Apportioning Transient Combustible Fire Frequency via Areal Factors: More Complicated Than It May Seem

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Abstract: Apportioning the frequency of transient combustible fires to vary within a physical analysis unit for a fire probabilistic risk assessment (PRA) has been discussed and attempted by various analysts to date with limited success. The technique presented here illustrates the complexity involved in such a calculation, considering the constraints on preserving transient fire ignition frequencies within the Fire PRA, which may lend insight into why this has proven a difficult process. While the approach offered can be used, the goal is more to provide "food for thought" that may lead to a more straightforward, even if approximate, technique that would reasonably represent the reality of the situation without being overly complex.

Key Words: Fire Frequency, Transient Combustibles, Apportionment, Fire PRA

1. INTRODUCTION[1]

NUREG/CR-6850 / EPRI (Electric Power Research Institute) 1011989, as enhanced by National Fire Protection Association (NFPA) 805 Frequently Asked Question (FAQ) 12-0064 [2], addresses "ignition source weighting factors" for transient combustibles located in the "physical analysis units (PAUs)" of a nuclear power plant to guide the allocation of transient fire ignition frequencies for Fire PRAs. Implicit in this modeling is an assumption that the weighting, or "influence," factors remain the same throughout the PAU, which is typically a "spatial subdivision of the plant ... generally defined in terms of fire areas and/or fire compartments," such as a fully enclosed room. [3] In the process of applying this guidance for Fire PRAs, especially ones developed to support transitions to 10CFR50.48(c), analysts have sought ways to account for variations within certain PAUs to represent particular sub-locations where reduced fire ignition frequency due to stricter transient combustible controls than generally present in the rest of the PAU can be credited, e.g., G. Zucal and R. White, "The Influence of Spatial Geometry on Transient Fire Likelihood." [4] However, due to the need to preserve the PAU frequency regardless of any redistribution within the PAU itself, this author shows that the process can be quite complicated, as demonstrated through an illustrative example.

2. ANALYSIS

Assume a plant has a total area of $10^2 = 100$ square units, divided into the seven PAUs shown in Figure 1. Each PAU is rated "average" for transient combustible fires for all four influence factors, i.e., 3 each for Hot Work Maintenance, Electrical/Mechanical (E/M) Maintenance, Occupancy and Storage. [1-2] Thus, for Hot Work maintenance, the total plant hot work ignition frequency, λ_{hw}, is apportioned equally among all seven PAUs, i.e., $\lambda_{hw,PAU-x} = \lambda_{hw}/7$. Likewise for E/M Maintenance, $\lambda_{e/m,PAU-x} = \lambda_{e/m}/7$. The fact that the PAUs have different areas does not affect the apportioning of the transient combustible fire frequency.

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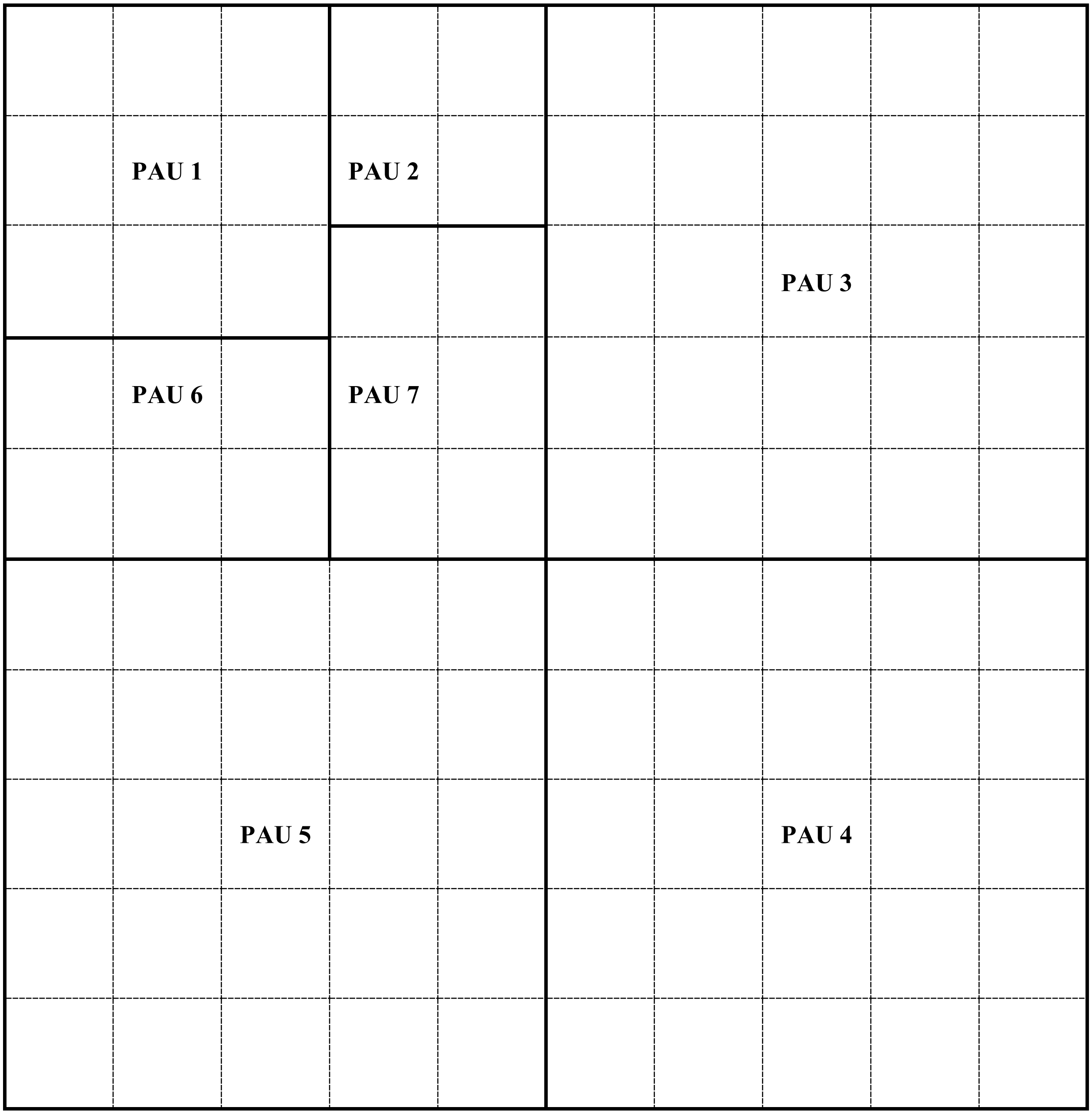
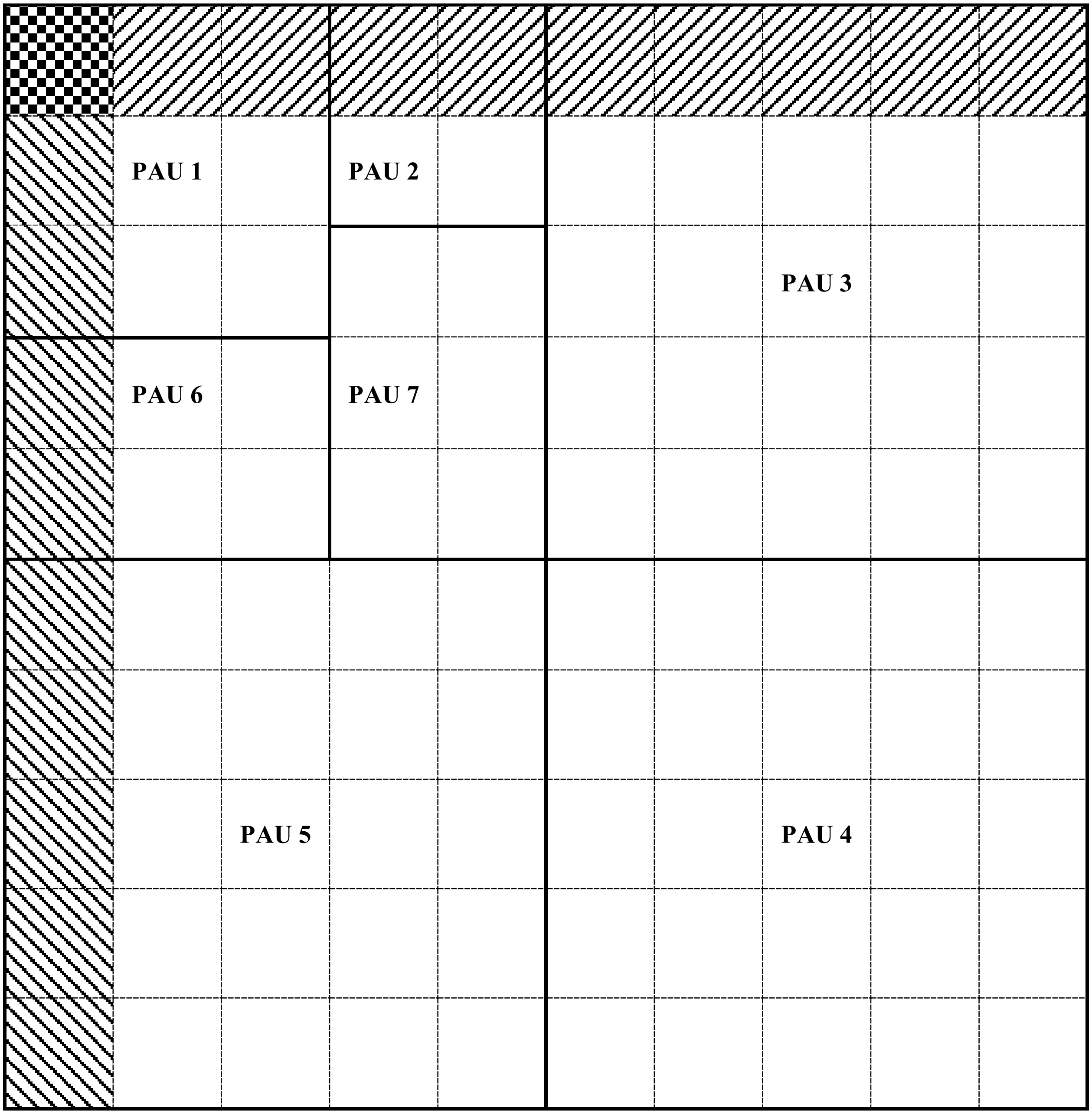
[1] This paper was prepared by an employee of the U.S. NRC. The views presented do not represent an official staff position.

Figure 1: Layout for Physical Analysis Units



Now, assume the only zones of influence (ZOIs) where fire damage can occur to risk-significant components at the plant are shown by the two single-hatched areas along the top and left side of the layout, with their intersection occurring only in one location in PAU 1 shown by the cross-hatching (Figure 2). The single-hatched areas could represent each of two redundant trains, with an associated conditional core damage probability (CCDP) = C_1. The cross-hatched area then represents the "pinch point" where both trains can be damaged, with CCDP = $C_2 > C_1$. We need to apportion the transient combustible fire frequencies such that they correspond to pairings of ZOI and CCDP, i.e., into three pairings: (1) no ZOI (no risk-significant components), shown non-hatched; (2) ZOI for single-train, i.e., pairing with CCDP = C_1 (single-hatch); (3) ZOI for "pinch point," i.e., pairing with CCDP = C_2 (cross-hatch).

Figure 2: Layout for Physical Analysis Units Showing Sub-locations where Potentially Risk Significant Fire Damage Can Occur



Where a PAU contains no ZOI (PAUs 4 and 7), there is no risk contribution, ($CDF_{PAU\text{-}4} = CDF_{PAU\text{-}7} = 0$), since there is no risk-significant component ZOI present. Transient combustible fires occurring here cannot contribute to risk. For the remaining PAUs, containing either or both a ZOI paired with C_1 or C_2, the apportioning of the transient combustible fire frequency within each depends on the likelihood of the fire being located within vs. without the ZOI.

<u>Simple Case</u>

The simplest case occurs if the fire is equally likely to be located anywhere within the PAU. For all but PAU 1, the corresponding CDFs are as follows (ignoring suppression, etc., i.e., considering only ignition and CCDP), dropping the subscript for Hot Work or E/M maintenance since the formulas would be the same for each:

$CDF_{PAU-3} = CDF_{PAU-5} = (\lambda_{PAU-3}/5) \text{ x } C_1 = (\lambda_{PAU-5}/5) \text{ x } C_1 = (\lambda/7)/5 \text{ x } C_1 = \lambda/35 \text{ x } C_1$, since the ZOI covers 1/5 of each PAU. (1)

$CDF_{PAU-2} = (\lambda_{PAU-2}/2) \text{ x } C_1 = (\lambda/7)/2 \text{ x } C_1 = \lambda/14 \text{ x } C_1$, since the ZOI covers 1/2 of PAU 2. (2)

$CDF_{PAU-6} = (\lambda_{PAU-6}/3) \text{ x } C_1 = (\lambda/7)/3 \text{ x } C_1 = \lambda/21 \text{ x } C_1$, since the ZOI covers 1/3 of PAU 6. (3)

For PAU 1, the analysis has an additional complication in that, within the ZOI, there are different CCDPs: $C_1 < C_2$. Therefore,

$CDF_{PAU-1} = (\lambda_{PAU-1} \text{ x } 4/9) \text{ x } C_1 + (\lambda_{PAU-1}/9) \text{ x } C_2 = \lambda_{PAU-1}/9 \text{ x } (4 \text{ x } C_1 + C_2) = (\lambda/7)/9 \text{ x } (4 \text{ x } C_1 + C_2) = \lambda/63 \text{ x } (4 \text{ x } C_1 + C_2)$, since the ZOI for a either single train covers 4/9 of PAU 1, while the ZOI for both trains ("pinch point") covers 1/9 of PAU 1.
(4)

Another way of viewing this, which will prove convenient, is to assign the probabilities of the transient combustible fire being located in each "unit square" of the plant as shown below. One can then express these CDFs as follows:

$CDF_{PAU} = \lambda/7 \text{ x } \Sigma_{ZOI} (\pi \, [P_u \text{ x } C_u])$ (5)

Where Σ = sum, π = product, P_u = probability of transient combustible fire in unit square, C_u = CCDP for transient combustible fire in unit square.

The previous equations are recalculated below to give the same results (see Figure 3):

$CDF_{PAU-3} = CDF_{PAU-5} = \lambda/7 \text{ x } (5 \text{ x } 1/25 \text{ x } C_1) = \lambda/35 \text{ x } C_1$. (6)

$CDF_{PAU-2} = \lambda/7 \text{ x } (2 \text{ x } 1/4 \text{ x } C_1) = \lambda/14 \text{ x } C_1$. (7)

$CDF_{PAU-6} = \lambda/7 \text{ x } (2 \text{ x } 1/6 \text{ x } C_1) = \lambda/21 \text{ x } C_1$. (8)

$CDF_{PAU-1} = \lambda/7 \text{ x } (4 \text{ x } 1/9 \text{ x } C_1 + 1/9 \text{ x } C_2) = \lambda/63 \text{ x } (4 \text{ x } C_1 + C_2)$. (9)

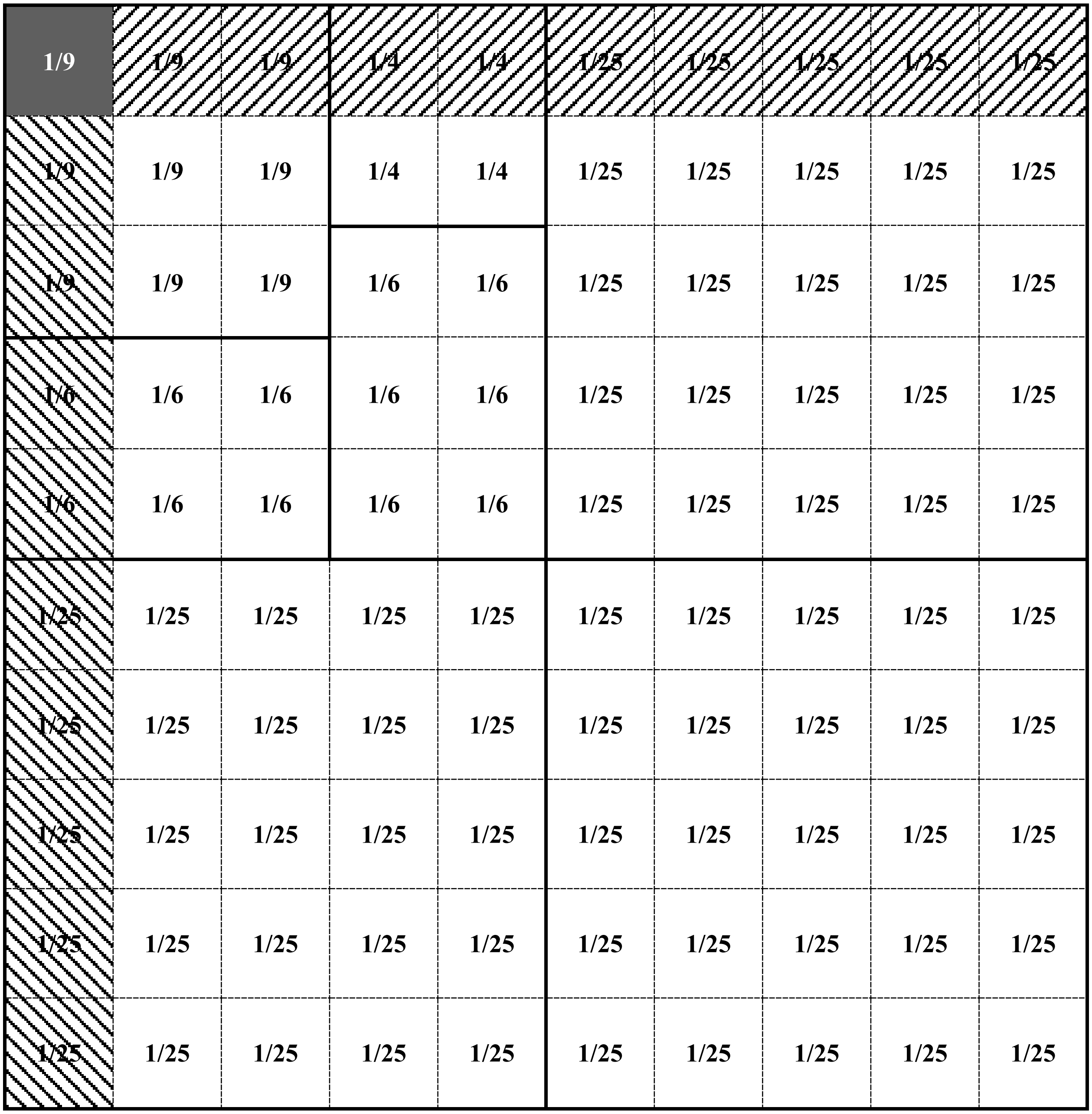
Adding Complexity

Let's consider some additional complexity. Assume that, in PAU 2, 3, 6 or 7 (PAU 1 is more complicated, and will be addressed subsequently), the analyst credits an effort to limit the potential for transient combustible fires within the risk-significant ZOI, perhaps by erecting at least a gated, cross-link fence around the ZOI with "combustible exclusion zone" signage. Further, assume as the result of this modification, the analyst can justify the likelihood of a transient combustible fire within the ZOI now being only 1/10 of that outside the ZOI within the PAU. That is,

Probability of transient fire within ZOI (P_{in}) = Probability of transient fire outside ZOI (P_{out})/10.

Total probability of transient fire within PAU = $P_{in} + P_{out} = P_{out}/10 + P_{out} = P_{out} \times 11/10 = 1$.
Therefore, $P_{out} = 10/11$ and $P_{in} = 1/11$.

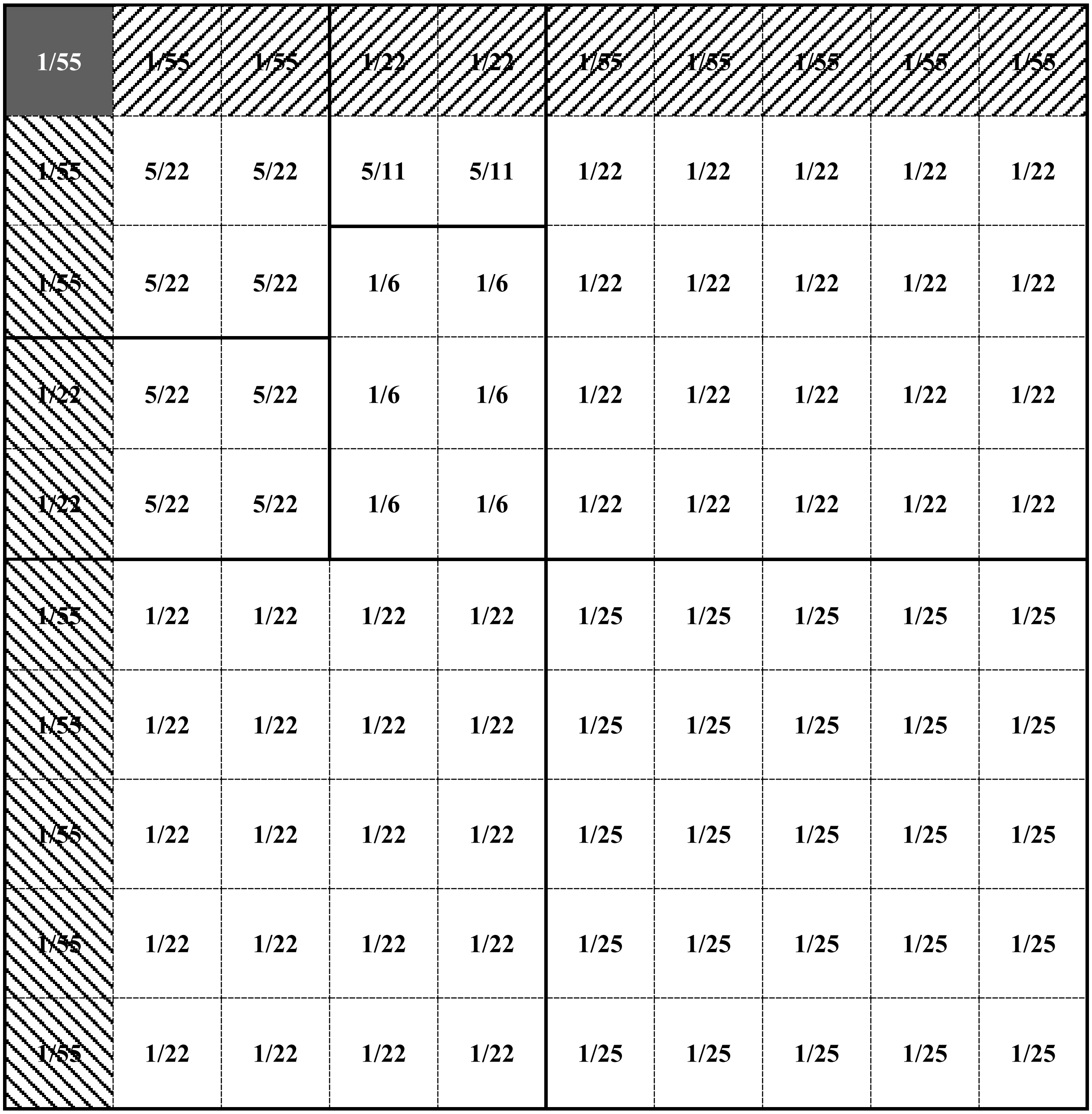
Figure 3: Layout for Physical Analysis Units Showing Equal Likelihoods among Sub-locations where Potentially Risk Significant Fire Damage Can Occur



1/9	1/9	1/9	1/4	1/4	1/25	1/25	1/25	1/25	1/25
1/9	1/9	1/9	1/4	1/4	1/25	1/25	1/25	1/25	1/25
1/9	1/9	1/9	1/6	1/6	1/25	1/25	1/25	1/25	1/25
1/6	1/6	1/6	1/6	1/6	1/25	1/25	1/25	1/25	1/25
1/6	1/6	1/6	1/6	1/6	1/25	1/25	1/25	1/25	1/25
1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25
1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25
1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25
1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25
1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25	1/25

These probabilities are then apportioned among the unit squares, which effectively reduces the CDF within the PAU, readily observable as shown below (e.g., in PAU 3, there are five unit squares within the ZOI whose total probability = 1/11, so each receives a 1/5 contribution, or 1/55; similarly for the 20 unit squares outside the ZOI, whose total probability = 10/11, each receives a 1/20 contribution, or 1/22) (see Figure 4):

Figure 4: Layout for Physical Analysis Units Showing Physically-Limited Access to Sub-locations where Potentially Risk Significant Fire Damage Can Occur



1/55	1/55	1/55	1/22	1/22	1/55	1/55	1/55	1/55	1/55
1/55	5/22	5/22	5/11	5/11	1/22	1/22	1/22	1/22	1/22
1/55	5/22	5/22	1/6	1/6	1/22	1/22	1/22	1/22	1/22
1/22	5/22	5/22	1/6	1/6	1/22	1/22	1/22	1/22	1/22
1/22	5/22	5/22	1/6	1/6	1/22	1/22	1/22	1/22	1/22
1/55	1/22	1/22	1/22	1/22	1/25	1/25	1/25	1/25	1/25
1/55	1/22	1/22	1/22	1/22	1/25	1/25	1/25	1/25	1/25
1/55	1/22	1/22	1/22	1/22	1/25	1/25	1/25	1/25	1/25
1/55	1/22	1/22	1/22	1/22	1/25	1/25	1/25	1/25	1/25
1/55	1/22	1/22	1/22	1/22	1/25	1/25	1/25	1/25	1/25

As is evident, the hatched squares (ZOI) now have reduced probabilities for transient fires while the unhatched (no ZOI, excluding PAUs 4 and 7) have increased probabilities. Nonetheless, the sum of all probabilities within each PAU equals 1, as it must since we are still requiring the transient combustible fire to be located with the PAU.

Using our summation technique, the reduced CDFs in each PAU are readily calculated, as follows:

$$\mathrm{CDF}_{\mathrm{PAU\text{-}3}} = \mathrm{CDF}_{\mathrm{PAU\text{-}5}} = \lambda/7 \times (5 \times 1/55 \times C_1) = \lambda/77 \times C_1. \qquad (10)$$

$\mathrm{CDF}_{\mathrm{PAU\text{-}2}} = \mathrm{CDF}_{\mathrm{PAU\text{-}6}} = \lambda/7 \times (2 \times 1/22 \times C_1) = \lambda/77 \times C_1.$ (11)

$\mathrm{CDF}_{\mathrm{PAU\text{-}1}} = \lambda/7 \times (4 \times 1/55 \times C_1 + 1/55 \times C_2) = \lambda/385 \times (4 \times C_1 + C_2).$ (12)

These results may not, at first, seem intuitively obvious, as one might have expected each of the previously calculated PAU CDFs to decrease by a factor of 11. In fact, each decreases by a factor equal to 11 divided by the ratio of the total number of unit squares to the number just for the ZOI (i.e., the ratio of the total PAU area to the area covered only by the ZOI). The latter ratios for PAUs 1, 2, 3, 5 and 6 were originally 9/5, 4/2 = 2, 25/5 =5, 25/5 =5, and 6/2 = 3, respectively. As a result, we see the CDF in each of these PAUs decreasing by factors of 11/(9/5) = 6.11, 11/2 = 5.5, 11/5 = 2.2, 11/5 = 2.2, and 11/3 = 3.67, respectively. This is evident from the denominators in the three equations above. For PAU 1, the denominator has increased from 63 to 385, a factor of 6.11; for PAU 2, from 14 to 77, a factor of 5.5; for both PAUs 3 and 5, from 35 to 77, a factor of 2.2; for PAU 6, from 21 to 77, a factor of 3.67.

<u>Most Complex</u>

As a final level of complexity, assume that within the gated fence in PAU 1, the analyst takes additional measures to ensure no combustible fires within the pinch-point ZOI (e.g., maybe a chain link with additional signage), such that the likelihood of a transient combustible fire is justified to be further reduced by a factor of 5. The analysis extends from the previous as follows:

Probability of transient fire within pinch-point zone ($P_{\mathrm{in,pinch}}$) = Probability of transient fire in single-train zone (P'_{in})/5.

Probability of transient fire in single train zone (P'_{in}) = Probability of transient fire outside ZOI (P'_{out})/10.

Given the transient fire occurs within the ZOI, $P_{\mathrm{in,pinch}} + P'_{\mathrm{in}} + P'_{\mathrm{out}} = P'_{\mathrm{in}}/5 + P'_{\mathrm{out}}/10 + P'_{\mathrm{out}} = (P'_{\mathrm{out}}/10)/5 + P'_{\mathrm{out}}/10 + P'_{\mathrm{out}} = P'_{\mathrm{out}} \times 56/50 = 1$. Therefore, $P'_{\mathrm{out}} = 50/56 = 25/28$, $P'_{\mathrm{in}} = 5/56$ and $P_{\mathrm{in,pinch}} = 1/56$.

As above, these probabilities are then apportioned among the unit squares, which effectively further reduces the CDF within PAU-1, readily observable in Figure 5 [for PAU 1 only; the "pinch point" unit square receives the full probability of 1/56; each of the four single-train ZOI unit squares receives a probability of (5/56)/4 = 5/224; each of the four non-ZOI unit squares receives a probability of (25/28)/4 = 25/112]:

Again using our summation technique, the new CDF in PAU-1 is readily calculated, as follows:

$\mathrm{CDF}_{\mathrm{PAU\text{-}1}} = \lambda/7 \times (4 \times 5/224 \times C_1 + 1/56 \times C_2) = \lambda/7 \times (5/56 \times C_1 + C_2/56) = \lambda/392 \times (5 \times C_1 + C_2).$ (13)

Depending how much C_2 exceeds C_1, this CDF may or may not be lower than the previous, even though we are further restricting the presence of transient combustible fires within the "pinch point." This is a consequence of the reallocation of likelihood of transient combustible fire location throughout the PAU. In fact, there will not be a decrease until $C_2 > 50 \times C_1$, as shown here. Assuming $C_2 = \alpha \times C_1$:

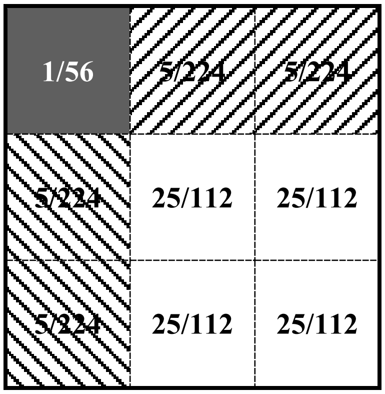
$\mathrm{CDF}_{\mathrm{PAU\text{-}1}}$ (1:10 ratio) $= \lambda/385 \times (4 \times C_1 + C_2) = \lambda/385 \times (4 \times C_1 + \alpha \times C_1) = \lambda/385 \times (4 + \alpha) \times C_1$ (14)

$$\mathrm{CDF}_{\mathrm{PAU\text{-}1}}\ (1{:}5{:}50 \text{ ratio}) = \lambda/392 \times (5 \times C_1 + C_2) = \lambda/392 \times (5 \times C_1 + \alpha \times C_1) = \lambda/392 \times (5 + \alpha) \times C_1. \quad (15)$$

$\mathrm{CDF}_{\mathrm{PAU\text{-}1}}\ (1{:}5{:}50 \text{ ratio}) < \mathrm{CDF}_{\mathrm{PAU\text{-}1}}\ (1{:}10 \text{ ratio})$ when $\lambda/392 \times (5 + \alpha) \times C_1 < \lambda/385 \times (4 + \alpha) \times C_1$, i.e., $\alpha > 51$

(16)

Figure 5: Layout for Physical Analysis Unit 1 Only, Showing Additional Physically-Limited Access to Sub-locations where Potentially Risk Significant Fire Damage Can Occur



3. SUMMARY

As demonstrated here, the technique by which an analyst may wish to vary transient combustible fire frequency within a PAU to account for physical limitations on access, etc., to reduce the potential for fire damage to risk-significant components can be quite complex. The example presented offers one approach to accommodate this, albeit it is not intuitively obvious or calculationally simple. Nonetheless, it is offered as a starting point toward developing a technique that may involve approximations , but ones which are sufficiently representative of reality to become practical tools.

References

[1] USNRC/EPRI, *EPRI/NRC-RES (Office of Nuclear Regulatory Research) Fire PRA Methodology for Nuclear Power Facilities*, NUREG/CR-6850 / EPRI 1011989 (2005).

[2] USNRC, “Close-out of NFPA Standard 805 FAQ 12-0064, ‘Hot Work/Transient Fire Frequency Influence Factors’” (2013), ADAMS (Agency-wide Documents Access and Management System) Accession No. ML12346A488.

[3] 10CFR50.48, “Fire Protection," Federal Register.

[4] G. Zucal and R. White, “The Influence of Spatial Geometry on Transient Fire Likelihood,” *ANS PSA Topical Meeting on Probabilistic Safety Assessment and Analysis*, September 22-26, 2013, Columbia, SC.