Quantification of Judgment: Defense-In-Depth and Safety Margin for Fire Protection

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Abstract - *This paper offers a thought process to facilitate the selection of qualitative provisions for defense-in-depth and safety margin in nuclear power plant Fire Protection using a quantitative approach based on probabilistic risk analysis (PRA). The influx of risk-informed, performance-based thinking to nuclear power plant Fire Protection regulation suggests that PRA be considered to assist in these traditional evaluations. One possible approach has been offered, combining aspects of uncertainty analysis in PRA with the estimates of failure probabilities provided by the Fire Protection Significance Determination Process. An approach such as this could ease the transition between deterministically-based Fire Protection programs and risk-informed, performance-based programs under 10CFR50.48(c) on risk-informed, performance-based Fire Protection in nuclear power plants, via the corresponding standard NFPA-805.*

I. INTRODUCTION[a]

The following grew from my presentation at the 2004 Nuclear Energy Institute (NEI) Fire Protection Information Forum [1] on transitioning deterministically-based Fire Protection programs at nuclear power plants to risk-informed, performance-based programs via 10 CFR 50.48(c) [2] and NFPA 805 [3]. There I offered the concept of employing quantitative measures associated with uncertainties in probabilistic risk analysis (PRA) to suggest deterministic provisions for defense-in-depth (DID) and safety margin (SM), as required in NFPA 805. What I have developed is strictly a personal view on how this approach might be expanded to address DID and SM in the Fire Protection arena, still required to be treated deterministically, by utilizing quantitative insights. As such, this is not a strict mathematical derivation, and any calculations have been used to provide relative, not absolute, rankings.

These relative rankings have subsequently been used to assign actions of prospective DID and SM aspects from the Fire Protection Significance Determination Process (FP SDP) [4] to varying levels of "comfort" with regard to providing DID and SM in Fire Protection applications. This is intended more to stimulate thought along the lines of utilizing quantitative insights in what has to date been exclusively a qualitative arena, namely the assignment of DID and SM measures for Fire Protection applications on a purely deterministic basis. The hope is that an approach such as this could ease the transition between deterministically-based Fire Protection programs and risk-informed, performance-based programs under 10 CFR 50.48(c) and NFPA 805.

[a] This paper was prepared by an employee of the U.S. Nuclear Regulatory Commission. The views presented do not represent an official staff position. The U.S. Nuclear Regulatory Commission has neither approved nor disapproved its technical content.

II. BACKGROUND

Traditionally, DID and SM for nuclear power plant applications have been treated in a deterministic way. With the advent of risk-informed, performance-based regulation, DID and SM are now being integrated in the broader framework of PRA. Examples follow.

II.A. NFPA 805, Section 2.4.4, "Plant Change Evaluation"

"A plant change evaluation ... to ensure that a change to a previously approved fire protection program element is acceptable ... shall consist of an integrated assessment of the acceptability of risk, defense-in-depth, and safety margins ... The plant change evaluation shall ensure that the philosophy of defense-in-depth ... [and] sufficient safety margins [are] maintained. The deterministic approach for meeting the [nuclear safety] performance criteria shall be deemed to satisfy [these] requirement[s]." [3]

II.B. NEI 04-02, Section 5.3, "Plant Change Process"

"Sections 2.4.4.2 and 2.4.4.3 [of NFPA 805] for defense-in-depth and safety margin ... [require] the adequate maintenance of these factors. Criteria complying with these requirements also are provided in Regulatory Guide 1.174 ... Note that Sections 2.4.4.2 and 2.4.4.3 also indicate that these requirements shall be deemed to [sic] [be satisfied] by complying with the deterministic approach for meeting the [nuclear safety] performance criteria." [5]

II.C. Regulatory Guide 1.174, Section 2.2.1.1, "Defense-in-Depth "

"The defense-in-depth philosophy ... has been and continues to be an effective way to account for uncertainties in equipment and human performance. If a comprehensive risk analysis is done, it can be used to help determine the appropriate extent of defense-in-depth ... to ensure protection of public health and safety. When a comprehensive risk assessment is not or cannot be done, traditional defense-in-depth considerations should be used or maintained to account for uncertainties ... [T]he licensee should select the engineering analysis techniques, whether quantitative or qualitative, traditional or probabilistic, appropriate to the proposed licensing basis change.

Consistency with the defense-in-depth philosophy is maintained if ... [among others,] system redundancy, independence, and diversity are preserved commensurate with the expected frequency, consequences of challenges to the system, and uncertainties (i.e., no risk outliers)." [6]

II.D. Regulatory Guide 1.174, Section 2.2.1.2, "Safety Margins"

"With sufficient safety margins ... [s]afety analysis acceptance criteria in the licensing basis are met, or proposed revisions provide sufficient margin to account for analysis and data uncertainty." [6]

II.E. Regulatory Guide 1.174, Section 2.2.6, "Integrated Decisionmaking"

"In making a regulatory decision, risk insights are integrated with considerations of defense-in-depth and safety margins ... Quantitative risk results from PRA calculations are typically the most useful and complete characterization of risk, but they are generally supplemented by qualitative risk insights and traditional engineering analysis ... Traditional engineering analysis provides insight into available margins and defense-in-depth ... With few exceptions, these assessments are performed without any quantification of risk." [6]

II.F. SECY 97-287, "Final Regulatory Guidance on Risk-Informed Regulation: Policy Issues"

"The mean value ... is appropriate for comparing with the [Regulatory Guide 1.174] acceptance guidelines. In recommending that the mean value should be used, the staff's overriding consideration is that the ... acceptance guidelines were established with the Commission's Safety Goals and subsidiary objectives in mind, and that those goals were meant to be compared with mean values. For the distributions generated in typical PRAs, the mean values typically corresponded to the region of the 70th to 80th percentiles, and coupled with a sensitivity analysis focused on the most important contributors to uncertainty, can be used for effective decision-making. The sources of uncertainty related to modeling or incompleteness should be identified along with whether there are any reasonable alternate assumptions or missing contributions that could change the results significantly enough to change the assessment. In this approach, the role of the uncertainty analysis is essential as a tool for analyzing the results of the PRA, to determine their robustness and to highlight possible areas of concern." [7]

III. THEORY

Ignition frequencies and conditional failure probabilities generated in PRA are typically characterized by lognormal distributions. The lognormal distribution has the interesting property that the product of lognormal variables is also lognormal. Thus, when developing a minimal cut set that characterizes an accident scenario, the distribution on the overall product is typically lognormal. Furthermore, the 90%, two-sided error factor on the product distribution is readily calculated from the 90%, two-sided error factors on the individual variables as follows.

For a given accident sequence (minimal cut set),

$$\text{Core Damage Frequency (CDF)} = \lambda \, \Pi \, p_i \qquad (1)$$

where λ is the initiator frequency and p_i is the ith conditional failure probability. Representing the 90%, two-sided error factor as f,

$$f_{CDF} = \exp\{[(\ln f_\lambda)^2 + \Sigma (\ln f_i)^2]^{0.5}\} \qquad (2)$$

where f_λ is the error factor on the initiator frequency and f_i is the error factor on the i^{th} conditional failure probability. Therefore, given the lognormal error factor on each of the terms in the CDF equation, the error factor on the lognormal product is readily calculated.

III.A. Risk Acceptance Criterion

The most restrictive threshold for acceptability of a CDF increase in Regulatory Guide 1.174 is ΔCDF < 1E-6/yr, where ΔCDF is represented as a mean value, plus satisfaction of defense-in-depth (DID) and safety margin (SM) considerations. While the latter are typically addressed qualitatively, it would be helpful if quantitative insights could be provided to help this qualitative evaluation. If the ΔCDF is characterized by a lognormal distribution with a known mean and error factor, some progress can be made.

In PRA, the 90%, two-sided percentile values are often considered a reasonable measure of uncertainty relative to the mean CDF. The corresponding upper bound, the limit of most interest, occurs at the 95^{th} percentile. For a lognormal variable with mean x_{av} and 90%, two-sided error factor f_{95}, the 95^{th} percentile upper bound is just

$$x_{95} = x_{av}f_{95}/\exp\{[(\ln f_{95})/1.645]^2/2\} \qquad (3)$$

For a lognormal mean ΔCDF of x_{av} < 1E-6/yr, insight on the "robustness" of the ΔCDF with respect to the Regulatory Guide 1.174 acceptance threshold can be obtained by estimating x_{95} and comparing it with the same threshold, i.e., 1E-6/yr. If x_{95} < 1E-6/yr as well, the ΔCDF estimate would appear to be robust with respect to satisfying the Regulatory Guide 1.174 acceptance criterion. The degree by which x_{95} < 1E-6/yr could be viewed as an indicator of safety margin. Even if x_{95} > 1E-6/yr (but x_{av} < 1E-6/yr), there may still be sufficient safety margin for the particular situation being considered. However, some degree of additional "comfort" seems plausible for the case where x_{95} < 1E-6/yr.

III.B. "Comfort" Level

The mean of a lognormal distribution always occurs at > 50^{th} percentile value, i.e., it always exceeds the median (the 50^{th} percentile value) due to its asymmetric shape which spreads out farther toward the upper end (i.e., higher values, which tend to shift the mean above the median). In Table 1, the ratio x_{95}/x_{av} has been calculated for lognormal means occurring at the 55^{th} through the 95^{th} percentile.

Over the range of possible percentile locations for the mean value, the maximum ratio of the 95^{th} percentile upper bound to the mean value does not exceed 4. This implies that a "comfortable" safety margin will exist whenever the mean ΔCDF < (1E-6/yr)/4 = 2.5E-7/yr, corresponding to a mean value occurring around the 80^{th} percentile. When the mean occurs at a percentile closer to one of the "extremes" (55^{th} or 95^{th} percentile value), a "comfortable" safety margin would seem to exist for a slightly higher mean CDF [e.g., at the 60^{th} percentile, a mean ΔCDF < (1E-6/yr)/2.02 = 5E-7/yr might be considered "comfortable"]. However, there are additional considerations.

For the case where the mean ΔCDF occurs at the 95^{th} percentile, the nature of the lognormal distribution indicates that this coincides with the 95^{th} percentile upper bound. If this mean ΔCDF < 1E-6/yr, we may be satisfying the Regulatory Guide 1.174 acceptance criterion, but the nature of the ΔCDF distribution is such that we would not necessarily consider the 95^{th} upper bound to represent a "comfortable" safety margin. For the mean to occur at such a high percentile value, there has to be some non-negligible probability that values much higher than 1E-6/yr are possible, more so than in the case where the mean occurs at lower percentile values. Therefore, we are not necessarily "comfortable."

In addition to examining the 95^{th} percentile upper bound for mean values of ΔCDF occurring at various percentiles, we must also consider the ratio of > 95^{th} percentile values (x_{ub}) to the mean, as shown in Table 2. (The reason for inverting the percentile values, i.e., starting with the higher and decreasing vertically and horizontally, will quickly become evident.)

Table 2 can be interpreted as follows. For the shaded value (60.8), the mean ΔCDF occurs at the 75^{th} percentile (which also implies f_{95} = 9.20). If we wanted an upper bound such that the probability of exceeding that upper bound would be no more than 100% - 99.99% = 0.01%, the ratio of that upper bound to the mean would have to be at least 60.8. For the situation discussed above (mean occurring at 95^{th} percentile), we would require an upper bound at least 919 times higher than the mean to have no more than that same 0.01% probability of exceeding it. On the other hand, for a mean occurring at the 55^{th} percentile, the ratio would only have to be 2.47.

One may feel "comfortable" with a factor of 4 between the 95th percentile upper bound and mean ΔCDF when the mean occurs at the lower percentile values (i.e., with lower error factors as well). Table 2 indicates that a ratio of x_{ub}/x_{av} of approximately 4 provides "comfort" at 99.9999% for a mean at the 55th percentile, at 99.9% for a mean at the 60th percentile, and at 99% for a mean at the 65th percentile. However, above these percentile values for the mean, we would be "more comfortable" with higher ratios.

III.C. Interpretation

Because these ratios compare probabilities involving extreme values, they should not be interpreted as numerical SMs directly. Ratios even as low as 10 are typically well beyond the magnitude of factors considered appropriate as SMs. Nonetheless, the relative magnitudes of these ratios may provide insight in suggesting appropriate degrees of SM and DID.

One possible interpretation is the following. Group the ratios by decades, i.e., factors of 10, to produce Fig. 1 (it is now evident why we chose to list decreasing values vertically and horizontally in Table 2). Level 1 represents the region where the ratio of the upper bound to the mean lies roughly between 1 and 10 for a given percentile where the mean occurs (y axis) and probability of exceeding the upper bound (x axis). Similarly, Level 2 represents the region where the ratio lies roughly between 10 and 100. Level 3 represents the region where the ratio lies roughly between 100 and 1000. Level 4 represents the region where the ratio exceeds 1000. For example, if the mean occurs at the 80th percentile (or, equivalently, with a lognormal error factor around 16), we would require the upper bound to be roughly 100-1000 times higher to "guarantee" a non-exceedance probability of no greater than approximately 0.01%.

There is no strict interpretation of these levels, other than a relative one, i.e., the lower the level, the less the ratio of the upper bound to the mean for a given (x, y) pairing. However, one possible interpretation is as follows. Given the percentile at which the mean occurs, one can suggest the level of DID that would be appropriate to provide some degree of "comfort" that the corresponding SM would not be exceeded at a selected probability.

Consider the above example. Given a mean ΔCDF at the 80th percentile value (or, equivalently, with a lognormal error factor around 16), a DID provision at Level 2 would be indicative that the probability of exceeding the SM corresponding to the Level-2 DID would not be higher than 1%. Meanwhile, a DID provision at Level 3 would be indicative that the probability of exceeding the SM corresponding to the Level-3 DID would not be higher than 0.01%.

This concept is not mathematically rigorous, nor is it intended as a replacement for applying engineering judgment when determining DID and SM. However, at least in the area of Fire Protection, it suggests a process which could enhance decisions as to what level of DID and SM might be appropriate.

IV. APPLICATION

The FP SDP offers several aspects that seem amenable as potential means of establishing DID and SM. Some of these are the following.

1. Increasing the time between occurrence of damage to critical equipment and detection of fire, so as to increase the likelihood of successful manual suppression (FP SDP Table 2.7.1). This could involve enhancement to fire detection capability (e.g., more or better fire detectors), more frequent intervals for fire patrol,[b] or enhancement to manual suppression capability (e.g., additional hose stations, staging of portable extinguishers, decreasing the Fire Brigade response time).
2. Improvements to performance shaping factors that influence the ability of operators to perform safe-shutdown manual actions outside the Control Room (FP SDP Tables 2.8.1 and 2.8.2). One example would be rerouting the path the operator must take to reach the manual action location such that the chances of encountering smoke would be minimized.
3. Decreasing the probability of cable failure by enclosing a critical cable at a vulnerable location in conduit (FP SDP Table 2.8.3).
4. If transient combustibles are a dominant concern, reducing the amount that could be located in a vulnerable fire location, either by procedural or physical means (FP SDP Table A4.1).
5. Increasing the time between occurrence of damage to critical equipment and automatic suppression of fire, so as to increase the

[b] More frequent fire patrols would likely only be effective for slow-developing fires where the damage does not occur quickly nor the symptoms manifest themselves beyond a very localized area.

likelihood of successful automatic suppression (FP SDP Table A8.2). This could involve enhancement to the detection or suppression capability of the automatic system, such as more rapid detector response or increased coverage by the suppressing agent (e.g., denser layout of sprinkler heads in a vulnerable location).

6. While this may go beyond what one typically associates with DID or SM, adding a fixed suppression system or replacing an existing fixed non-wet-pipe system with wet-pipe sprinklers (FP SDP Section 6.2.7.4).[c]

IV.A. "Quantifying" Defense-in-Depth

For all of the above aspects, one can estimate the decrease in failure probability that would be possible by reviewing the associated tables or sections of the FP SDP. In doing so, the following ranges of decrease are roughly evident.

1. FP SDP Table 2.7.1. Using the "All Events" column, the probability of manual non-suppression decreases by the following factors given the following increases in time between damage and detection: (1) increase by 5-10 minutes provides a probability decrease up to a factor of 2; (2) increase by 15 minutes provides a probability decrease up to a factor of 3; (3) increase by 20 minutes provides a probability decrease up to a factor of 4; (4) increase by 25 minutes provides a probability decrease up to a factor of 6; (5) increase by 30 minutes provides a probability decrease up to a factor of 8.[d]
2. FP SDP Tables 2.8.1 and 2.8.2. These tables imply factor-of-10 decreases in human error probability for changes in "evaluation" of performance shaping factors. The probability of operator failure to accomplish a safe-shutdown manual action outside the Control Room decreases by the following factors given the following decreases in "evaluation" of performance shaping factors: (1) decrease by β (including $\alpha \rightarrow 2\beta$ and $\beta \rightarrow \gamma$) provides a probability decrease up to a factor of 5; (2) decrease by 2β (including $\alpha \rightarrow \beta$ and $2\beta \rightarrow \gamma$) provides a probability decrease up to a factor of 20; (3) decrease from $\alpha \rightarrow \gamma$ provides probability decrease up to a factor of 100.[e]
3. FP SDP Table 2.8.3. Considering only the potential for placing an existing cable inside a conduit, the probability of cable failure decreases by the following factors given the following cable types and interactions: (1) for thermoset, inter-cable interactions, and thermoplastic intra-cable interactions, enclosing in conduit provides a probability decrease up to a factor of 2; (2) for thermoset, intra-cable interactions, enclosing in conduit provides a probability decrease up to a factor of 4.
4. FP SDP Table A4.1. Considering situations where ignition of transient combustibles is a dominant concern, the probability (frequency) of transient combustible ignition decreases by the following factors given the following decreases in amount of transient combustibles: (1) decreasing from a medium to low amount provides a probability (frequency) decrease up to a factor of 3; (2) decreasing from a high to medium amount provides a probability (frequency) decrease up to a factor of 10; (3) decreasing from a high to low amount provides a probability (frequency) decrease up to a factor of 30.
5. FP SDP Table A8.2. The probability of automatic non-suppression decreases by the following factors given the following increases in time between damage and suppression: (1) increase by 1-2 minutes provides a probability decrease up to a factor of 2; (2) increase by 3-4 minutes provides a probability decrease up to a factor of 5; (3) increase by 5-6 minutes provides a probability decrease up to a factor of 8.
6. FP SDP Section 6.2.7.4. The probability of fixed non-suppression decreases by the following factors given the following changes for fixed suppression: (1) replacing a fixed gaseous or non-wet-pipe water suppression system with a fixed wet-pipe water suppression system provides a probability decrease up to factor of 3; (2) installing a fixed gaseous or non-wet-pipe water suppression system where none existed

[c] This measure is included mainly to address the Level-4 region, which would typically fall beyond the magnitude of measures taken solely for DID or SM.

[d] The potential to achieve increases between times to damage and detection that exceed 15 minutes is speculative but provided here for comparison purposes.

[e] The α, β and γ factors represent varying degrees of "degradation" in the ability of operators to perform manual actions outside the Control Room based on evaluating the effect of fire on the performance shaping factors. If there is little or no degradation, a γ factor is assigned. Intermediate degradation merits a factor of β or, if more severe, 2β. The α factor is assigned for the most severe degradation, possibly precluding the performance of the manual action altogether.

before provides a probability decrease up to a factor of 20; (3) installing a fixed wet-pipe water suppression system where none existed before provides a probability decrease up to a factor of 50.

If we treat these factors by which the failure probabilities for the above aspects decrease in a relative sense, we can align them into a rough rank as shown in Table 3. In addition, we somewhat arbitrarily assign the actions for the various DID/SM Fire Protection aspects to the levels previously developed when considering ratios of ΔCDF upper bounds to mean values. This assignment is not strictly numerical, but reflects relative differences on an order-of-magnitude scale, as well as differences between degrees within a certain aspect.

For example, increasing the time between damage and automatic suppression by 5-6 minutes, which reduces the failure probability up to a factor of 8, has been assigned to Level 3. Meanwhile, most other Level-3 assignments indicate reductions by factors of at least 10. This assignment represents a desire to show contrast between increasing the time between damage and automatic suppression by 3-4 minutes (assigned to Level 2) vs. 5-6 minutes (assigned to Level 3).[f] The dotted lines between levels indicate that all assignments are approximate and no strict boundaries exist between levels.

V. SUMMARY

In this paper, I have attempted to present a thought process to facilitate the selection of DID/SM provisions for Fire Protection using a PRA approach. It is recognized that the assignment of DID measures remains mainly in the deterministic realm. Nonetheless, it seems plausible that the influx of risk-informed, performance-based thinking to nuclear power plant Fire Protection regulation suggests that quantitative aspects of PRA be considered to assist in these traditional evaluations. One possible approach has been offered, combining aspects of uncertainty analysis in PRA with the estimates of failure probabilities provided by the FP SDP. At least in a relative sense, levels of DID/SM can be assigned to actions that would typify attempts to enhance a nuclear power plant Fire Protection program..

[f] Likewise, the safe-shutdown operator manual action decrease in performance shaping "evaluation" factor by 2β, with an approximate decrease factor of 20, has been assigned to Level 3 to show contrast with the analogous decrease from α→γ, assigned to Level 4.

VI. REFERENCES

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TABLE 1. Ratio of 95th Percentile Upper Bound to Mean for a Lognormal Distribution

Percentile at which mean occurs	x_{95}/x_{av}	f_{95} (pre-determined by mean percentile)
55	1.47	1.51
60	2.02	2.30
65	2.64	3.55
70	3.24	5.61
75	3.70	9.20
80	3.87	15.9
85	3.53	30.2
90	2.54	67.8
95	1.00	224

TABLE 2. Ratio of Variable Percentile Upper Bound to Mean for a Lognormal Distribution

%ile at which mean occurs	x_{ub}/x_{av} for ub =					Lognormal Error Factor
	99.9999%	**99.999%**	**99.99%**	**99.9%**	**99%**	
95	27600	5540	919	116	9.41	**224**
90	7320	2090	517	103	14.6	**67.8**
85	2220	806	260	70.6	14.5	**30.3**
80	724	318	127	44.0	12.2	**15.9**
75	245	127	60.8	26.0	9.28	**9.20**
70	84.4	50.6	28.5	14.8	6.62	**5.61**
65	29.0	19.9	13.1	8.04	4.46	**3.55**
60	9.77	7.63	5.79	4.21	2.86	**2.30**
55	3.20	2.83	2.47	2.11	1.74	**1.51**

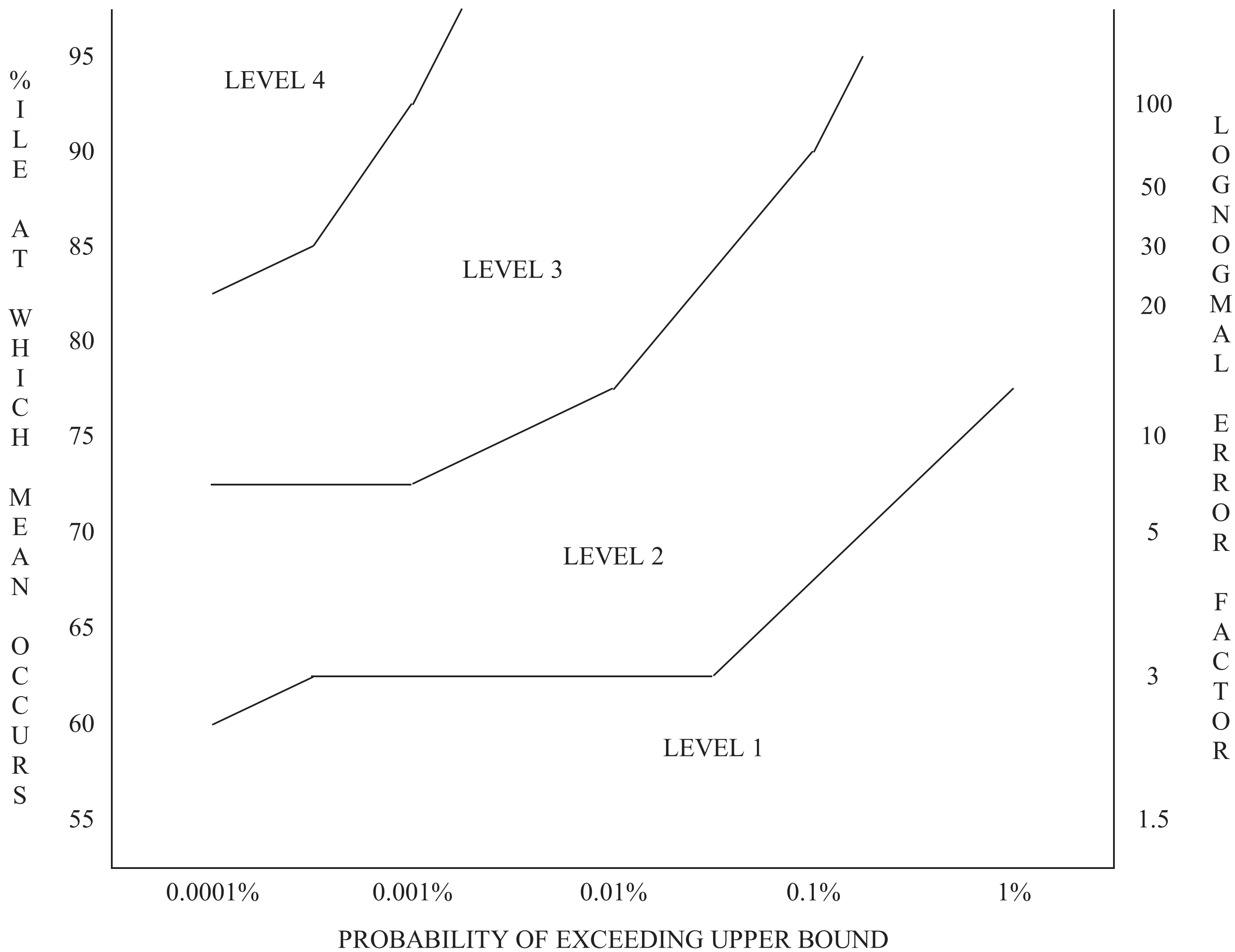

Fig. 1. "Comfort" Level Provided by Defense-in-Depth for Lognormal Mean at a Specific Percentile for a Selected Probability of Exceeding Lognormal Upper Bound

TABLE 3. Approximate Factors by Which Failure Probabilities Decrease for Specific Fire Protection Aspects of Defense-in-Depth and Safety Margin

DID/SM Aspect	Action	Approximate decrease factor for failure probability	DID/SM Level
Automatic non-suppression probability	Increase time between damage and suppression by 1-2 minutes	2	Level 1
Cable failure probability	Enclosing a cable in conduit: thermoset, inter-cable interactions; thermoplastic, intra-cable interactions	2	
Manual non-suppression probability	Increase time between damage and detection by 5-15 minutes	2-3	
Transient combustibles	Decrease amount from medium to low	3	Level 2
Fixed non-suppression probability	Replacing a gaseous or non-wet-pipe water system with a wet-pipe water system	3	
Cable failure probability	Enclosing a cable in conduit: thermoset, intra-cable interactions	4	
Automatic non-suppression probability	Increase time between damage and suppression by 3-4 minutes	5	
Safe-shutdown operator manual actions outside Control Room	Decrease performance shaping "evaluation" factor by β	5	
Manual non-suppression probability	Increase time between damage and detection by 20-25 minutes	4-6	
Automatic non-suppression probability	Increase time between damage and suppression by 5-6 minutes	8	Level 3
Manual non-suppression probability	Increase time between damage and detection by 30 minutes	8	
Transient combustibles	Decrease amount from high to medium	10	
Fixed non-suppression probability	Installing gaseous or non-wet-pipe water suppression where none existed	20	
Safe-shutdown operator manual actions outside Control Room	Decrease performance shaping "evaluation" factor by 2β	20	
Transient combustibles	Decrease amount from high to low	30	Level 4
Fixed non-suppression probability	Installing wet-pipe water suppression where none existed	50	
Safe-shutdown operator manual actions outside Control Room	Decrease performance shaping "evaluation" factor from α→γ	100	