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THE "INCREDIBLE" DIFFICULTY OF PROVING "INCREDIBILITY"

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BACKGROUND (1)

- “Risk-informed” regulation is often an alternative to “deterministically-based” regulation that offers relaxation in criteria for acceptability while possibly requiring greater analytical effort.
- In the “deterministic” world, regulatory guidance employs the concept of “worst case” or “design basis” accidents.
  - Consistent with this is the concept that accidents rarer than these should be “incredible,” although no strict mathematical definition has ever been provided.
- In the risk-informed world, mathematical definitions, at least on an order-of-magnitude level, are employed for qualitative terms such as “small,” minimal,” “negligible,” etc.
- “Risk-informed determinism” is an attempt to meld the best of both worlds by using risk information to set deterministic acceptance criteria *a priori.*

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BACKGROUND (2)

- A joint effort by the US NRC's Office of Regulatory Research (RES) and Electric Power Research Institute (EPRI) originally endeavored to do this for several examples involving fire-induced multiple spurious operations (MSOs).
  - The original RES-EPRI effort did not consider the actual probability distributions involved in the events, limiting the analysis to mean values and, in some cases, qualitative considerations.
    - (In the final version, RES-EPRI removed any quantitative basis for its recommendations, but it was the original version that prompted the author to pursue the analysis presented here.)

OUTLINE

- A much more comprehensive and defensible approach is performed here where the probabilistic distributions for all the factors are considered via simulation to meet quantitative acceptance criteria related to the concept of “incredibility” that is often the figure of merit that must be met in a deterministic world.
  - This paper reanalyzes one particular example to show how difficult it can be to translate risk information into deterministic guidance when that guidance is held to a standard analogous to the concept of “worst case” or “design basis” accidents, signified by the term “incredible.”

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EXAMPLE (1)

- "If the MSO requires (a) three or more concurrent fire-induced cable shorts on separate target cables in non-latching circuits and (b) the hot shorts must be sustained for more than 10 min to cause the MSO condition, then the MSO is not required to be considered …
- "Using the mean values [from NUREG/CR-7150, *Joint Assessment of Cable Damage and Quantification of Effects from Fire* (2014)], the probability of three separate target cables with aggregate hot short failure mode for single break SOV grounded AC and thermoplastic cables is $0.44^3 = 0.0852$.

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EXAMPLE (2)

- "Using the spurious operation duration joint minimum value of 10^{-5}, then this probability reduces further … [to] 0.0852 x 10^{-5} = 8.5 x 10^{-7} …
- "Considering a conservative fire ignition frequency of 0.01, and a reasonably conservative CCDP of 0.1, then the probability of core damage is further reduced by approximately 0.001 … [to] 8.5 x 10^{-10} or less …
- "[T]hese MSO scenarios are not 'safety significant'* and they do not warrant further consideration."
  - (*The original version used "incredible." There was no issue with "safety significant," used in an intermediate version. The original version merely inspired the author to address the more restrictive concept of deterministic "incredibility," the topic of this presentation.)

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DEFINING "INCREDIBILITY" (1)

- Defining "incredibility" for use in the deterministic world, as with any other non-numerically-specific, quasi-quantitative terminology, can be a slippery slope.
  - NUREG/CR-7150 discusses this concept for spurious operation probabilities in terms of "implausible" or "incredible" scenarios.
    - "The term 'incredible' … signifies … that the event will not occur … The term 'implausible' … supports … [a] conclusion that the happening, while theoretically possible, would require the convergence of a combination of factors that are so unlikely to occur that the likelihood of the phenomenon can be considered statistically insignificant …"

DEFINING “INCREDIBILITY” (2)

- www.thefreedictionary.com cites “incredible” as “[s]o ‘implausible,’ as to elicit disbelief; unbelievable.”
- NUREG/CR-7150, for the probabilities of spurious operation for solenoid- and motor-operated valve (SOV and MOV), provides lowest 5th %ile probabilities ($< 10^{-5}$) of 4.9, 8.6, 1.2, 0.52, 4.1, 7.1, 1.0 and 0.45×10^{-6}, whose mean is 3.5 (arithmetic) or 2.1 (geometric) $\times 10^{-6}$.
  - On an order-of-magnitude level, this suggests a “working” definition of “incredible” for the example of $< 1 \times 10^{-6}$ strictly for the likelihood of MSOs.

CALCULATING "INCREDIBILITY" (1)

- Spurious operation probabilities are beta-distributed; the probability distribution of 'n' independent MSOs is $(p_1)(p_2)(p_3)\ldots(p_n)$, 'p' = probability distribution of just one.
  - At what %ile would one expect to reach 10^{-6} for "incredibility" via stochastic simulation of the probability distribution of this product, i.e., the maximum likelihood at which to accept occurrence $< 10^{-6}$?
- Acceptance level:
  - Once in a lifetime, ~ 1/100 y on an order-of-magnitude?
  - Once in a millennium, 1/1000 y?
  - Once in recorded human history, roughly since the last Ice Age, or ~ 1/10,000 y?

CALCULATING "INCREDIBILITY" (2)

- I contend that the event should never occur over the operating history of commercial nuclear power, i.e., < 1/3500 y ≈ 3 x 10^{-4} y (US) or < 1/15,000y ≈ 7 x 10^{-5} y (worldwide).
- Speaking in terms of orders of magnitude, both estimates are ~ 10^{-4} (0.01%), or once in recorded human history.
  - Use this as working definition of the %ile at which the probability of the MSOs must be < 10^{-6}, that is 100% - 0.01% = 99.99% of the resultant probability distribution must be < 10^{-6}

SIMULATING MSO PROBABILITY (1)

- From NUREG/CR-7150, aggregate probability (intra- or inter-cable) SO for a grounded AC SOV single-break, thermoplastic-insulated control circuit is beta distributed with corresponding 5th %ile, mean and 95th %ile values of 0.27, 0.44 and 0.61.
  - From stochastic simulation (10,000 trials) of one to 12 MSOs for this circuit:

Statistic	Probability of Number of MSOs			
	Three	Six	Nine	Twelve
5th %ile	0.0344	0.00189	1.14E-04	7.11E-06
Median	0.0773	0.00581	4.38E-04	3.34E-05
Mean	0.0827	0.00683	5.67E-04	4.75E-05
95th %ile	0.147	0.00157	0.00137	1.21E-04
99th %ile	0.187	0.0217	0.00224	2.23E-04
99.9th %ile	0.247	0.0311	0.00355	3.98E-04
99.99th %ile	0.300	0.0402	0.00476	5.31E-04

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SIMULATING MSO PROBABILITY (2)

- Not surprisingly, even after considering 12 MSOs, not even the 5th %ile has reached 10^{-6}.
  - One could deduce this just from the mean and number 'n,' where the number needed to reach a multiple occurrence probability of 10^{-6} would be:
    - $0.44^n = 10^{-6} \rightarrow n = \ln(10^{-6})/\ln(0.44) \approx 17$.
    - No progress can be made by considering only the occurrence probability for these MSOs.
    - Might some relaxation be possible by considering "incredibility" for a core damage frequency (CDF) metric instead of "just" the probability of MSOs?

CORE DAMAGE FRE-QUENCY (CDF) METRIC (1)

- Fire “risk equation:”
  - CDF = (fire ignition frequency) x (MSO occurrence probability) x (MSO duration exceedance probability) x (fire non-suppression probability) x (conditional core damage probability [CCDP])
    - All except CCDP can be viewed as probabilistically distributed
      - Deterministically, since fire can occur anywhere, CCDP = 1 cannot be dismissed *a priori* (e.g., Main Control Board or Cable Spreading Room)
- Develop a quantitative definition of “incredible” for the CDF metric.
  - Expand probability of MSOs to address potentially catastrophic consequences.

CDF METRIC (2)

- Five major extinctions have occurred since the "Cambrian Explosion" of "advanced" life 5.5 x 10^8 years ago.
  - These have occurred on average once per 1.1 x 10^8 years, suggesting a starting metric of < 10^{-8}/y.
    - However, some total CDFs are on the order of 10^{-6}/y, a threshold for "very small" changes (RG 1.174); defining "incredibility" for CDF only two orders of magnitude lower stretches the limit of credibility.
- For ~100 US commercial plants, lower threshold by a factor of 100 to address the event as possibly "incredible" for the entire fleet, suggesting a new threshold of < 10^{-10}/y.
  - Four orders of magnitude below the lowest that might be employed when "truncating" quantification of cutsets in a PRA.
  - Consistent with the age of the earth (~ 5 x 10^9 years) for order-of-magnitude (frequency ~ 2 x 10^{-10}/y) as never having occurred.
  - As metric for "incredibility," adopt CDF < 10^{-10}/y for analysis.

SIMULATING CDF WITH MSOs (1)

- With CCDP fixed at 1, stochastically simulate (10,000 trials) the fire "risk equation" using distributions for the other parameters with increasing numbers of MSOs
  - Address "wrinkles" (discussed in paper) associated with MSO duration exceedance probability to derive a closed form distribution
  - Develop distributions for time duration of MSOs and time available to suppress fires (electrical fire non-suppression probability [NSP])
  - Select appropriate fire ignition frequency from fires in Main Control Board (MCB) and Electrical Cabinets, primary sources of MSOs
    - Frequency for MCB fires ≈ 1/6 that for all Electrical Cabinets in a plant, so use as a bounding surrogate
  - MCB fire frequency and electrical fire NSP from NUREG-2169, *Updated Nuclear Power Plant Fire Ignition Frequency and NSP Estimation* (2014)

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SIMULATING CDF WITH MSOs (2)

- To ensure a CDF of < 10^{-10}/y at the 99.99th %ile level, 13 MSOs must be considered, a prohibitive number.
  - Essentially no "relaxation" for considering a practical number of MSOs even when CDF is selected as the metric.

Statistic	Core Damage Frequency for Number of MSOs (MCB Fire Frequency)					
	Three	Six	Nine	Twelve	Thirteen	Fourteen
5th %ile	1.04E-10	2.29E-13	1.61E-14	1.18E-15	4.68E-16	2.00E-16
Median	4.10E-09	1.14E-11	8.66E-13	6.45E-14	2.79E-14	1.17E-14
Mean	4.14E-08	1.53E-10	1.21E-11	9.96E-13	4.26E-13	1.82E-13
95th %ile	1.15E-07	4.04E-10	3.22E-11	2.78E-12	1.21E-12	5.07E-13
99th %ile	6.32E-07	2.36E-09	2.02E-10	1.51E-11	6.53E-12	2.90E-12
99.9th %ile	3.74E-06	1.25E-08	9.41E-10	7.63E-11	3.40E-11	1.40E-11
99.99th %ile	8.93E-06	5.49E-08	2.22E-09	2.72E-10	1.41E-10	4.94E-11

  - Consider alternative to MCB fire frequency – Welding/Cutting Fires (Control/Aux/Reactor Bldg), ~1/40 that for all Electrical Cabinets

SIMULATING CDF WITH MSOs (3)

- Although the results still indicate a prohibitive number of MSOs, there has been some relaxation.
  - To ensure a CDF of < 10^{-10}/y at the 99.99th %ile level, "only" ten MSOs must be considered.

Statistic	Core Damage Frequency for Number of MSOs (Welding/Cutting Fire Freq.)				
	Three	Six	Nine	Ten	Eleven
5th %ile	3.54E-11	7.52E-14	5.32E-15	2.15E-15	8.99E-16
Median	9.81E-10	2.71E-12	2.08E-13	8.63E-14	3.70E-14
Mean	6.61E-09	2.45E-11	1.96E-12	8.29E-13	3.69E-13
95th %ile	2.04E-08	7.18E-11	5.84E-12	2.87E-12	1.14E-12
99th %ile	9.44E-08	3.58E-10	3.06E-11	1.27E-11	5.54E-12
99.9th %ile	4.53E-07	1.54E-09	1.28E-10	4.63E-11	2.43E-11
99.99th %ile	1.05E-06	6.86E-09	2.77E-10	1.50E-10	8.74E-11

  - What about a "per-cabinet" fire frequency from the Fire Protection Significance Determination Process (FPSDP, *Inspection Manual Chapter 0609, Appendix F*, ~1/800 that for all Electrical Cabinets?

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SIMULATING CDF WITH MSOs (4)

- Quite a bit more promising.
  - To ensure a CDF of < 10^{-10}/y at the 99.99th %ile level, as few as five MSOs must be considered.

Statistic	Core Damage Frequency for Number of Multiple Spurious Operations			
	Three	Four	Five	Six
5th %ile	1.99E-11	8.17E-12	3.36E-12	3.70E-14
Median	1.55E-10	6.45E-11	2.74E-11	4.35E-13
Mean	3.16E-10	1.37E-10	5.97E-11	1.17E-12
95th %ile	1.01E-09	4.56E-10	1.96E-10	4.04E-12
99th %ile	2.67E-09	1.17E-09	5.25E-10	1.17E-11
99.9th %ile	6.07E-09	2.61E-09	1.30E-09	3.01E-11
99.99th %ile	1.14E-08	5.90E-09	2.45E-09	8.88E-11

  - Of course, this is for a fire in only one electrical cabinet, a rather limited fire scenario.
    - How practical would this result be in the “deterministic” world?

SIMULATING CDF WITH MSOs (5)

- For a highly localized fire scenario, i.e., single location where, given total loss of all equipment and preclusion of any possible mitigative human actions, with CCDP < 1.
  - Promising reduction with decreasing CCDP (as low as three).

Statistic	Core Damage Frequency for Number of Multiple Spurious Operations					
	MCB Fire Frequency			Weld/Cut Cable Fire Frequency		
	CCDP = 0.1	CCDP = 0.01	CCDP = 0.001	CCDP = 0.1	CCDP = 0.01	CCDP = 0.0001
	Eleven	Eight	Six	Eight	Six	Four
5^{th} %ile	2.75E-16	3.91E-16	2.29E-16	1.28E-15	7.52E-16	1.46E-15
Median	1.55E-14	2.05E-14	1.14E-14	4.93E-14	2.71E-14	4.14E-14
Mean	2.27E-13	2.80E-13	1.53E-13	4.52E-13	2.45E-13	2.88E-13
95^{th} %ile	6.18E-13	7.34E-13	4.04E-13	1.30E-12	7.18E-13	9.10E-13
99^{th} %ile	3.48E-12	4.63E-12	2.36E-12	7.29E-12	3.58E-12	4.22E-12
99.9^{th} %ile	1.74E-11	2.41E-11	1.25E-11	2.96E-11	1.54E-11	1.99E-11
99.99^{th} %ile	6.99E-11	6.68E-11	5.49E-11	8.35E-11	6.86E-11	6.21E-11

  - Again, how practical would it be “deterministically” to “guarantee” a specific fire scenario” in a single location (with “guaranteed” bounding CCDP)?

CONCLUSION

- An evaluation based on mean probabilities falls short of the much more stringent requirements for “incredibility” in a deterministic sense, as per the MSO example.
  - Modeling the actual distributions for MSO occurrence and duration exceedance, ignition frequency and non-suppression probability for the CDF case is necessary in the “deterministic” vs. “risk-informed” world - the first step toward “risk-informed determinism.”
- Re-examination of the example indicates that the number of MSOs to be considered for “incredibility” is prohibitive, whether based on occurrence probability or CDF.
  - A “risk-informed” vs. “deterministic” approach limits the number of MSOs.
  - While proving “incredibility” deterministically can be “incredibly” difficult, this need not be discouraging for “risk-informed determinism;” a similar approach with a less likely phenomenon should prove more successful.