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Updates to Uncertainty Model within the DoW Risk-Based Explosives Safety Siting Methodology

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Introduction

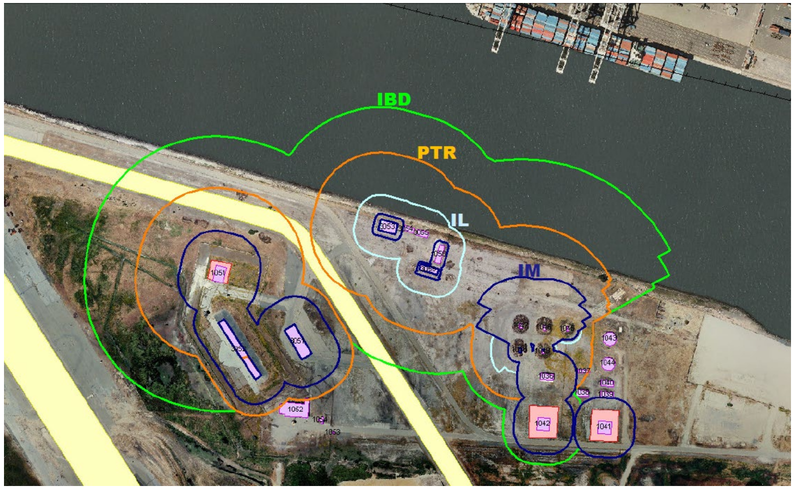
- The U.S. Department of War Explosives Safety Board (DoW ESB) implements policy to provide the maximum possible protection to people and property from ammunition and explosives (AE)
- Objective is implemented via policy defined within Defense Explosives Safety Regulation (DESR) 6055.09
- A primary method of hazard mitigation is prescribing minimum separation distances based on the quantity/type of AE present, commonly referred to as quantity-distance (QD)
- As an alternative to QD, DoW ESB has established an approved quantitative risk assessment methodology (QRA) for evaluating and accepting risks associated with explosives storage and operations
- DoW ESB Technical Paper (TP) 14 defines that approved QRA methodology

Facility Siting in Explosives Safety

- DoW explosives safety site plans generally reply upon QD arcs

- QD provides (approximate) acceptable hazard levels from (primarily) highly unlikely events assuming the event occurs via prescribed minimum separation distances

- Deterministic method with pass/fail result



- *However*, there are intrinsic risk-based aspects within QD criteria
  - PTRD for medium traffic density roads is defined as 60% IBD
    - Function on non-constant exposure and “structural” hazards
  - Instances of low occupancy or minimal exposure requiring < IBD
  - K18 vs. K24 for Intraline Distance (ILD) for higher risk operations
  - Intentional detonation criteria

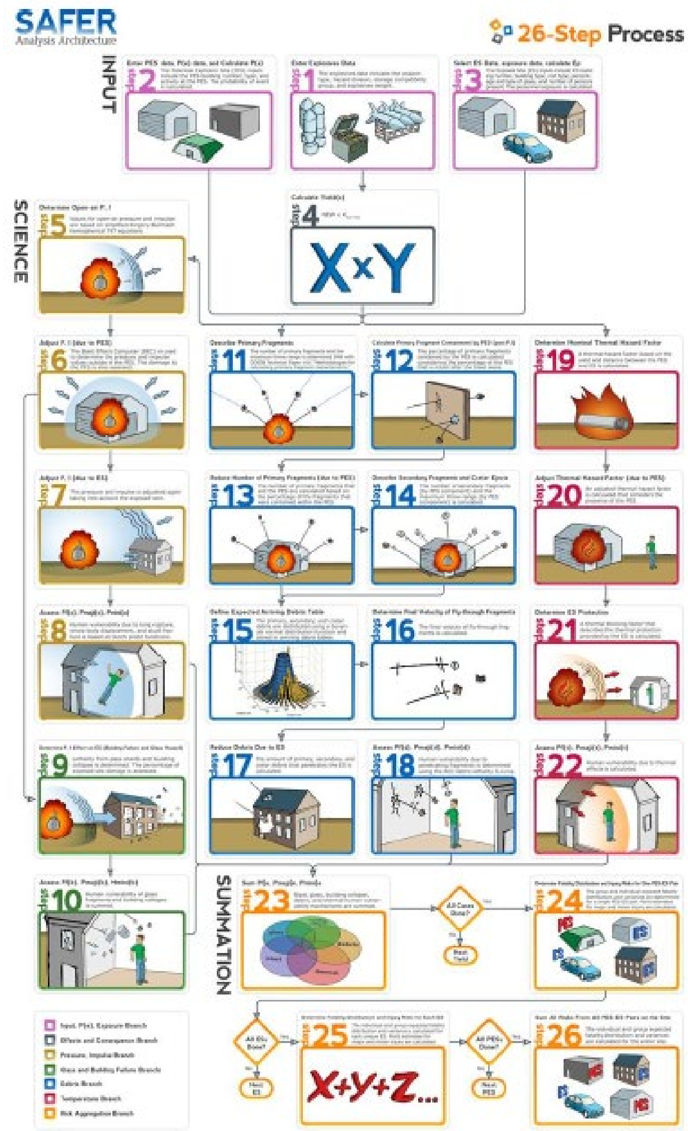
TP-14 QRA Model

- **TP-14 employs a 26-step process**
  - **The first step is to admit that you have a QD violation…**

- **The architecture is defined by a logical flow:**
  - **Starts at the scenario input**
  - **Accounts for all of the potential harmful effects generated by an explosion**
  - **Quantifies both the individual and group risk**

Risk = Likelihood * Consequence * Exposure

$$Risk = P_f = P_e * P_{f|e} * E_p$$



Why Uncertainty is Needed in Risk Models

- Nature of explosives safety is low probability, high consequence events
- Singular estimate of risk does not convey entirety of the situation
  - Goal is to provide decision makers a complete picture of risk
- Two cases can have same expected value, but very different consequence outcomes at the 95th percentile
- Need to account for both Aleatory and Epistemic Uncertainty
  - Aleatory Uncertainty: Real-world randomness that cannot be known or predicted with any certainty (e.g., specifics of the accident, exact location of the event in the operating location, wind direction, etc.)
  - Epistemic Uncertainty: Introduced by the “model” itself, which inherently becomes a simplified representation of the real world (e.g., finite discretization of debris, assumptions on detonations, assumed orientations of persons at the ES, etc.)

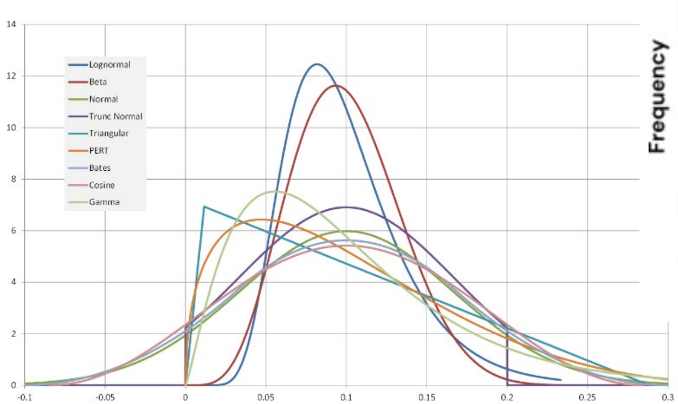
Application of Uncertainty on TP-14

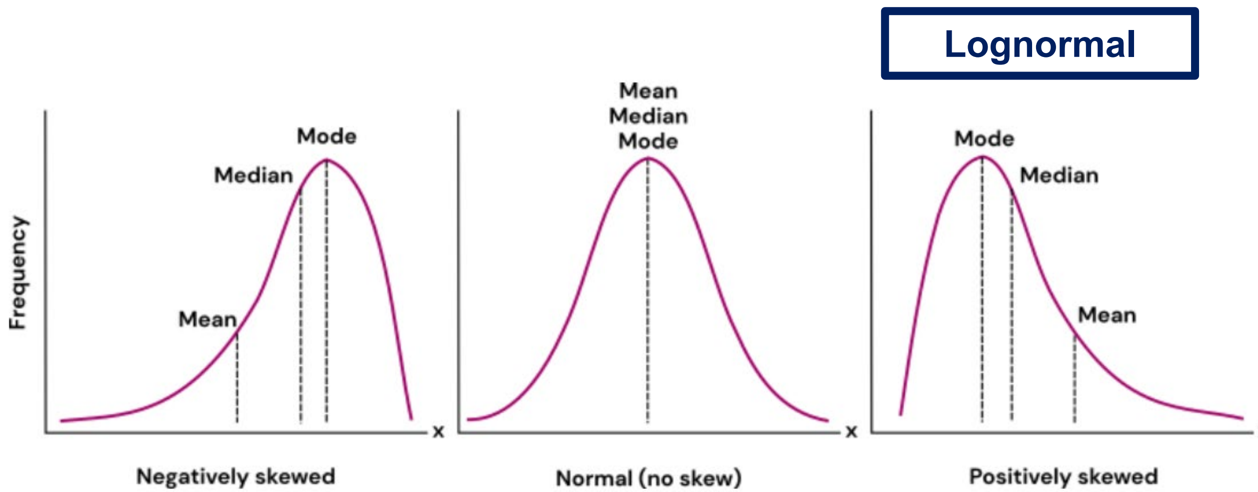
- **TP-14 basic risk equation:** $F = \Delta t * S * \lambda(NEW,E) * P_{f|e}(NEW, Yield, Effects) * E$

Symbol	Short Title	Symbol	Short Title
Δt_o $\sigma_{\Delta t}$	median value of Δt standard deviation of Δt	σ_y σ_{yo}	standard deviation yield epistemic standard deviation yield
S_o σ_S	median value of environmental factor standard deviation of environmental factor	ρ_{Ne} ρ_{Ae}	correlation between NEW and exposure correlation between PES activity and exposure
λ_{oo} $\sigma\lambda_o$	median value of lambda standard deviation of lambda	σ_{NEW1} σ_{NEW2}	standard deviation NEW standard deviation NEW
E_{oo} σ_e σ_{e1} σ_{Eo}	epistemic median daily exposure random variation standard deviation exposure random variation in lambda due to exposure epistemic standard deviation of exposure	σ_1 σ_2 σ_3 σ_4	standard deviation for variation in o/p standard deviation for variation in b/c standard deviation for variation in debris standard deviation for variation in glass
$P_{f\|1oo}$	epistemic median $P_{f\|e}$ blast	σ_{1o}	epistemic standard deviation for overpressure
$P_{f\|2oo}$	epistemic median $P_{f\|e}$ building damage	σ_{2o}	epistemic standard deviation for bldg damage
$P_{f\|3oo}$	epistemic median $P_{f\|e}$ debris	σ_{3o}	epistemic standard deviation for debris
$P_{f\|4oo}$	epistemic median $P_{f\|e}$ glass	σ_{4o}	epistemic standard deviation for glass

TP-14 Uncertainty Distributions

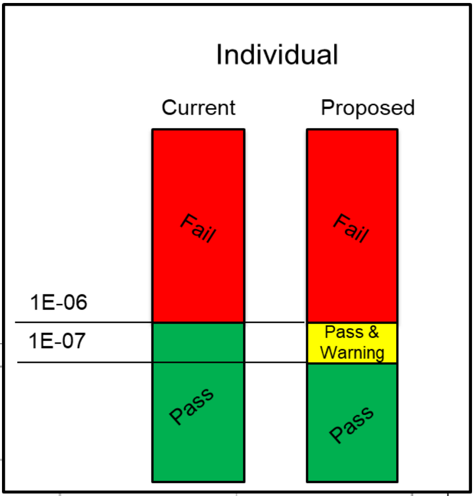
- All TP-14 uncertainty distribution for elemental sub-factors are lognormal
- Estimate for elemental sub-factors are taken as the <u>median</u> of the distribution
- Final Risk Estimate is product terms in risk equation, and final Risk Estimate is taken as the <u>mean</u> of final risk distribution
  - Product of lognormal distributions is a lognormal distribution
- Note that to be philosophically consistent with QD approach, the sited quantity of NEW and maximum yield of explosives are for DoW ESB Risk-Based Site Plan submittals

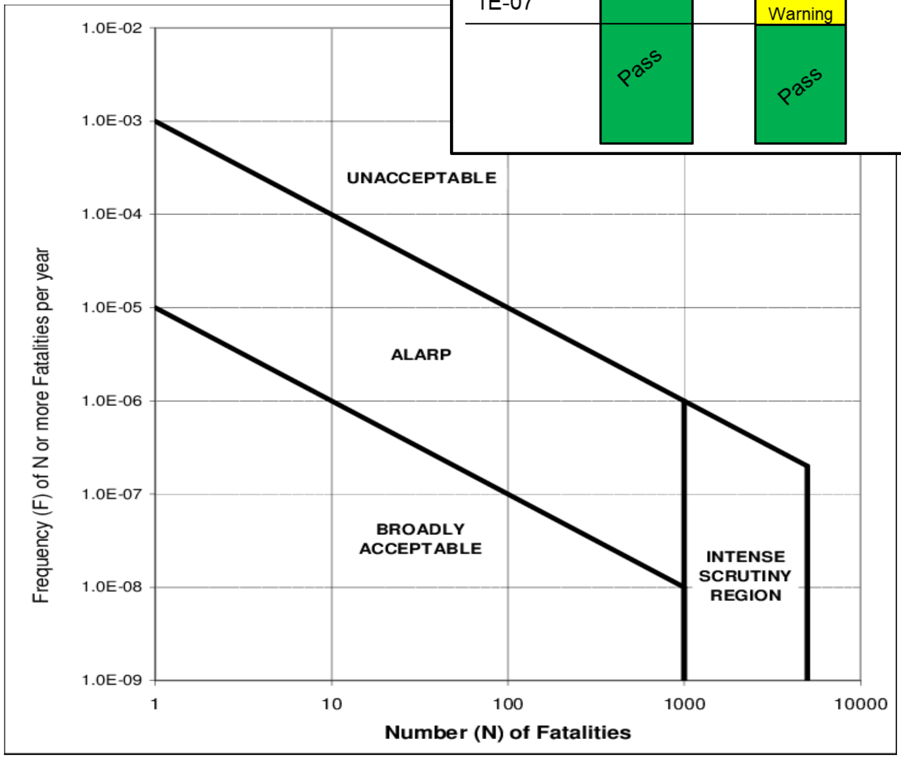




Evaluation of Risk Estimates

- **Multiple ways to evaluate/compare risk estimates**
- **MIL-STD 882E – qualitative Risk Assessment Code**
- **Numeric thresholds**
  - **Single or multiple points**
  - **E.g., compare at mean and 95th percentile**
- **ALARP**
- **Implement Catastrophic Risk Aversion**
- **Some combination of the above**





RISK ASSESSMENT MATRIX

SEVERITY / PROBABILITY	Catastrophic (1)	Critical (2)	Marginal (3)	Negligible (4)
Frequent (A)	High	High	Serious	Medium
Probable (B)	High	High	Serious	Medium
Occasional (C)	High	Serious	Medium	Low
Remote (D)	Serious	Medium	Medium	Low
Improbable (E)	Medium	Medium	Medium	Low
Eliminated (F)	Eliminated			

DoW ESB Risk-Based Site Plan Criteria

- Acceptance criteria differs for type of exposure and differs by two orders of magnitude
  - Related – those requiring ILD separation
  - Unrelated – those requiring IBD separation
- Group risk criterion originally not a requirement
- Current group risk criterion set as order of magnitude greater than individual for both related and unrelated exposures
- Individual risk criterion evaluated against other voluntary and involuntary risks across society
  - *An Update to the Universal Risk Scales – A Tool for Developing Risk Criteria by Consensus*, APT Tech Memo CE1-1800, April 2016

Risk to:	DESR 6055.09	DoD 1999-2004
Any one related individual - Related P_f	$\leq 1x10^{-4}$ per year	Limit maximum risk to $1X10^{-4}$
All related individuals - Related E_f	$\leq 1x10^{-3}$ per year	Attempt to lower risk to $1X10^{-3}$; Accept above $1x10^{-2}$ with significant national need
Any one unrelated individual - Unrelated P_f	$\leq 1x10^{-6}$ per year	Limit maximum risk to $1X10^{-6}$
All unrelated individuals - Unrelated E_f	$\leq 1x10^{-5}$ per year	Attempt to lower risk to $1X10^{-5}$; Accept above $1x10^{-3}$ with significant national need

Need to Update TP-14 Uncertainty Model

- **After over a decade of implementation, several areas for improvement were noted based on feedback from users and peers**

- **Does the approach used in the TP-14 risk model depend on use of lognormal distributions to model each of the risk sub-factors?**
  - Does the current analytical approach remain valid when using other distributions (normal, truncated normal, triangular, beta, etc.) to model sub-factors?
  - Would use of different sub-factor distribution types invalidate the treatment of the resulting risk distribution as lognormal?

- **Could sub-factor point estimates be treated as the means of their individual distributions rather than as the median (as current TP-14 does)?**
  - Can the current analytical approach be modified to accommodate this change?
  - What is the effect on the computed risk estimate?
  - How would this change affect the treatment of uncertainty in the model and associated risk acceptability criteria?

- **Can the TP-14 risk model be simplified for communication/understanding purposes without impacting the academic rigor of the accepted model?**

Assessment of Non-Lognormal Distributions for Elements Sub-Factors

- **Central Limit Theorem**
  - Sum of multiple distributions of random variables tends towards a normal distribution
  - Product of random (positive) distributions tends towards a lognormal distribution

- **Product of multiple lognormal distributions = lognormal distribution**
  - If element sub-factor distributions within TP-14 framework are not lognormal, what is the (mathematical) effect on final TP-14 risk distribution which is assumed to be lognormal?

- **Goal: Does analytical, closed-form solution of TP-14 provide sufficient accuracy when sub-factor distributions are not lognormal?**

Distribution Assessment Approach

- Analytical Approach employed TP-14 framework to calculate the risk estimate when element sub-factor distributions were modified to the statistical distribution assigned to that investigation

- Monte Carlo study (Experimental Approach) was conducted to produce 50,000 estimates of estimating annual risk when modeling each sub-factor with the assigned distribution

- Four standard test cases previously used in TP-14 sensitivity studies were assessed:
  – Case 1: Low Risk, Wide Uncertainty
  – Case 2: Low Risk, Narrow Uncertainty
  – Case 3: High Risk, Wide Uncertainty
  – Case 4: High Risk, Narrow Uncertainty

- Three distribution assignments:
  – Part 3A: Skewed Triangular Distribution
  – Part 3B: Normal Distribution
  – Part 3C: Mixed Distributions (Normal, Lognormal, & Skewed Triangular)

Skewed Triangular Distribution Comparison

- The differences found between Expected Values of the Analytical calculations and the Monte Carlo study are less than 1% across the four standard test cases
- While the differences between Standard Deviations and 95th percentile results are greater than for the Expected Values, these results are also very similar – varying by less than 25%
- These results indicate that the use of non-lognormal, skewed distributions for risk sub-factors in the Analytical Model is feasible

Solution Method	Part 3a, Case 1 (Low-Wide)			Part 3a, Case 2 (Low-Narrow)		
	Expect Val	Std Dev	95th %	Expect Val	Std Dev	95th %
Analytical Method	6.00E-11	6.46E-11	1.73E-10	2.29E-15	2.16E-15	6.19E-15
Experimental (Monte Carlo)	5.96E-11	7.08E-11	1.99E-10	2.28E-15	2.44E-15	7.15E-15
Δ%	0.72%	9.58%	14.85%	0.43%	13.20%	15.47%

Solution Method	Part 3a, Case 3 (High-Wide)			Part 3a, Case 4 (High-Narrow)		
	Expect Val	Std Dev	95th %	Expect Val	Std Dev	95th %
Analytical Method	1.01E-02	1.13E-02	2.97E-02	7.42E-04	7.48E-04	2.07E-03
Experimental (Monte Carlo)	1.01E-02	1.29E-02	3.41E-02	7.37E-04	9.31E-04	2.58E-03
Δ%	0.74%	13.72%	14.93%	0.72%	24.41%	24.46%

Normal Distribution Comparison

- Differences in Expected Values of the Analytical calculations and the Monte Carlo study are less than 0.5% across the four standard test cases
- While the differences between Standard Deviations and 95th percentile results are greater than for the Expected Values, these results are also very similar – varying by less than 6% for the 95th percentile results
- These results indicate that the use of non-lognormal, symmetric distributions for risk sub-factors in the Analytical Model is feasible.

Solution Method	Part 3b, Case 1 (Low-Wide)			Part 3b, Case 2 (Low-Narrow)		
	Expect Val	Std Dev	95th %	Expect Val	Std Dev	95th %
Analytical Method	3.25E-16	1.21E-16	5.51E-16	1.48E-17	5.61E-18	2.53E-17
Experimental (Monte Carlo)	3.25E-16	1.22E-16	5.47E-16	1.48E-17	5.00E-18	2.40E-17
Δ%	0.10%	0.58%	0.64%	0.31%	10.81%	5.23%

Solution Method	Part 3b, Case 3 (High-Wide)			Part 3b, Case 4 (High-Narrow)		
	Expect Val	Std Dev	95th %	Expect Val	Std Dev	95th %
Analytical Method	1.75E-05	6.69E-06	3.00E-05	2.28E-04	8.76E-05	3.92E-04
Experimental (Monte Carlo)	1.75E-05	6.02E-06	2.85E-05	2.29E-04	7.84E-05	3.72E-04
Δ%	0.18%	10.00%	5.07%	0.45%	10.46%	5.09%

Mixed Distribution Input

- **Elemental distributions selected for demonstration purposes only**

INPUT VARIABLES	
median value of delta t	Δt_o
std dev of delta t	$\sigma_{\Delta t}$
median value of Scale Factor	S_o
std dev of Scale Factor	σ_S
median value of λ_O	λ_{oo}
std dev of λ_O	$\sigma_{\lambda o}$
Ep Median Daily Exposure	E_{oo}
Rand Var std dev Exposure	σ_e
Ep std dev of Exposure	σ_{Eo}
Ep Median Pf|e blast	$P_{f\|1oo}$
Ep std dev for blast	σ_{1o}
std dev for variation in blast	σ_1
Ep Median Pf|e bldg damage	$P_{f\|2oo}$
Ep std dev for bldg damage	σ_{2o}
std dev for variation in bldg damage	σ_2
Ep Median Pf|e debris	$P_{f\|3oo}$
Ep std dev for debris	σ_{3o}
std dev for variation in debris	σ_3
Ep Median Pf|e glass	$P_{f\|4oo}$
Ep std dev for glass	σ_{4o}
std dev for variation in glass	σ_4
Ep std dev Pf|e due to Yield	σ_{yo}
Std Dev Pf|e due to Yield	σ_y
Std Dev Rnd Var λ due to NEW	σ_{NEW1}

Input Distribution	Variable	Normal	Lognormal	Triangular
Delta t	Median of delta t	X		
	Std dev of delta t			
Scale Factor	Median of Scale Factor			X
	Std dev of Scale Factor			
Lambda	Median of lambda		X	
	Std dev of lambda			
Daily Exposure	Ep Median Daily Exposure	X		
	Ep std dev of Exposure			
	Rand Var std dev Exposure			X
Blast	Ep Median Pf|e blast		X	
	Ep std dev for blast			
	Std dev for variation in blast	X		
Building Collapse	Ep Median Pf|e bldg collapse		X	
	Ep std dev for bldg collapse			
	Std dev for variation in bldg collapse	X		
Debris	Ep Median Pf|e debris		X	
	Ep std dev for debris			
	Std dev for variation in debris	X		
Glass	Ep Median Pf|e glass		X	
	Ep std dev for glass			
	Std dev for variation in glass	X		
Yield	Ep std dev Pf|e due to Yield		X	
	Std dev Pf|e due to Yield	X		
NEW	St dev Pfe due to NEW		X	

X = Distribution for subject input variable

Mixed Distribution Comparison

- The differences found between Expected Values of the Analytical calculations and the Monte Carlo study are less than 6% across the four standard test cases
- While the differences between Standard Deviations and 95th percentile results are greater than for the Expected Values, these results are also very similar – varying by less than 23% with the exception of the Standard Deviation in Case 1 (38%)
- These results indicate that the use of a mixture of distributions for risk sub-factors in the Analytical Model is also feasible

Solution Method	Part 3c, Case 1 (Low-Wide)			Part 3c, Case 2 (Low-Narrow)		
	Expect Val	Std Dev	95th %	Expect Val	Std Dev	95th %
Analytical Method	5.51E-15	4.57E-15	1.39E-14	1.30E-16	8.35E-17	2.88E-16
Experimental (Monte Carlo)	5.80E-15	6.30E-15	1.68E-14	1.38E-16	1.02E-16	3.30E-16
Δ%	5.27%	37.78%	20.57%	5.90%	22.49%	14.48%

Solution Method	Part 3c, Case 3 (High-Wide)			Part 3c, Case 4 (High-Narrow)		
	Expect Val	Std Dev	95th %	Expect Val	Std Dev	95th %
Analytical Method	3.66E-04	4.87E-04	1.16E-03	3.23E-04	3.70E-04	9.57E-04
Experimental (Monte Carlo)	3.85E-04	5.53E-04	1.30E-03	3.38E-04	4.26E-04	1.04E-03
Δ%	5.26%	13.51%	11.94%	4.63%	15.21%	8.50%

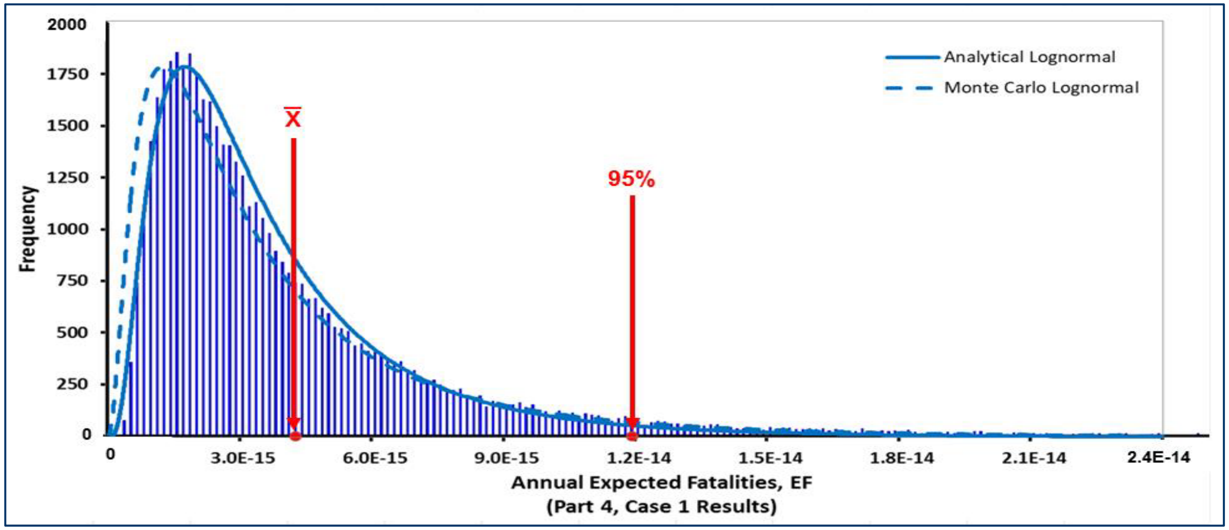
Use of Point Estimate in Distribution

- To assess ability of TP-14 framework to treat the point estimates as mean (rather than median) of the elemental distributions, a similar approach of comparing the Analytical Model to the Monte Carlo study was conducted

- Case 3C (Mixed Distributions) was analyzed again, with the only difference being assignment of the point estimates to the mean rather than the median

- Very little difference than results presented on the previous slide
  - Demonstrates that the Analytical Approach can be modified accordingly

- Analytical vs. Monte Carlo lognormal for Risk Distribution for Case 1 depicted the right
  - Expected Value
    - AA: 3.92E-15
    - MC: 4.13E-15
  - 95th % Value
    - AA: 9.9E-15
    - MC:1.19 E-14



Enhancing Risk Communication

- TP-14 basic risk equation: $F = \Delta t * S * \lambda(NEW,E) * P_{f|e}(NEW, Yield, Effects) * E$
- Original Uncertainty Model described in paper "Revised Analytical Approach" by Dr. Richard Mensing (November 2003) contained nearly 10 pages of complex equations to provide the academic rigor required by the Risk Model
- Risk communication hindered by known increases in base risk estimate having a different effect on final risk estimate
- Risk equation reformulated to assist in communication (details provided in paper)
  - Base Risk Estimate = product of the four Point Estimates
  - Uncertainty Factor = product of the four Uncertainty Factors
  - Correlation/Confidence = product of the three Corr/Conf Factors

$$E_{ep}(EF) = \underbrace{(R_S * R_{Pe} * R_{Pf|e} * R_E)}_{\text{base risk estimate}} * \underbrace{(U_S * U_{Pe} * U_{Pf|e(eff)} * U_E)}_{\text{uncertainty factor}} * \underbrace{(C_{PeE} * C_{NE} * C_{confidence})}_{\text{correlation/confidence}}$$

Proposed Improvements to TP-14 Uncertainty Model

1. **Use uncertainty distributions other than lognormal for element sub-factors that are better represented by alternate distributions**
   - Proposed distributions proposed on following slides
   - Will be reassessed and refined if warranted via additional studies

2. **Investigate path forward for assignment of mean to point estimate for element sub-factors**
   - Assess impact on acceptance criteria

3. **Decouple uncertainty in the risk estimate to enhance communication of risk results**
   - Information presented on previous slide will be implemented in next version of TP-14 and associated explosives safety QRA tool

Proposed Distributions for TP-14 Random Variables

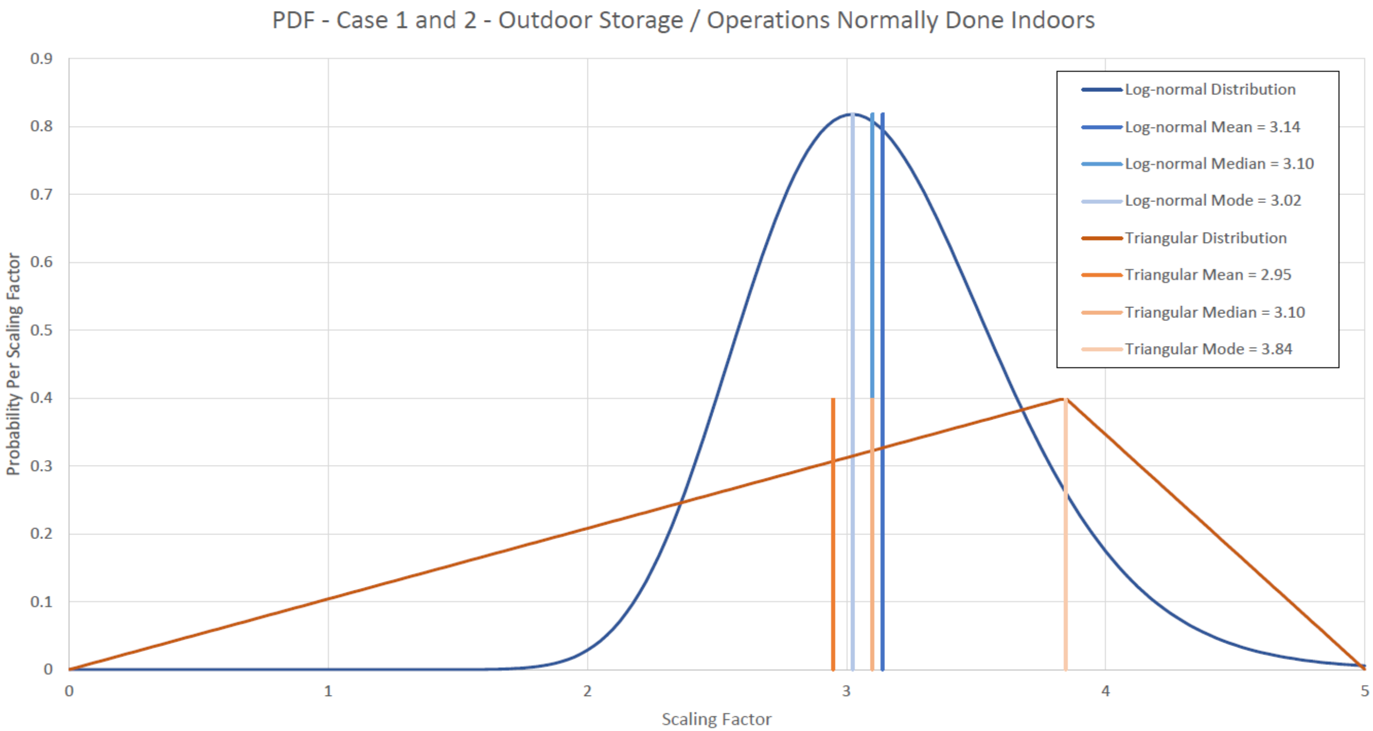
- **Proposed distributions based on assessment of each random variable**
- **Selections subject to change pending additional studies or assessments**

Original Input Description	Symbol	Random Variable Ref.	Aleatory or Epistemic	Original Distribution	Proposed Distribution
Median Value of Delta t	Δt_0	RV1	Epistemic	Lognormal	Normal
Standard Deviation of Delta t	$\sigma_{\Delta t}$				
Median Value of Scale Factor	S_0	RV2	Epistemic	Lognormal	Triangular
Standard Deviation of Scale Factor	σ_S				
Median Value of Lambda	λ_0	RV3	Epistemic	Lognormal	Lognormal
Standard Deviation of Lambda	σ_λ				
Median Daily Exposure	E_{00}	RV4	Aleatory	Lognormal	Normal
Standard Deviation of Variation in Exposure	σ_e				
Standard Deviation of Exposure	σ_{E0}	RV5	Epistemic	Lognormal	Normal
Median Value of Overpressure $P_{f\|e}$	$P_{f\|100}$	RV6	Epistemic	Lognormal	Lognormal
Standard Deviation of Overpressure $P_{f\|e}$	σ_{10}				
Standard Deviation for Variation in Overpressure	σ_1	RV7	Aleatory	Lognormal	Normal
Median Value of Building Collapse $P_{f\|e}$	$P_{f\|200}$	RV8	Epistemic	Lognormal	Lognormal
Standard Deviation of Building Collapse $P_{f\|e}$	σ_{20}				
Standard Deviation for Variation in Building Collapse	σ_2	RV9	Aleatory	Lognormal	Normal
Median Value of Debris $P_{f\|e}$	$P_{f\|300}$	RV10	Epistemic	Lognormal	Lognormal
Standard Deviation of Debris $P_{f\|e}$	σ_{30}				
Standard Deviation for Variation in Debris	σ_3	RV11	Aleatory	Lognormal	Normal
Median Value of Glass $P_{f\|e}$	$P_{f\|400}$	RV12	Epistemic	Lognormal	Lognormal
Standard Deviation of Glass $P_{f\|e}$	σ_{40}				
Standard Deviation for Variation in Glass	σ_4	RV13	Aleatory	Lognormal	Normal
Standard Deviation for Variation in $P_{f\|e}$ Due to Yield	σ_y	RV14	Aleatory	Lognormal	Lognormal
Standard Deviation in $P_{f\|e}$ Due to Yield	σ_{y0}	RV15	Epistemic	Lognormal	Normal
Standard Deviation in $P_{f\|e}$ Due to NEW	σ_{NEW}	RV16	Aleatory	Lognormal	Normal

Effect on Change in Distribution

- Example provided for Probability of Event Environmental Scaling Factor for Outdoor Operations
  - Center Value = 3.1
  - Upper Bound = 5

- Effect on mean and overall shape can be seen



Impacts of Assigning Mean as Point Estimate

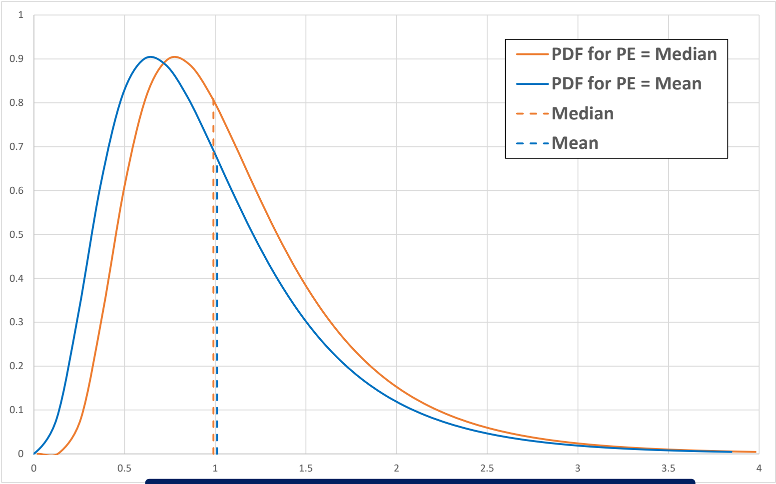
- **Development of risk acceptance criteria involves:**
  1. Literature review across multiple industries identifying annual consequence risk
  2. Detailed comparison with current deterministic standards (QD) and analysis of resulting pass/fail risk distribution
  3. Assessment of public perception of risk tolerance for particular industry

- **Current DoW ESB Risk-Based Site Plan Criteria developed via extensive review of all three efforts**
  - Sub-factor point estimates assigned as median in elemental distribution

- **Assignment of point estimate as the mean in elemental distribution changes the final risk estimate (i.e., calculated risk is lower)**

- **If a single risk estimate threshold is used for pass/fail check with mean as point estimate, uncertainty does not affect check with criteria**

- **A secondary criteria check on final risk distribution (e.g., 95th %) would add value**



Sample Elemental Distribution

Summary & Conclusions

- Given the high degree of uncertainty associated with accidental explosions, the risk estimate produced by a QRA needs to include Uncertainty to fully convey the risk profile for decisional purposes

- Based on feedback received, several improvements have been proposed to the TP-14 Uncertainty model

- The DoW Explosives Safety Board is currently in the process of updating TP-14, and focus on Uncertainty methodology improvements are:
  - Enhance treatment of uncertainty within the risk equation to improve fidelity
  - Improvements to risk communication