assumed that P(T) and P(A) inversely varied quadratically and quartically to represent the situation where the probability of HEMYC® ERFBS failure is expected to exhibit a rapid initial rise, followed by a more gradual increase. The equations are as follows:

$$P(T) = \left(\frac{T - 703.83}{920 - 703.83}\right)^x$$

$$P(A) = \left(\frac{A - 4870}{46470 - 4870}\right)^x$$

where x = 0.5 for the quadratic case and 0.25 for the quartic case. Following a parallel approach as in the linear model, we calculate the following maxima for P(A) x PNS and corresponding maximum CDFs, as shown in the Microsoft Excel® attachment:

Quadratic: P(A) x PNS ≈ 9.57E-4 at t ≈ 32.5 → CDF ≈ 7.1E-9/y

Quartic: P(A) x PNS ≈ 0.00237 at t ≈ 30 → CDF ≈ 1.8E-8/y

Thus, even under these very conservative bounding assumptions, we satisfy our criterion that P(A) x PNS be < 0.14 for the CDF to be < 1E-6/y.

REFERENCES

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2. Peacock, R. D., Jones, W. W., and Forney, G. P, “CFAST: Consolidated Model of Fire Growth and Smoke Transport (Version 5), User's Guide,” NIST SP 1034, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, December 2004.

3. USNRC Inspection Manual Chapter 0609, Appendix F, “Fire Protection Significance Determination Process,” May 2004.