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

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Abstract

The U.S. Department of War Explosives Safety Board (DoW ESB) has established an approved quantitative risk assessment (QRA) methodology for evaluating and accepting risks associated with explosives storage and other activities. In the explosives safety community, QRA represents an alternative path for regulator acceptance to the long-established, deterministic method of quantity-distance (QD), where a singular distance as a function of explosives weight is used to determine acceptable risk for a given exposure. DoW ESB Technical Paper (TP) 14 defines the approved QRA methodology, and quantifies the annual risk as a function of the probability of event, consequences given the event, and exposure. Additionally, an uncertainty distribution is applied to each of the individual elements of the risk equation, to ensure a comprehensive estimation of risk is provided which considers applicable unknown variation. The QRA model presented within TP-14 is regularly being updated to improve the efficacy of the results provided, reduce unnecessary conservatism, and to satisfy end user requirements. The most recent technical improvements have focused on the uncertainty algorithms and approach within the methodology. This paper provides a background on risk assessments & communication methods, a summary of planned improvements to TP-14, and identification of future work within the TP-14 QRA application of uncertainty to risk-based siting for explosives safety.

Introduction

The U.S. Department of War (DoW) implements policy to provide the maximum possible protection to people and property from the damaging effects of DoW military munitions and minimize exposures consistent with safe and efficient operations. This policy is often succinctly summarized via the "Cardinal Rule" of explosives safety – expose the minimum number of persons for the minimum amount of time to the minimum quantities of explosives. This objective is implemented via robust explosives safety management programs developed by the Services, which incorporate the minimum protection criteria for personnel and property as defined within Defense Explosives Safety Regulation (DESR) 6055.09 [1]. This protection is primarily achieved via prescribed minimum separation distances based on the quantity of the explosives present, a method commonly referred to as quantity-distance (QD).

As an alternative to QD, the U.S. Department of War Explosives Safety Board (DoW ESB) has established an approved quantitative risk assessment (QRA) methodology for evaluating and accepting risks associated with explosives storage and other activities. In the explosives safety community, QRA represents an alternative path for regulator acceptance to the long-established, deterministic method of QD, where a singular distance as a function of explosives weight is used to determine acceptable risk for a given exposure.

DoW ESB Technical Paper (TP) 14 [2] defines the approved QRA methodology for the US DoW and quantifies the annual risk as a function of the probability of event, consequences given the event, and exposure. This methodology was first established and approved in 1999, and has been refined over the years. In 2007, an uncertainty methodology was included and approved in the methodology, an enhancement to the risk assessment that accounts for multiples sources of uncertainty in the outcome. The uncertainty distribution is applied to each of the individual elements of the risk equation, to ensure a comprehensive estimation of risk is provided which considers applicable unknown variation. Note that while the Department of Defense changed its name to the DoW in 2025, legacy documents and references currently retain the "Defense" moniker (e.g., DESR).

Consistent with the approach to continually improve the methodologies within TP-14 and the risk estimations provided to the Services for use in explosives safety, the current uncertainty methodology has been reassessed, and improvements are planned for the next update to the methodology, which will become TP-14 Revision 5.

Use of Uncertainty in Quantitative Risk Assessment

Importance of Including Uncertainty

Advantages of explosives safety QRA over traditional QD siting include a comprehensive assessment of risk to all personnel exposed to explosives operations, which consider probability of event associated with different explosives operation types, as well as consideration of risk to all persons exposed rather than treatment of consequence on an individual basis. Additionally, there are a significant number of assumptions made in establishment of minimum separation distances associated with QD that provide inherent limitations in this deterministic approach. This aspect provides an additional advantage for QRA, as it gives a fuller picture of the risk exposure of a given scenario and allows decision makers to have a greater understanding of the risk being accepted.

For example, the probability of an accidental event associated with a given explosive activity type requires a numeric value to estimate the risk, and in within the TP-14 methodology is based on historical data. However, using a singular value based on precedent to represent the probability of a future occurrence at a given location is incredibly simplistic, and a more defensible approach is to represent the probability of event of a given potential explosion site (PES) with a probabilistic distribution. A numeric value can still be utilized as a representative point of this distribution, but the probabilistic outcome requires a distribution to truly model the situation.

This concept can be applied to all elements within the risk assessment, to include number of personnel at an exposed site (ES), duration those personnel are present and exposed to the explosives risk, location and manner in which the accident occurs within the PES, physical effects and hazards generated by the explosive event, and consequences to personnel due to the hazards generated. All of these can be considered random variables when assessing the risk, and all have some degree of uncertainty distribution associated with them. Many of these random variables are typically represented by distributions with a long tail, meaning there is a non-zero possibility of an extreme result occurring, though the magnitude and other specifics of the distribution depend on the random variable being modeled.

Finally, within any risk model there are two types of uncertainty that need to be considered: epistemic and aleatory. Epistemic uncertainty is that which is introduced via the model itself. At its core, a model is inherently a simplistic representation of the real world. And to achieve the efficiencies associated with simplicity, some amount of inherent uncertainty is introduced into the model developed. This epistemic uncertainty needs to be accounted for in any risk model. An example of this is how a risk model represents secondary debris generated by the PES due to an internal detonation. The inherent complexity of the problem requires discretization and other fundamental assumptions to create a fast-running model, which results in loss of fidelity in the answer. Another example is simplifying consequence algorithms by defining assumed locations and/or orientations of personnel within the ES, which defines how the explosion effects impact them (e.g., blast wave, glass hazards, etc.).

The second type of uncertainty in a risk model is aleatory uncertainty. This is the real-world randomness that is completely unknown, and the model needs to represent a probabilistic outcome without knowing specifics of the actual scenario. For example, in a detonation the manner of initiation, specifics of explosives material present, and even the wind direction will have an impact of what the blast load is going to be at a given distance from the PES. These are all associated with the aleatory uncertainty that cannot be captured, no matter how detailed your risk model is.

Implementation of Uncertainty with TP-14

TP-14 includes estimations of injury and asset damage, but the primary focus and criteria basis is probability of fatality. In assessing risk, the basic equation that serves as the mathematical origin is given as:

$$Risk = Likelihood * Consequences * Exposure$$

This basic formulation is used to estimate the annual probability of fatality, P_f, as follows:

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

where P_e is defined as the annual probability that an explosives event will occur at a particular PES of interest. $P_{f|e}$ is defined as the probability of fatality given an explosives event and the presence of a person. E_p is defined as the exposure of one person to the PES on an annual basis.

A second measure is associated with group risk: expected fatalities, E_f. This is defined as the summation of individual risks and provides an expectancy or expected value (i.e., the average number of fatalities expected per year) as shown:

$$E_f = \sum_n (P_e * P_{f|e} * E_p)$$

Where n is defined as the number of people in the group.

The full risk equation utilized in TP-14 is presented in Reference [3], and is notionally referred to as the Model of the World (MOW). The MOW leveraged the risk equation used by TP-14 to formulate the risk estimator for the expected number of fatalities per year.

$$F = \Delta t * S * \lambda(NEW, E) * P_{f|e}(NEW, Yield, Effects) * E$$

The entirety of the equation is incredibly complex, and provides the following factors which are lognormally distributed:

Δt = the fraction of the personnel exposure time that explosives are present

λ = the probability of an explosive event during a given year based on the type of explosives present and the activity performed at the explosives site, also referred to as P_e

S = an environmental factor that increases the probability of an event based on extenuating circumstances at the site – such as operations in a remote area or under combat conditions

$P_{f|e}$ = the probability of fatality given an explosive event and exposure – this factor aggregates the effects of the fatality mechanisms: overpressure, debris, building collapse, glass hazards, and thermal effects

E = the exposure of personnel to an explosive event based on the number of people present in a facility during the year and the number of hours the exposed site is occupied

NEW = the Net Explosive Weight of hazardous material contributing to the event

Yield = the percentage of the material contributing energy to the event

Effects = the four fatality mechanisms computed by Safety Assessment For Explosives Risk (SAFER) science algorithms

The risk model input parameters are provided in Table 1, along with a short title explaining the purpose of each parameter.

Table 1. Risk Model Input Parameters

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

In an effort to better communicate the risk estimations to the end user, an effort was undertaken to reformulate the MOW into terms that clearly identify the base risk estimate, uncertainty factors, and correlation/confidence of input. The result of this effort is shown below:

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

Though not currently implemented within TP-14, this improvement and many others discussed later in this paper, will be implemented in TP-14 Revision 5.

Log-normal Distribution of Uncertainty in TP-14

The selection of appropriate distributions to represent each of the independent variables in the risk equation is critical to the quality of the risk estimate produced. Given the wide variety of random variables within the risk equation, it becomes difficult to assign specific distributions. Additionally, some of the variables are representing extremely low probability events, or phenomena with minimal data, which makes assignment of the “correct” uncertainty distribution curve all the more challenging.

Reference [3] addressed the difficulty of this topic and acknowledged the difficulty in assigning the appropriate family of distributions to this problem. Mensing suggested the distribution must be defined over positive space and that the distribution is skewed, i.e., having a long tail towards higher values. The recommendation for the long-tailed distribution is particularly appropriate for some of the blast effects and consequence models, where there is a non-zero probability of some extreme event occurring. One example is ballistic flight of fragments & debris. Within the bounds of the launch condition parameters, a maximum credible throw distance can be calculated. However, there is still a non-zero probability of the upper extremes of launch velocity, launch angle, and mass to coincide, and there may even be an extremely efficient ballistic condition of the fragment that is not inherently accounted for within the model. These low-probably uncertainties can be accounted for with a long-tailed distribution.

For example, consider the case where the fraction of the personnel exposure time that explosives are present (*Δt*) is set to 0.1, and it has an upper bound of 0.3 (Upper Bound Multiplier = 3). Various distribution types can be used to represent this case, as illustrated in Figure 1. The following curves are shown: Lognormal, Beta, Normal, Truncated Normal, Triangular, PERT, Bates, Cosine, and Gamma. All nine of these curves have a mean of 0.1 and a standard deviation of 0.066, but they provide varying differences as to the probability distribution. Without extensive study on the particular application, it is difficult to state which curve is “right”. Additionally, if one were to analyze two different scenarios and tabulate the presence of explosives and personnel on an hourly basis and tabulate after one year, you could have both scenarios with *Δt* = 0.1 and an upper bound of 0.3, but each scenario is much better represented by different distribution curves.

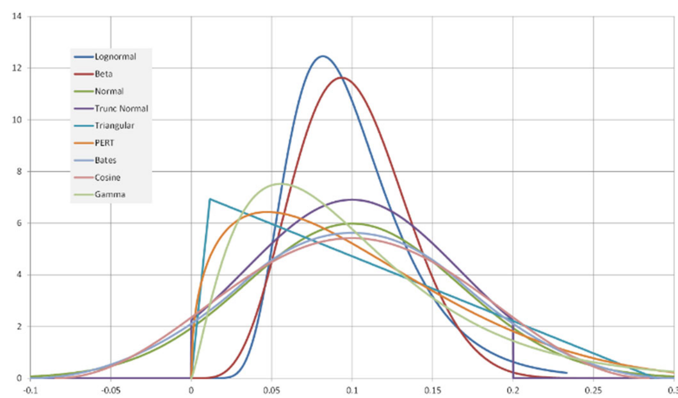

Figure 1. Uncertainty Distribution Curve Options

In development of the uncertainty model for TP-14, the Risk-Based Explosives Safety Criteria Team (RBESCT) elected to use lognormal distributions to represent each of the random variables. During discussions on how to implement multiple random variables in the comprehensive risk model, there was concern by some parties that the product of multiple random distributions would not result in a lognormal distribution. Given the desire for the final risk estimate to be a lognormal distribution, and the dissent over which non-lognormal distributions to represent the independent variables within the risk equation, the TP-14 uncertainty model utilized lognormal distributions for all independent variables.

Risk Assessment Evaluation Criteria

Various Approaches of Risk Evaluation

A critical step within the risk assessment process is evaluation of the assessed risk. Significant work can go into the identification and documentation of hazards, calculation of probabilities, and modeling of potential scenarios and outcomes, but without clear metrics for comparison or guidance on risk tolerability, the risk assessment process does not provide appropriate value. The most fundamental form of risk assessment is presented in MIL-STD-882E [4]. Severity Categories and Probability Levels are defined, and though the preference is always to use quantitative measures, qualitative descriptions are presented if frequency/rate of occurrence or quantitative consequence measurements are not feasible to generate. The assessed risk is expressed as a Risk Assessment Code (RAC), which is a combination of one severity category and one probability level. A RAC is assigned a risk level of High, Serious, Medium, or Low, as shown in Table 2.

Table 2. MIL-STD 882E Risk Assessment Matrix

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			

The risk identification and acceptance process requires clear organizational guidance regarding what steps must be taken once the adjectival risk level is determined. For example, a risk approval structure can be put in place that identifies what an acceptable risk level is for a given operation. If that risk level is not satisfied, and risk mitigation measures do not reduce the risk to the acceptable threshold, then the risk approval structure will identify at what higher authority level that risk will need to be accepted and documented. This process will greatly depend on the operation, as some processes are inherently risky but are of grave importance, while other operations are routine and typically pose very minimal risk.

Similar to the qualitative risk assessment, the same process can be done for a quantitative risk assessment. The likelihood can be determined by examining frequency failure rates or developing fault trees. The consequence can be calculated via detailed engineering analysis or numerical modeling. Exposure can be determined via studies of work history and population data. The product of these terms can then be used to calculate a numeric risk value. For persistent operations, i.e., non-event based risk, this term is usually presented as an annual basis. In explosives safety and other high consequence, low probability of event industries, the individual risk metric typically assessed is annual probability of fatality.

While the increased fidelity of a quantitative analysis provides significantly more information to the risk decision maker, the specifics of that number have very little meaning if further context is not provided. For example, if the annual probability of fatality for an individual is calculated as $4.2X10^{-5}$, this miniscule number provides no information regarding the acceptability of the risk. For a quantitative metric to provide value, quantitative acceptance thresholds must also be developed. While the risk of 42 chances in one million seems incredibly small, if the risk acceptance criterion is only $1X10^{-5}$ (i.e., 10 chances in one million), the results would be that the risk is unacceptable.

Developing quantitative risk acceptance criterion is a difficult task and involves a comprehensive process of: 1) literature review across multiple industries identifying annual consequence risk, 2) a detailed assessment of current deterministic standards and the resulting risk distribution, and 3) an assessment of public perception of risk tolerance for the organization and industry being assessed. For the third item, commercial fishing or mining has a much higher perceived risk by the general public than government construction of bridges and dams. In developing risk criterion thresholds for TP-14, a detailed assessment of annual risk across multiple industries was conducted and is detailed in [5]. Additionally, a significant number of risk scenarios were analyzed at Inhabited Building Distance (IBD) and Intraline Distance (ILD) in support of developing those criteria.

There are alternatives to singular risk metrics that are used for comparison. One example is the use of a concept to reduce the risk As Low As Reasonably Practicable (ALARP). Whereas a binary risk threshold utilizes a singular value and presents a “Go/No Go” paradigm, ALARP utilizes a three-tiered system, with a green/yellow/red concept. A notional example of an ALARP risk assessment system is shown in Figure 2. If the annual individual risk is less than the proposed acceptance criteria (1E-7 in Figure 2), then the risk is deemed acceptable, and no further action is required. If the risk is between the lower/upper bounds and within the ALARP region (between 1E-6 and 1E-7), then all “practicable” steps must be taken to reduce the risk. If the risk is greater than the upper bound value (1E-6 in Figure 2), then the risk is unacceptable, and the operation should not be permitted. The word “practicable” does not have a clear definition here; it is intentionally subjective. Many times, it is tied to the financial cost associated with each risk reduction measure considered, but adverse impacts other than financial are typically considered in the “practicable” judgement.

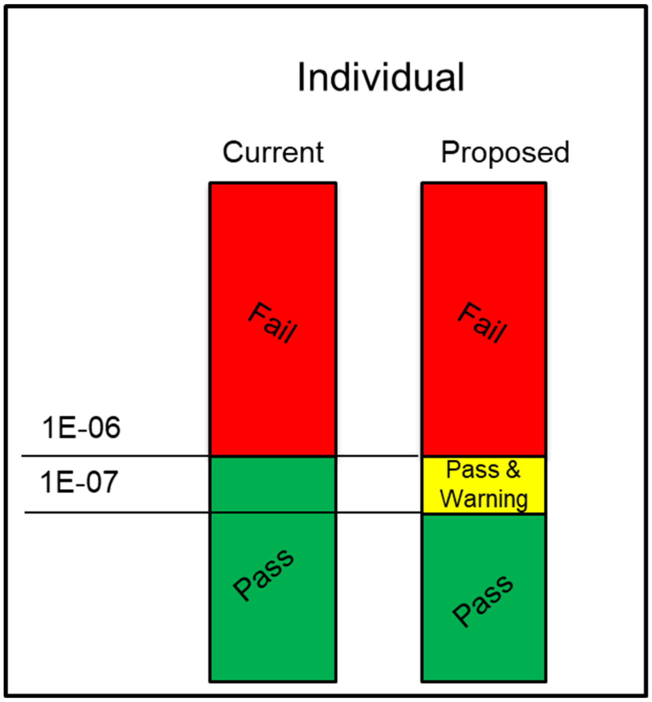

Figure 2. Notional Example of ALARP criteria for Individual Risk

Beyond the assessment of just individual risk, group risk is also a metric that is assessed. This is another advantage of risk assessments, as alterative deterministic codes typically are focused on individuals, and don't fully consider consequence in large population areas. Similar to the individual risk criterion development, group risk criterion thresholds can be developed in a similar manner. One additional metric that group risk can account for is limits on the total loss, no matter how small the probability. This is often referred to as risk aversion criteria. For example, no matter how small the probability of event, a decisional authority may decide that a loss of more than 100 lives is completely unacceptable. This means that even if steps are taken to reduce the probability of occurrence to once in a billion years, the risk will never be deemed acceptable. The actual development of such a curve is not a trivial task, and is operation dependent, usually being reserved for multi-step operations with varying hazards and exposures. These curves are referred to as frequency/number (F/N) curves and present the total loss of life and the associated probability of event. An example of this is presented in Figure 3 (Note that Figure 3 also depicts implementation of ALARP within the F/N curve). A F/N curve for a specific operation is compared against applicable criteria. The constant slope of the F/N criteria corresponds for a constant group risk criterion. The threshold curve shows a vertically line at N=1000 persons, which represents implementation or risk aversion criteria. In this particular risk acceptance criteria, a scenario which could produce a loss of life in excess of 1,000 persons is deemed not broadly acceptable no matter how small the probability is associated with it.

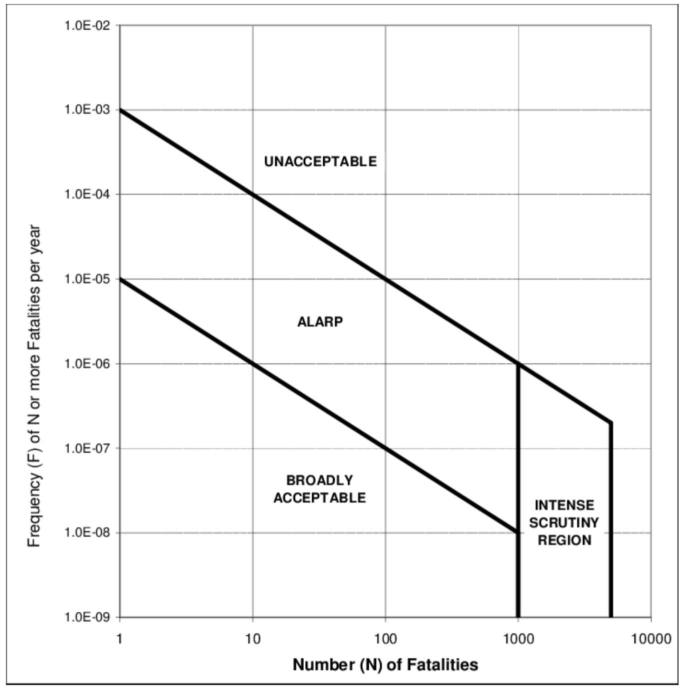

Figure 3. Example F/N Curve for Societal Risk

All of the risk evaluation options discussed have only focused on comparing the risk estimate to a governing risk criterion threshold. A truly comprehensive risk assessment should include uncertainty, otherwise the risk values being conveyed could be quite incomplete. It is possible to have the same singular risk estimate for two cases, but having drastically different levels of uncertainty associated with each. The first case may have a narrow uncertainty distribution around the estimate, and even though the best estimate (mean value of the risk distribution) is being compared against a risk acceptance criterion, the 95% confidence value of the risk distribution is close to the mean. Conversely, the second case may have a large degree of uncertainty (a wide uncertainty distribution). The mean values of the two distributions are the same, and are compared against the risk acceptance thresholds, but in the second case the 95% confidence level could have consequence levels two orders of magnitude larger than the mean. Thus, only presenting and comparing the mean against a threshold may not accurately represent the entire risk picture, particularly for those operations or governing bodies where the risk tolerance is low.

DoW ESB Risk-Based Site Plans

DESR 6055.09 Volume 6 – Enclosure 5 (V6.E5) provides guidance and minimum requirements for quantitative risk-based siting within the DoW. Requirements for preparing, submitting, and periodically reviewing site plans are given. Note that one fundamental requirement for use of this method is that it is only applicable if all PESs are separated by Intermagazine Distance (IMD). If not separated by IMD, the individual net explosives weight for quantity-distance (NEWQDs) for each PES are summed and treated as a single PES, exactly how it is prescribed for QD siting.

DESR V6.E5.3 defines the conditions that must be satisfied for ESB approval of a risk-based explosives safety site plan. An initial assumption/requirement within the DoW risk-based siting process is that a PES/ES pair does not meet QD separation criteria, as that defines the ES that requires risk-analysis and defines the ES group. All ESs that are exposed to non-negligible risk from the PES that do not meet QD separation criteria must be included in the analysis. For each ES, P_f is determined by summing the risks from ***all*** PESs that expose that ES to non-negligible risk. The distance of non-negligible risk is defined where P_f equals 1×10^{-8} for an individual present 24/7/365 in the open or IBD, whichever distance is greater.

In addition to individual risk at each ES in the evaluation, group risk must also be checked. The ES group is defined as all ESs that are exposed to a non-negligible risk from the PES that does not satisfy QD, and the group risk is calculated by summing all P_f for all of the ESs within the ES group.

Finally, a key aspect of DoW-approved risk based site plans is that the full siting amount of the NEWQD and the full yield must be used for the calculated P_f and E_f. This aspect deviates from most risk analysis applications, but it remains consistent with the QD approach. The deterministic distances of QD are intended to represent a defined consequence level assuming full yield and the full sited amount present. This philosophical approach provides inherent conservatism in explosives safety for both DoW-approved siting methodologies.

DoW risk-based siting acceptance criteria is provided in Table 3 and provides threshold acceptance values for both related and unrelated personnel, with checks for both individual and group risk. While these multiple checks are required for acceptance, there is still only a singular check as to whether or not the calculated value of expected risk is acceptable, and the uncertainty distribution is not explicitly evaluated (e.g., the 3-sigma value is not checked against an additional upper bound acceptance criteria).

Table 3. Risk-Based Explosives Siting Acceptance Criteria

Risk to:	Criteria:
Any one related individual – Related P_f	$\leq 1 \times 10^{-4}$ per year
All related individuals – Related E_f	$\leq 1 \times 10^{-3}$ per year
Any one unrelated individual – Unrelated P_f	$\leq 1 \times 10^{-6}$ per year
All unrelated individuals – Unrelated E_f	$\leq 1 \times 10^{-5}$ per year

Need and Basis to Update TP-14

After over more than a decade of field use, several questions have been raised that warranted detailed studies to determine the validity and usefulness of postulated changes to the uncertainty treatment within the TP-14 Quantitative Risk Model. This section describes those efforts and their findings.

At a top level, these questions can be summarized by the following:

- 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?

A multi-year series of investigative tasks were performed culminating in a December 2017 technical report [6]. Figure 4 shows how the investigations were broken into sub-tasks and the technical reports used to document their findings.

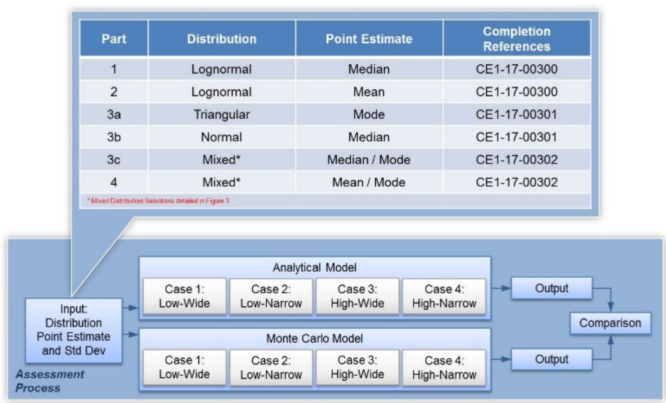

Figure 4. Investigations Performed on Uncertainty Application

The sub-sections that follow provide only a summary of the investigations performed to answer the questions posed, addressing Parts 3 and 4 of Figure 4. These summary sections reference and/or include Technical Reports documenting the findings. The conclusions documented here provide the framework and supporting rationale for changes undertaken in TP-14, Revision 5 as described in a following section of this paper.

Use of Non-Log Normal Distributions to Model Elemental Sub-Factors

The questions posed about incorporation of non-lognormal sub-factor distributions into the risk model can be summarized as follows.

- 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?

Parts 3a and b of the uncertainty task investigated whether normal or triangular statistical distributions could be substituted for lognormal distributions to model the Risk model sub-factors. Part 3c reviewed whether a mix of sub-factor distributions (including normal, triangular, and lognormal) could be successfully represented by modification of the Analytical Approach. The original investigation (2003-2004) [repeated in Part 1] validated the Analytical Approach by comparison with the results of a parallel Monte Carlo study. A similar approach was used to conduct Parts 3a, 3b, and 3c of this Task.

For each sub-part, the Analytical Approach to calculating the risk estimate was modified to model each sub-factor with the statistical distribution assigned to that investigation. A Monte Carlo study was conducted to produce 50,000 estimates of annual risk when modeling each sub-factor with the assigned distribution. For each investigation, the standard four test cases (low-risk/high-uncertainty [Case 1], low-risk/low-uncertainty [Case 2], high-risk/high-uncertainty [Case 3], and high-risk/low-uncertainty [Case 4]) were used to develop comparisons of Analytical results to those produced by a Monte Carlo study applying the same type of risk factor input distributions. Results of each investigation are summarized in the sub-sections below.

Evaluation of Triangular Distribution Use for Sub-factors – Part 3a

The Analytical and Monte Carlo results when using non-lognormal, skewed (triangular) distributions to model the risk sub-factors are compared in Table 4.

Table 4. Part 3a Comparison of Analytical and Monte Carlo Results

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%

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.

Evaluation of Normal Distribution Use for Sub-factors – Part 3b

The Analytical and Monte Carlo results when using non-lognormal, symmetric (normal) distributions to model the risk sub-factors are compared in Table 5.

Table 5. Part 3b Comparison of Analytical and Monte Carlo Results

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%

The differences found between 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.

Evaluation of Using a Mixture of Distributions for Sub-factors – Part 3c

This investigation addresses the case where a mixture of sub-factor distributions has been selected based on individual review by Subject Matter Experts (expert elicitation). For purposes of Part 3c, the mixture of distributions indicated in Figure 5.

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 Std dev of delta t	X		
Scale Factor	Median of Scale Factor Std dev of Scale Factor			X
Lambda	Median of lambda Std dev of lambda		X	
Daily Exposure	Ep Median Daily Exposure Ep std dev of Exposure	X		
	Rand Var std dev Exposure			X
Blast	Ep Median Pf|e blast Ep std dev for blast		X	
	Std dev for variation in blast	X		
Building Collapse	Ep Median Pf|e bldg collapse Ep std dev for bldg collapse		X	
	Std dev for variation in bldg collapse	X		
Debris	Ep Median Pf|e debris Ep std dev for debris		X	
	Std dev for variation in debris	X		
Glass	Ep Median Pf|e glass Ep std dev for glass		X	
	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

Figure 5. Distributions used to Model Risk Sub-Factors for Part 3c

The comparison results when using a mixture of distributions to model the risk sub-factors are provided in Table 6.

Table 6. Part 3c Comparison of Analytical and Monte Carlo Results

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%

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.

Conclusions From Parts 3a, 3b, and 3c

The investigations undertaken in Parts 3a-c were devised to answer the questions relating to use of non-lognormal distributions to model risk model sub-factors:

- Confirmation that an Analytical Model can be devised that produces comparable results to a Monte Carlo study when using non-lognormal (skewed, symmetric, and mixed) distributions for the risk sub-factors clearly demonstrates that the TP-14 risk model does NOT depend on use of lognormal distributions to model these sub-factors.
- The lognormal nature of each of the Monte Carlo studies conducted for comparison demonstrates that the use of different sub-factor distribution types does NOT invalidate the treatment of the resulting risk distribution as lognormal.

Treating Point Estimates as the Mean of Elemental Distributions

The questions posed about treating sub-factor point estimates as the distribution mean can be summarized as:

- 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?

The Uncertainty Task parts that address this question are comparison of Part 1 results to Part 2 and comparison of Part 3c results to Part 4. Parts 1 and 2 demonstrated use of the point estimate as the distribution mean when all the sub-factors are lognormal. Parts 3c and 4 extended these results for cases with sub-factors modeled by a mixture of distributions.

For Part 4, the same mix of input distributions used in Part 3c was developed with one change. The point estimates from the science models were treated as the mean of each distribution instead of the median. The input distribution parameters were shifted from those used in Part 3c in a manner similar to that used to develop Part 2 inputs to replace those used in Part 1. No modification to the equations used in Part 3c were required to perform Part 4.

As with other comparisons, the four original test cases were run to generate 50,000 annual risk estimates. This generated a risk distribution formed without assumption of a lognormal results distribution. The statistical parameters calculated for both the Analytical and the Monte Carlo results are shown in Table 7.

Table 7. Comparison of Part 4 Analytical Results to the Monte Carlo Study

Solution Method	Part 4, Case 1 (Low-Wide)			Part 4, Case 2 (Low-Narrow)		
	Expect Val	Std Dev	95th %	Expect Val	Std Dev	95th %
Analytical Method	3.92E-15	3.24E-15	9.90E-15	1.12E-16	7.22E-17	2.49E-16
Experimental (Monte Carlo)	4.13E-15	4.44E-15	1.19E-14	1.19E-16	8.85E-17	2.85E-16
Δ%	5.34%	36.92%	19.78%	5.93%	22.62%	14.37%

Solution Method	Part 4, Case 3 (High-Wide)			Part 4, Case 4 (High-Narrow)		
	Expect Val	Std Dev	95th %	Expect Val	Std Dev	95th %
Analytical Method	2.35E-04	3.12E-04	7.42E-04	2.19E-04	2.51E-04	6.49E-04
Experimental (Monte Carlo)	2.47E-04	3.54E-04	8.32E-04	2.29E-04	2.89E-04	7.04E-04
Δ%	5.01%	13.50%	12.11%	4.70%	15.22%	8.55%

Figure 6 depicts the distribution of the Part 4 Monte Carlo results when compared to the Analytical calculation of the distribution.

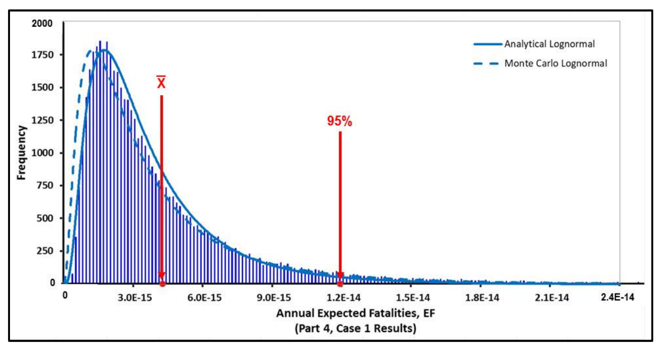

Figure 6. Part 4, Case 1 Results Demonstrating Log Normal Nature of Risk Results

Conclusions Regarding Assignment of Point Estimates as Sub-factor Means

These results show that the Analytical Approach can be modified to accommodate use of the sub-factor point estimates as means of the input distributions and that the resulting risk distribution remains lognormal in nature.

One effect of this change that should be noted here, though, is that use of point estimates as means of the sub-factor distributions prevents sub-factor uncertainties from impacting the mean of the Risk distribution. Since current acceptability criteria consider only a threshold Expected Value for the calculated risk, Uncertainty would no longer impact the acceptability decision. A secondary criterion that sets acceptability limits on a measure of the distribution upper bound (such as the distribution's 95th percentile would be necessary to ensure that uncertainty impacts the risk decision).

Method to Enhance Communication of Risk Results

The questions posed about enhancing communication/understanding of the risk results can be summarized as:

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

The original SAFER Uncertainty Model was described in the paper "Revised Analytical Approach" by Dr Richard W. Mensing published in November 2003 [3]. This paper contained nearly 10 pages of complex equations to provide the academic rigor required by the Risk Model.

Operational experience with the SAFER [7] and Institute of Makers of Explosives Safety Analysis for Risk (IMESAFR) [8] statistical models described in this paper has clearly demonstrated the need for a less complex construct that assists in communicating risk results. While retaining the academic rigor of the accepted model, the construct breaks the model into communicable segments that can be examined individually, by type, or as part of the full model. The risk equation in this Uncertainty model contains several factors that together duplicate exactly the full Uncertainty Model of the original paper to produce the exactly the same risk estimate. For each of these factors, IMESAFR has incorporated a module that computes point estimates, applies the effects of aleatory and epistemic uncertainties, and considers the effects of correlations where appropriate. This module is transportable and can be added to SAFER, if desired.

The original Mensing paper was extended in August 2009 and September 2013 to describe the model known as the Uncertainty Communication Module. The equations that follow place the entirety of the model described in Mensing's paper into one of three types of factors: Point Estimates (the median values, denoted by R), Uncertainty Factors (U), or Correlation/Confidence Factors (C). Since this construct is simply a re-arrangement of the original equations, the communication module will compute the same results for Expected Fatality and Variance, but the factors are split in such a way that additional outputs can be produced for the sole purpose of risk communication.

1. Expected Value
   The model of the world (MOW) has an expected value of:

   $$E\text{ep}(EF) = E_{\text{ep}}(\text{S})*E_{\text{ep}}(\text{Pe})*E_{\text{ep}}[E(\text{Pf|e})]*E_{\text{ep}}[E(\text{E})]$$

   To simplify the model for communication purposes, we define each of the expected values in terms of Point Estimates (medians), Uncertainty Factors, and Correlation / Confidence Factors as follows:

   $$E_{\text{ep}}(\text{S}) = \text{R}_\text{S}*\text{U}_\text{S}$$

   $$E_{\text{ep}}(\text{Pe}) = \text{R}_{\text{Pe}}*\text{U}_{\text{Pe}}$$

   $$E_{\text{ep}}[E(\text{Pf|e})] = \text{R}_{\text{Pf|e}}*_{\text{UPf|e(eff)}}$$

   $$E_{\text{ep}}[E(\text{E})] = \text{R}_\text{E}*\text{U}_\text{E}*\text{C}_{\text{PeE}}*\text{C}_{\text{NE}}*\text{C}_{\text{conf}}$$

   which produces a model of the form:

   $$E_{\text{ep}}(EF) = (\text{R}_\text{S}*\text{R}_{\text{Pe}}*\text{R}_{\text{Pf|e}}*\text{R}_\text{E})*(\text{U}_\text{S}*\text{U}_{\text{Pe}}*\text{U}_{\text{Pf|e(eff)}}*\text{U}_\text{E})*(\text{C}_{\text{PeE}}*\text{C}_{\text{NE}}*\text{C}_{\text{conf}})$$

where the first group of terms forms the base risk estimate, the second group forms the factor describing the impact of uncertainty on the risk estimate, and the third group aggregates the effects of input confidence and two correlations on the estimate.

The individual factors are defined in terms of variables in the preceding sections with two changes: λ has been changed to Pe and V (variance) replaces σ^2. Factor definitions are:

<u>Point Estimates:</u>

$\text{R}_\text{S} = \text{S}_\text{o}$ = Median of Scaling Factor [no change]

$\text{R}_{\text{Pe}} = \text{Pe}_{\text{oo}}$ = Median of Probability of Event [no change]

$\text{R}_{\text{Pf|e}} = \text{Pf|e}_\text{o} = 1 - (1-\text{P}_{\text{f|1oo}})(1-\text{P}_{\text{f|2oo}})(1-\text{P}_{\text{f|3oo}})(1-\text{P}_{\text{f|4oo}})$
[back to original]

$\text{R}_\text{E} = \text{E}_{\text{oo}}$ = Median of Exposure [no change]

<u>Uncertainty Factors:</u>

$\text{U}_\text{S} = \exp[0.5\text{V}_\text{S}]$

$\text{U}_{\text{Pe}} = \exp[0.5\text{V}_{\text{Pe}}]$

$$\begin{aligned}\text{U}_{\text{Pf|e(eff)}} = \{&[\text{SUMk}(\text{Pf|koo}*\text{U}_\text{k})]*\text{U}_\text{Y}*\text{U}_{\text{NEW2}}\\ &-[\text{SUMik}(\text{Pf|ioo}*\text{Pf|koo}*\text{U}_\text{i}*\text{U}_\text{k})]*\text{U}^2_\text{Y}*\text{U}^2_{\text{NEW2}}\\ &+[\text{SUMijk}(\text{Pf|ioo}*\text{Pf|joo}*\text{Pf|koo}*\text{U}_\text{i}*\text{U}_\text{j}*\text{U}_\text{k})]*\text{U}^3_\text{Y}*\text{U}^3_{\text{NEW2}}\\ &-[\text{PRODUCTi}(\text{Pf|ioo}*\text{U}_\text{i})]*\text{U}^4_\text{Y}*\text{U}^4_{\text{NEW2}}\}/\text{R}_{\text{Pf|e}}\end{aligned}$$

where,

$\text{U}_\text{k} = \exp[0.5*(\text{V}_\text{k} + \text{V}_{\text{ko}})]$

$\text{U}_\text{Y} = \exp[0.5(\text{V}_\text{y} + \text{V}_{\text{yo}})]$

$\text{U}_{\text{NEW2}} = \exp[0.5\text{V}_{\text{NEW2}}]$

$\text{U}_\text{E} = \exp[0.5\text{Ve}]$

<u>Correlation / Confidence Factors:</u>

$\text{C}_{\text{PeE}} = \exp[0.5(\text{r}^2\text{V}_\text{e}+2\text{rV}_\text{e}+2\text{r}*\text{Corr}_{\text{NEW}}\text{V}^{0.5}_{\text{NEW1}}\text{V}^{0.5}_\text{e})]$

$\text{C}_{\text{NE}} = \exp[0.5(\text{V}_{\text{NEW1}} + 2\text{Corr}_{\text{NEW}}\text{V}^{0.5}_{\text{NEW1}}\text{V}^{0.5}_\text{e})]$

$\text{C}_{\text{conf}} = \exp[0.5\text{V}_{\text{Eo}}]$

In addition to these less complex factors, this construct provides the ability to easily compute additional risk measures that are more easily communicated:

Base Risk Estimate = product of the four Point Estimates

Total Uncertainty Factor = product of the four Uncertainty Factors

Factor Due to Correlations/Confidence = product of the three Corr/Conf factors.

The product of these three measures will always produce the total Expected Value estimate produced by the full uncertainty model.

2. Variance
The variance described in Section D.2 of Mensing's paper can also be written in terms of the factors described above and the variances of a few parameters identified in earlier sections. The epistemic variance of Expected Fatality then becomes:

$V_{ep}(E) = E^2_{ep}(S) * E^2_{ep}(Pe) * E^2_{ep}[E(Pf|e)] * E^2_{ep}[E(E)] * \{[PROD(1+CV^2_x)] - 1\}$

where,

$E_{ep}(X)$ = the expressions used in expected value computation

CV^2_X = $V_{ep}(X) / E^2_{ep}(X)$

$V_{ep}(X)$ = $X^2_{oo} * U^2_X * [U^2_X - 1]$ for factors S and Pe

$V_{ep}(E)$ = $E^2_{00} * U^2_E * C^2_{PeE} * C^2_{NE} * C^2_{conf} * [C^2_{conf} - 1]$

$V_{ep}(Pf|e)$ = $SUM\{P^2_{f|koo} * U^2_k * U^2_Y * U^2_{NEW} * [\exp(V_{ko} + V_{yo}) - 1]\}$
$+ 2 * SUM\{P_{f|ioo} * P_{f|koo} * U_I * U_k * U^2_Y * U^2_{NEW} * [\exp(V_{yo}) - 1]\}$

Though much more directly communicated, this construct for variance produces the same value as that computed by the original Mensing equations. Since the components are broken into a relatively small number of items each of which can be simply described, this model provides the desired improvement in communicability of the Uncertainty model. Using these factors, the Risk Estimate produced by the full model can be broken up into portions representing the Base Risk, the Uncertainty multiplier, and a Correlation/Confidence multiplier to clearly separate the contribution of each factor to the Total Risk Estimate.

Uncertainty Communication Conclusion

The additional results produced by the proposed Communication Module provide insights into the impact of Uncertainty and Correlations on the calculated risk. The work summarized above demonstrated that this re-arrangement of risk model equations produces identical estimates for both the total risk and its Variance.

Improvements to the TP-14 Uncertainty Model

Based on investigation findings summarized in a previous section, several significant updates will be implemented by TP-14, Rev 5.

Non-lognormal Probability Distribution for Random Variables

Proposed Distributions for TP-14

The RBESCT investigated alternative distributions to assign to each of the random variable in the TP-14 uncertainty model. This effort, fully documented in [9], independently assessed the probably distribution of input and results associated with each random variable, and determine whether lognormal distribution should be retained or if an alternative distribution should be used. Given the limitations on data distribution for some of these random variable, alternative distributions were limited to either a normal or triangular distribution. A summary of the results for each random variable is provided in Table 8.

Table 8. Summary of Proposed Distributions for TP-14 Random Variables

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

To illustrate the changes and effects on representation of probabilistic distribution for each random variable, plots of the original distribution versus the proposed distribution were generated within Reference [9]. This has been generated for both the probability density function (PDF) and the cumulative density function (CDF). Excerpts from Reference [9] are provided in Figure 7, Figure 8, and Figure 9, with the environmental scaling factor PDFs selected for illustrative purposes. Results for Cases 1 through 4 are again used to show the effect on the random variable distributions.

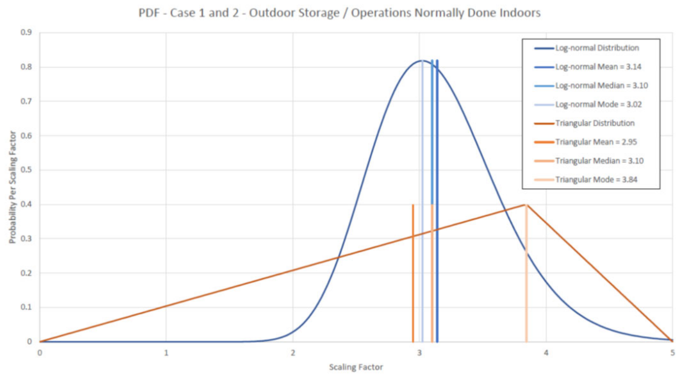

Figure 7. PDF for Environmental Scaling Factor, Outdoor Operations, Case 1 & 2

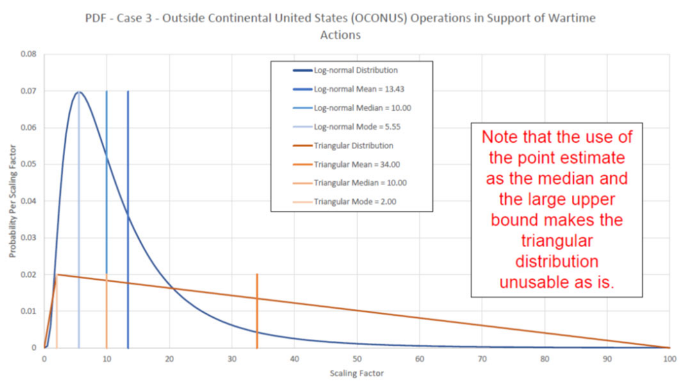

Figure 8. PDF for Environmental Scaling Factor, OCONUS Operations, Case 3

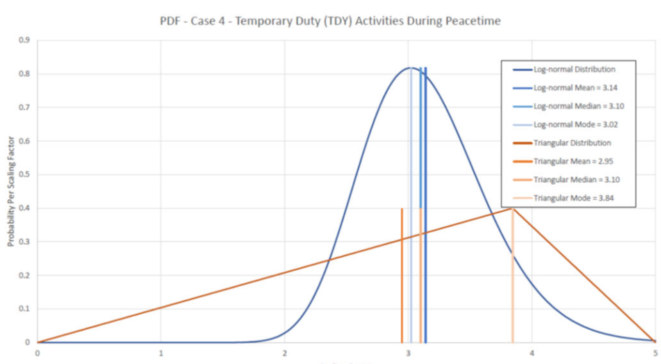

Figure 9. PDF for Environmental Scaling Factor, TDY Activities, Case 4

Justification for Implementation of Non-lognormal Distributions

A previous section of this paper provided results of multiple analytical studies examining the feasibility of using non-lognormal distributions to represent random variables within the TP-14 risk model, with the conclusion that this does not invalidating the treatment of the resulting risk distribution as lognormal. Given the number of random variables within the TP-14 risk equation, and the general bounds of those random variables, the resulting differences were deemed acceptable. While acknowledged as not mathematically equivalent, for the application of this risk model enhanced accuracy in representing the actual distribution of the random variables was deemed a much greater priority and would increase the efficacy of the final risk distribution estimate. The end result is a better representation of the final risk distribution, even if the final product of non-lognormal random variable distributions isn't "perfectly" lognormal in this particular application.

Mean vs median as point estimate

As discussed in previous sections, there are multiple options to compare the calculated risk distribution to risk acceptance criteria. Additionally, development of such criteria involves a comprehensive process of: 1) literature review across multiple industries identifying annual consequence risk, 2) a detailed assessment of current deterministic standards and the resulting risk distribution, and 3) an assessment of public perception of risk tolerance for the organization and industry being assessed.

The DoW explosives safety risk acceptance criteria for ESB risk-based site plans have been presented herein. They were developed via detailed studies of annual individual and group risk across a wide variety of industries and activities [10]. Additionally, a comprehensive assessment of over 60,000 explosives safety siting scenarios have been developed to assess risk at IBD and ILD defined per DESR 6055.09 [5]. These examined multiple PES, ES, activities, and NEWs. The result of the studies plotted a distribution of cases that passed and failed the DESR risk criteria shown in Table 3. The results of these studies supported the DoW and Services to accept and codify these risk criteria, and alleviated concern at the time that risk analysis would show all of these QD violations to be satisfactory via a ESB risk-based site plan approval. While most of these scenarios did have a passing result per the risk analysis, there were a non-trivial number of cases where a case that passed QD failed the risk analysis, and these tended to be those higher risk operations. However, the risk analyses generated in these studies had used the median as the point estimate, in accordance with the current (and legacy) versions of TP-14. Given the lognormal random variable distributions currently employed in TP-14, if those calculations were redone and the point estimate was assigned as the mean rather than the median, all of the final calculated risk estimates (mean value of the final distribution) would result in a lower risk. Additionally, the proposed change in some of the uncertainty distributions for the random variables would have an effect on this end result as well; though it is expected to have less impact than changing the point estimate to the mean of the individual parameter distribution.

Additionally, if the point estimate is assigned as the mean of the uncertainty distribution for each random variable, another result is that the actual uncertainty calculated doesn't have any impact on the risk assessment for ESB risk-based site plans. If the decision is made to assign the point estimates as the means in TP-14 Revision 5, in order to not lose the additional fidelity generated via the uncertainty distribution, one solution would be to establish criteria checks at the 95% confidence level of the distributions. These could be advisory or mandatory, but if implemented would provide more information in the risk decision process regarding the level of risk that is being accepted.

Decoupling Uncertainty in the Risk Estimate to Enhance Communication of Results

As previously discussed, the additional results produced by the proposed Communication Module provide insights into the impact of Uncertainty and Correlations on the calculated risk. The work detailed in this paper and listed references demonstrate that this re-arrangement of risk model equations produces identical estimates for both the total risk and its Variance. The RBESCT previously concurred with implementing these changes into TP-14 Revision 5 and other associated documents that support risk communication.

Summary/Conclusions

Department of War explosives operations are of critical importance to national security but pose an inherent risk to persons and assets with the potential for unintentional energetic events. It is imperative to conduct comprehensive explosives safety management programs to assess and mitigate risks throughout the munition lifecycle process. To fully quantify the risks associated with such low probability, high consequence events, the DoW ESB has established an approved quantitate risk assessment methodology published within TP-14. Additionally, ESB has established risk thresholds for both individual and group risks of affected populations with DESR 6055.09.

Given the high degree of uncertainty associated with these accidental events, the risk estimate produced by a quantitative risk assessment should include uncertainty if it is to fully convey the risk profile for decisional purposes to the competent authority having jurisdiction. Additionally, any singular point on the risk estimate used for decisional purposes or comparison with criterion needs to be used within the appropriate context and consider the level of risk tolerance for that specific application. Alternatively, multiple aspects of the risk estimate distribution can be used for comparisons purposes, with establish criterion or otherwise, such as utilizing the mean value of the risk estimate as well as the 95% confidence level.

The ESB is currently in the process of updating TP-14 Revision 5, and a focus of that update is to improve the treatment of uncertainty within the risk equation to improved fidelity, as well as improvements of the risk communication in general. The improvements to the uncertainty model will improve the overall quantitative risk assessment process used for explosives operations within the DoW and provide decision makers with a clearer picture of risk.

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Definitions/Abbreviations

ALARP	As Low As Reasonably Practicable
CDF	Cumulative Density Function
DDESB	Department of Defense Explosives Safety Board
DESR	Defense Explosives Safety Regulation
DoW	Department of War
DoW ESB	Department of War Explosives Safety Board
DoW ESO	Department of Way Explosives Safety Office
ES	Exposed Site
F/N	Frequency / Number
IBD	Inhabited Building Distance
ILD	Intraline Distance
IMD	Intermagazine Distance
IMESAFR	Institute of Makers of Explosives Safety Analysis for Risk
IR	Individual Risk
MOW	Model of the World
NEW	Net Explosives Weight
NEWQD	Net Explosives Weight for Quantity Distance
PDF	Probability Density Function
PES	Potential Explosion Site
QD	Quantity Distance
QRA	Quantitative Risk Assessment
RAC	Risk Assessment Code
RBESCT	Risk Based Explosives Safety Criteria Team
SAFER	Safety Assessment For Explosives Risk
TP	Technical Paper
US	United States