PACIFIC GAS AND ELECTRIC COMPANY

2020 RISK ASSESSMENT AND MITIGATION PHASE (RAMP) REPORT

ENTERPRISE RISK MODEL USER GUIDE

JULY 17, 2020

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1. Introduction and Purpose

PG&E's Enterprise Risk Model User Guide (User Guide) contains a description of the Python-based[1] analytical risk model (the Model) PG&E used to compute Risk Scores and Risk Spend Efficiency (RSE) values for the risks and associated mitigation and control programs presented in PG&E's Risk Assessment and Mitigation Phase (RAMP) report filed June 30, 2020 (Application (A.) 20-06-012). This User Guide also describes each sheet (or tab) in the Excel-based input workbook (Risk Input File) that contains information necessary to calculate Risk Scores and Risk Spend Efficiency values of a given risk event and associated mitigations.

The User Guide includes screenshots from an example Risk Input File, as well as key example calculations that are not otherwise described in Chapter 3 of PG&E's RAMP Report, Risk Modeling and Risk Spend Efficiency. The values in this example calculation are provided for demonstration purposes and should not be used as a benchmark for judging accuracy of the Model runs.

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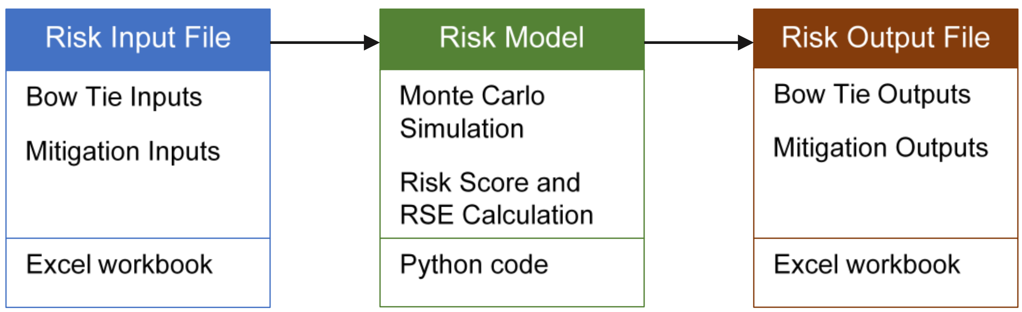
1 Python is the programming language upon which PG&E's risk model is constructed.

2. Model Overview

2.1. Model Architecture

Each risk event is defined in an Excel workbook, the Risk Input File, which includes all of the necessary elements for calculating risk scores and Risk Spend Efficiencies: risk exposures, risk event likelihood; risk event consequence; and mitigation program scope, effectiveness and cost. Additionally, the Risk Input File includes modeling parameters specifying the Model run characteristics such as the number of iterations for a Monte Carlo Simulation and span of years to be simulated (analysis horizon).

FIGURE 2-1 – ENTERPRISE RISK MODEL ARCHITECTURE



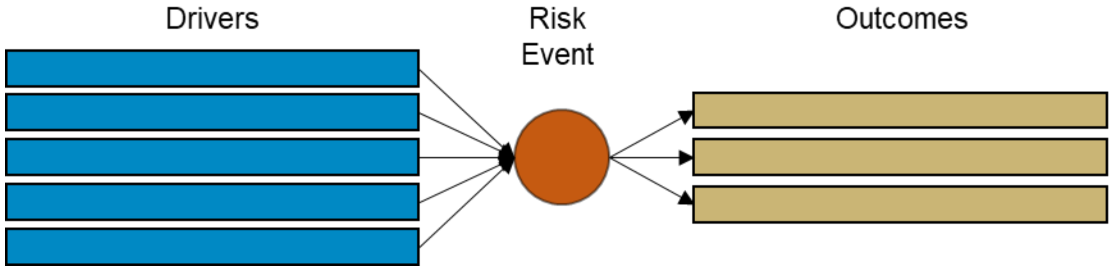
Note: PG&E is providing the Risk Output Files for each of the 12 RAMP Risks. The Risk Output Files contain the Bow Tie and Consequence Table graphics included in each RAMP risk chapter (Chapters 7 to 18), the risk scores, RSE, and risk reduction score for each mitigation and the RSE and risk reduction score for each alternative mitigation plan. In addition, the Risk Output File includes detailed output for driver frequency, outcome frequency, tranche level exposure, risk score by outcome, risk score by tranche, risk score by outcome by attribute, and driver contribution to risk scores. Bow Tie files are made available in soft copy.

The Model was developed using Python. The Model reads and parses the data provided in the Risk Input File and computes Risk Scores and Risk Spend Efficiency values across relevant dimensions of the Bow Tie (e.g., year, tranche, outcome). The results are written to an Excel workbook (the Risk Output File). The results for the 2023 Test Year Baseline case are used to produce the values in the Bow Tie visuals as well as consequence tables presented in each RAMP Risk chapter.

2.2. Bow Tie Framework

The Model is built on a Bow Tie framework, where the center of the Bow Tie represents a Risk Event, the left-hand side represents risk drivers, and the right-hand side represents risk outcomes. This is illustrated in Figure 2-2.

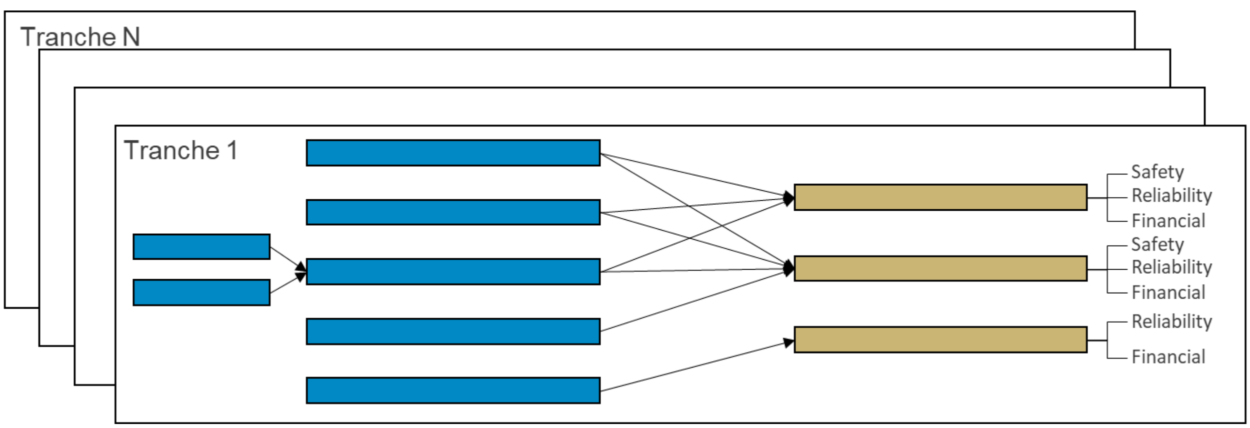
FIGURE 2-2 – CONCEPTUAL MODEL OF THE BOW TIE FRAMEWORK, WITH DRIVERS ON THE LEFT, THE RISK EVENT IN THE CENTER, AND OUTCOMES ON THE RIGHT



Note: The left-hand side of the Bow Tie is quantified using likelihood of a risk event; and the right-hand side of the Bow Tie is quantified using an outcome consequence of a risk event.

The quantification is calculated at the Tranche level. A Tranche represents a logical disaggregation of a group of assets (physical or human) or systems into subgroups with similar risk profiles for the purpose of risk quantification. Thus, the final risk event Bow Tie is constructed from a series of tranche-level Bow Ties that are ultimately combined and presented as a single Bow Tie. Figure 2-3 shows the individual tranche-level Bow Ties.

FIGURE 2-3 – CONCEPTUAL ILLUSTRATION OF THE RELATIONSHIPS BETWEEN DRIVERS (LEFT) AND OUTCOMES (RIGHT) WITH CONSEQUENCE ATTRIBUTES, WHERE THERE IS ONE SET OF EACH FOR EVERY TRANCHE



Note: Even though graph shows an arrow from drivers (five blue boxes) to outcomes for visualization purposes, Bow Tie implemented in the Risk Input File and Model is more correctly represented by having arrows to come from sub-drivers (two blue boxes on the left) to outcome directly without being aggregated into drivers.

Risk drivers, which can be further broken down into sub-drivers, are factors that contribute to the occurrence of a risk event.[2] Sub-driver inputs represent the expected likelihood of a risk event (LoRE) per unit of exposure. Sub-driver likelihood values (the probability of a risk outcome per unit of exposure per year from that sub-driver) are characterized at the Tranche × Sub-Driver × Outcome level.

For a risk event with five tranches, six sub-drivers, and three outcomes, the number of likelihoods that are required by the Model as an input is 5 × 6 × 3 = 90 (with 0 being an acceptable value).

The event frequency is the product of the exposure and expected annual likelihood of a risk event per unit exposure. The LoRE and event frequency are aggregated across sub-drivers, drivers, outcomes and/or tranches to show different levels of aggregated LoRE and event frequency. Note that the number of risk events is not simulated.

Outcomes are characterized by statistical distributions of the potential levels of impact from a risk event across four different attributes, which are listed in Table 2-1 Consequences are sampled from their respective distributions for each set of tranche, outcome, and attribute and for each year of the analysis period.

TABLE 2-1 – CONSEQUENCE ATTRIBUTES AND THEIR NATURAL UNITS

ATTRIBUTE	NATURAL UNIT
Safety	Equivalent Fatality
Electric Reliability	Customer-Minutes Interrupted
Gas Reliability	Customers Affected
Financial	Dollars

2 For example, the risk driver "D-Line Equipment Failure" in the Failure of Electric Distribution Overhead Assets risk event includes sub-drivers such as Conductor, Pole, Recloser, Cross-Arm, Switch, Cutout/Fuse, etc.

Each set of consequence outputs are represented in their natural units.[3] Using PG&E's Multi-Attribute Value Function (MAVF),[4] these natural-unit consequences are then represented as consequence of risk event (CoRE) values.

$$\text{Attribute Risk Score} = \text{Exposure} \times \text{LoRE} \times \text{Attribute CoRE} = \text{Frequency} \times \text{Attribute CoRE}$$

Attribute Risk Scores can be aggregated across consequence attributes, outcomes, and/or tranches to show different levels of aggregated risk scores.

Risk, as measured by the Risk Scores, can be reduced by implementing mitigation and/or control projects or programs. Details on project/program effectiveness calculations and allocations are provided in Section 4 of this document.

Listed below are the steps used to fully characterize a Bow Tie risk model. Walking through these steps mirrors moving through the worksheets in the Risk Input File workbook, each of which is discussed in detail beginning in Section 3.

1) Define risk event, drivers/sub-drivers, and outcomes.
2) Define tranches and tranche-level exposure over time.
3) Define sub-driver LoRE for all relevant Tranche-Sub-Driver-Outcome combinations (unit: events/year/unit exposure):
   a) Escalation factors can be defined for sub-drivers where expected LoRE is anticipated to change over time; and
   b) Multipliers can be applied to account for cross-cutting factors,[5] which may or may not vary with time).
4) Define conditional consequence distributions for all relevant Tranche-Outcome-Attribute combinations, which have the following elements:
   a) Distribution probability, which captures the probability of the Attribute consequence given the Outcome;

---

3 As defined by the Phase Two Decision Adopting Safety Model Assessment Proceeding (S-MAP) Settlement Agreement, the Natural Unit of an attribute is the way the level of an attribute is measured or expressed. For example, the natural unit of a financial attribute may be dollars. Natural units are chosen for convenience and ease of communication and are distinct from scaled units. (Decision (D.) 18-12-014, p. 17).

4 The Multi-Attribute Value Function is a tool for combining all potential consequences of the occurrence of a risk event, and for creating a single measurement value. D.18-12-014, p. 17.

5 Cross-cutting factors are not risk events themselves, but rather they impact either the likelihood or consequence of risk events.

b) A probability distribution and its parameters defining each Attribute consequence in Natural Units;

c) Optional operator(s) (sum, prod) if the Attribute consequence is characterized by multiple distributions;

d) Escalation factors for parameters that are anticipated to change with time; and

e) Multipliers to the Attribute consequence to account for cross-cutting factors, which may or may not vary with time.

The Baseline Risk Scores for each year included in the analysis can be computed for the risk event given these model inputs. The Proposed and Inherent Risk Scores[6] require Mitigation or Control programs to be defined. The process to do so is reviewed in Section 1.

2.3. Mitigation Analysis Methodology

Mitigation projects and programs impact some portion(s) of the quantified Bow Tie. Depending on the type of project or program, the mitigation can either reduce the event likelihood or the consequence magnitude of a risk event when it occurs. The adjusted, or mitigated, event frequency and/or risk event consequence are used to compute a Mitigated Risk Score (aka Post-Mitigation Risk Score).

$$\text{Mitigated Risk Score} = \text{Exposure} \times \text{LoRE}_{\text{mit}} \times \text{CoRE}_{\text{mit}} = \text{Frequency}_{\text{mit}} \times \text{CoRE}_{\text{mit}}$$

For each model year, the Mitigated Risk Score is compared to the Baseline Risk Score to compute a Risk Reduction score.

The steps to build out the Mitigation and Control Programs within the model are as follows. These steps align with the four input worksheets described in Section 2.4.4.

1) Define mitigation or control program(s), specifying whether they mitigate event likelihood, consequence magnitude, or both, and placing them in the appropriate Case (e.g., Proposed or Alternative) as the basis for defining a Portfolio of projects.[7]

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6 The Proposed Risk Score accounts for the risk reduction impacts of the planned mitigations. The Inherent Risk Score removes the benefits of on-going risk control work and does not incorporate risk reduction impacts from planned mitigations.

7 PG&E develops and analyzes different project Portfolios. The initial Portfolio includes the mitigations proposed for the General Rate Case (GRC) period (the Proposed Plan). Additional Portfolios will include some or all of the proposed mitigations plus some number of alternative mitigations (Alternative Plan(s)). The Proposed Plan and Alternative Plan(s) are described in each of the RAMP Risk chapters (Chapters 7-18).

2) Characterize program exposure (scope) and estimated program costs over the appropriate time period.
3) Define mitigation program effectiveness (percent of frequency or natural unit consequence reduced), duration of benefits, and the degradation of benefits for relevant Tranche-Sub-Driver-Outcome (frequency mitigation) or relevant Tranche-Outcome-Attribute (consequence mitigation).[8]

2.4. Risk Input File Metadata

This section broadly describes the organization of the Risk Input File.

2.4.1. Table of Contents (TOC)

The TOC lists the tabs in the Risk Input File and includes a description of what each tab contains.

FIGURE 2-4 – RISK INPUT FILE TABLE OF CONTENTS

Tab #	Tab	Description
0	0-Global Parameters	Global Parameters for Model Run
1	1-Risk	Define Risk
2	2-BowTie	Define Drivers, Sub-Drivers, Outcome and Consequences Attributes
3	3-Tranche	Define Tranches for the Risk
4	4-Freq	Specify Likelihood and Frequency of Risk Event inputs
5	5-FreqMult	Specify Multipliers for Likelihood/Frequency of Risk Event inputs
6	6-Conseq	Specify Consequence Distributions
7	7-ConseqMult	Specify multipliers for Consequence values simulated
8	8-Program	Define Programs and association with other programs
9	9-ProgramExposureSpend	Define Program units and spend
10	10-ProgramFreqEff	Specify Program Effectivenesses on Frequency
11	11-ProgramConseqEff	Specify Program Effectivenesses on Consequences
12	12-esc_method	Define custom case for escalation methods
13	13-DistributionParameters	Distribution Parameter Characteristics
14	REF_Tranche	Reference data for Tranches
15	REF_CC	Reference data for cross-cutting factors
16	REF_Freq	Reference data for Frequencies
17	REF_Conseq	Reference data for Consequences
18	REF_ProgramExposureSpend	Reference data for program exposure and cost
19	REF_FreqEff	Reference data for effectiveness of programs that impact Frequency

8 PG&E developed mitigation effectiveness workpapers for each RAMP risk. The mitigation effectiveness workpapers describe each mitigation (or control) program, the assumed effectiveness of the program, the justification for the assumed effectiveness, the duration of the program benefit and the justification for the assumed benefit length. The mitigation effectiveness workpapers were provided June 30, 2020 along with PG&E's RAMP Report (A.20-06-012) and are provided again on July 17, 2020 as part of the modeling workpapers supporting PG&Es 2020 RAMP Report.

- Input Sheet 0 includes the global parameter used in the Model for the specific risk event;
- Input Sheets 1 through 7 are the tabs used for the Bow Tie inputs;
- Input Sheets 8 through 11 are the tabs used for mitigation inputs;
- Input Sheets 12 and 13 are auxiliary tabs that are used to define parameters or functions used in other tabs;
- The names of certain Input Sheets in the Risk Input Files start with "REF" (for reference) which indicates that the sheet contains reference data used by the other sheets to perform various calculations (in the example TOC above, the Risk Input File includes reference data for Tranche, Cross-Cutting Factors, Frequencies and Consequences, program exposures, cost and effectiveness).

2.4.2. Risk Model Parameters

The Model includes three tabs wherein the user defines fundamental information needed to model the risk event.

2.4.2.1. Tab 0-Global Parameters

The 0-GlobalParameters tab is the first tab in the Risk Input File with fields that directly impact the analytical model processing. This tab includes:

- Number of Simulations:[9] the number of values that should be sampled from each statistical distribution specified for each year as part of the Monte Carlo simulation.
- Baseline/Proposed/Inherent Case: a Boolean flag, TRUE or FALSE, that determines whether or not the model should process the specified case. The cases can be defined as:
  - Baseline Case: This represents the model scenario where risk controls are implemented, but the impact of proposed mitigations are not taken into account for calculation;
  - Inherent Case: This represents the model scenario where specified risk controls (defined on the #8, #9, #10, and #11 tabs of the Risk Input File) are no longer being implemented, simulating what risk scores would be without specified risk controls;
  - Mitigated Case: This represents the model scenario where proposed and/or alternative mitigations (defined on the #8, #9, #10, and #11 tabs of the Risk Input File), are implemented, providing a reduction in risk score.

---

9 Technically this indicates the number of iterations of Monte Carlo Simulations to perform.

- Diagnostic Run: This Boolean flag, when TRUE, sets the specified Number of Simulations and Number of Batches to 1, in order to test that the Risk Input File is valid for model processing, without running unnecessary iterations of the distribution sampling functions;
- Archive Run: This Boolean flag allows the model to store the values sampled for *all* iterations rather than only retaining the mean value of simulated Consequence of Risk Event values in natural units; and
- Number of Batches: If greater than 1, the simulation is run in batches. Multiple batches should be run when the Number of Simulations necessary to achieve a desired level of convergence would lead to memory issues. These memory issues are driven by the size of the data/arrays required in the computation.

FIGURE 2-5 – 0-GLOBALPARAMETERS TABLE

Number of Simulation	Baseline Case	Mitigated Case	Inherent Case	Diagnostic Run	Archive Run	Number of Batches
50000	TRUE	TRUE	FALSE	FALSE	FALSE	50

2.4.2.2. Tab 12-esc_method

Tab 12-esc_method describes different escalation methods that can be specified by the user throughout the Risk Input File for specifying how to adjust base year values to derive the values for each future year in the analysis horizon, without having to specify the values for every year.

Escalation methods are used to extrapolate the base input parameters for frequencies, consequences, exposures, frequency or consequence multipliers, and mitigation effectiveness across the entire timeframe of the analysis horizon.

There are five available escalation methods implemented in the Model, each of which is listed and defined on Tab 12:

Method 1: esc

Input Parameter: escFactor

Description: growth rate increase

Formula:

$$\textit{active year value} = \text{prior year value} \times (1 + \text{escFactor})$$

This method requires at least one year of input data for the parameters and uses the escFactor parameter as the growth rate to escalate the parameters across all years in the simulation.

Method 2: inc

Input Parameter: escFactor

Description: arithmetic increase

Formula:

$$\begin{aligned} \textit{active year value} \\ &= \text{prior year value} \\ &+ (\text{prior year value} - \text{value from two years prior}) \times (1 + \text{escFactor}) \end{aligned}$$

This method requires at least two years of input data for the parameters and uses the escFactor parameter as the arithmetic growth rate to escalate the parameters across all years in the simulation.

Method 3: cagr

Input Parameter: n

Description: compound annual growth at rate n

Formula:

$$\textit{active year value} = \left(\frac{x[-1]}{x[-1-n]}\right)^{1/n} - 1$$

where x[-1] is the last yearly value provided.

This method requires at least n years of input data for the parameters, where n is the number of years for which the compound annual growth is applied.

Method 4: avg

Input Parameter: n

Description: mean of last n years

Formula:

$$\textit{active year value} = \frac{\sum_{y-n}^{y} x}{n}$$

where *y* is the index of the last yearly value provided, and *x* is the value in each year used for the average calculation.

This method requires at least *n* years of input data for the parameters, where *n* is the number of years for which the formula is applied. This calculated value is then applied to all remaining values.

Method 5: match

When a user chooses the "match" escalation method, the user can define a custom escalation methodology on the 12-esc_method tab by using the table shown in Figure 2-6.

FIGURE 2-6 – CUSTOM ESCALATION METHODS FOR THE 'MATCH' ESCALATION METHOD

x_match	Description	2019	2020	2021	2022	2023
case1		1	1	1	1	1
ClimateCase1		0.01	0.01	0.01	0.01	0.01
linear_0_30_5		1	1	1	1	1

The user specifies which set of escalation values should be used for matching. The value in the "x_match" column denotes the escalation parameter that must be entered alongside the "match" escalation method.

Input Parameter: x_match

Description: match the values from another series

Formula:

$$Active\ Year\ Value = Prior\ Year\ Value \times \frac{Active\ Year\ Match\ Table\ Value}{Prior\ Year\ Match\ Table\ Value}$$

This method requires at least one year of input data for the parameters and of the input file to provide the match table values.

2.4.2.3. Tab 13-DistributionParameters

Sheet 13 contains the distribution types with the associated parameters.

FIGURE 2-7 – DISTRIBUTION PARAMETER TABLE FROM TAB 14

Distribution Type	_param1	_param2	_param3	_param4	_param5	_param6
Poisson	Mean					
Ztpoisson	Mean					
Discrete	Discrete_params_1	Discrete_params_2	Discrete_params_3	Discrete_probs_1	Discrete_probs_2	Discrete_probs_3
Triangular	Tri_left	Tri_mode	Tri_right			
Binomial	N_Trials	Probability				
Ztbinomial	N_Trials	Probability				
Ztnbinomial	N_Successes	Probability				
Normal	Mean	Standard_Dev				
Truncnormal	Mean	Standard_Dev	Trunc_left	Trunc_right		
Lognormal	Mean	Standard_Dev				
Rtlognormal	Mean	Standard_Dev	Trunc_right			
Exponential	Beta					
Deterministic	D_Value					
Uniform	Min	Max				
Ztpoisson_bernoulli_ef	Mean	Probability				
Rtlognorm_bernoulli_ef	Mean	Standard_Dev	Trunc_right	Probability		
Binomial_ef	N_Trials	Probability				

The choice of distribution is driven by available data to characterize the outcome consequence. It is often the case that insufficient data are available to fit a parametric distribution, especially for rare events. As such, the user must choose which distribution best represents the data that is often supplemented by Subject Matter Expert (SME) judgement regarding key distribution characteristics (e.g., mean or median, 95th percentile, skewed or not skewed).

All of the available distributions are described in the following section. The order provided is roughly by the most commonly used distributions to the least used.

2.4.2.4. Standard Distributions

Poisson

The Poisson distribution is a discrete probability distribution that expresses the probability of a given number of events occurring in a fixed interval of time or space if these events occur with a known constant mean rate and independent of the time since the last event.

A Poisson-distributed random variable, X, can take the values k= 0, 1, 2, ... with probability $P(X = k) = \lambda^k e^{-\lambda}/k!$, where parameter λ is the positive real number equal to the expected value of X and to its variance.

The Poisson distribution is useful for random variables of discrete outcomes like total serious injuries or fatalities given a safety incident, and only requires one parameter, the mean. It is a common choice when describing a discrete random variable and there is not much data to fit additional parameters. One drawback with using this distribution is that Poisson random variables have equal mean and variance, so plausible scenarios with very high consequences may not be captured with the simulation of Poisson distribution when the true distribution has a larger variance than Poisson distribution.

Parameter Specification: Use sample average as Mean.

Zero-Truncated Poisson (Ztpoisson)

The Zero-Truncated Poisson (ZTP) distribution is the conditional probability distribution of a Poisson-distributed random variable, given that the value of the random variable is not zero. Thus, it is impossible for a ZTP random variable to take the value zero.

Parameter Specification: Use the average of the sample excluding zeroes as Mean.

The choice between a Poisson and a zero-truncated Poisson depends on how sample data were used to represent the consequence of a risk event. The following example illustrates how to define a zero-truncated Poisson distribution.

> Here is a vector with observed serious injuries or fatalities (SIF) in a dataset of 10 risk events:
>
> [0 0 0 0 19 0 0 0 25 0]
>
> Eight events have zero SIFs, two have non-zero SIFs. The expected number of SIFs per event given these 10 observations is (19 + 25)/10 = 4.4. However, the expected number of SIFs given a risk event with non-zero SIF is (19 + 25)/2 = 22.
>
> To check whether to use a Poisson distribution for the number of SIFs per event represented by this dataset, compute the probability of having zero SIF from an event as:
>
> P(k=0) = $e^{-\lambda}$= exp(-4.4) = 0.012
>
> Compare that to the fraction of samples which are 0
>
> 8/10 = 0.8
>
> These are an order of magnitude different, suggesting a ZTP is the preferred distribution compared to the Poisson distribution which will overestimate the probability of events with non-zero SIF consequence. The ZTP distribution is parametrize as follows:
>
> Distribution probability: 2/10 = 0.2
> ZTP sample mean: 22

Normal

A normal distribution is a symmetrical, continuous distribution, useful when skewness can be assumed to be zero.

Parameter Specification: Use the sample average and standard deviation as Mean and Standard_Dev, respectively.

Truncated Normal (Truncnormal)

Truncated normal distribution is the probability distribution derived from that of a normally distributed random variable by bounding the random variable from either below or above (or both).

Parameter Specification: Use the mean and standard deviation of Normal distribution before truncation.

Lognormal

The Lognormal distribution is a continuous, non-zero distribution, useful for characterizing Financial or Reliability outcomes believed to have a long tail. To ensure mean convergence, the model will automatically truncate the lognormal distribution at 5 times the specified standard deviation.

Parameter Specification: Specify the mean and standard deviation in linear space.

Truncated Lognormal (Rtlognormal)

If the upper bound of a lognormally distributed random variable is known or reasonable to be enforced, then the Truncated Lognormal distribution can be used.

Parameter Specification: Specify the mean, standard deviation, and upper bound in linear space. Note that the mean and standard deviation are those before truncation.

Deterministic

A point estimate used when no reasonable information is available to inform a range of possible values, or the value is known not to vary.

Discrete

The Discrete distribution allows the user to specify up to three discrete values each with a certain probability.

Parameter Specification: Each discrete value of param1, param2, and param3 with the associated probabilities prob1, prob2, prob3.

Uniform

The Uniform distribution is used for continuous random variables. It is useful when a range of values can be assumed to be equally likely (i.e., very little is known about the probability distribution of the values within the range).

Parameter Specification: The range [Min, Max] of values that the variable can take

Triangular

The Triangular distribution is used for continuous random variables. It is useful when a range of values is known, and the most commonly occurring value (the mode) can be estimated.

Parameter Specification: The range (Tri_left, Tri_right) of values that the variable can take, and the most commonly occurring value, Tri_mode.

Binomial

The Binomial distribution is used to model a discrete number of adverse outcomes with a certain Probability given the N_Trials number of times an incident occurs.

Parameter Specification: Specify N_Trials and the Probability of an adverse outcome, between 0 and 1.

Zero-Truncated Binomial (Ztbinomial)

The Zero-Truncated Binomial distribution is used when, given N_Trials number of times an incident occurs, one expects at least one adverse outcome with a certain Probability of occurrence.

Parameter Specification: Specify N_Trials and the Probability of an adverse outcome between 0 and 1.

Zero-Truncated Negative Binomial (Ztnbinomial)

The Zero-Truncated Negative Binomial distribution models the number of non-adverse outcomes (where *Probability* = probability of an adverse outcome) up to an *N_Success* number of adverse outcomes. "Zero-Truncated" means that at least one non-adverse outcome is expected. This distribution is used when the Poisson distribution does not provide enough variance for describing the variable (i.e., when one believes the variance is greater than the mean).

Parameter Specification: Specify N_Success as the number of adverse outcomes, where the probability of an adverse outcome is specified by Probability.

Exponential

The Exponential distribution is typically used to model the time between events in a Poisson process where the average rate of occurrence of the event is known.

Parameter Specification: Specify Beta = 1/rate of occurrence of the event.

2.4.2.4.1. Safety Attribute Distributions

Zero-Truncated Poisson and Bernoulli Compound Distribution Adapted for Equivalent Fatality (Ztpoisson_bernoulli_ef)

The equivalent fatalities Y following this distribution is constructed as follows:

$$Y = \sum_{i=1}^{N} \left(X_i(p) + \left(1 - X_i(p)\right) * EFfactor \right)$$

Where N is Zero-Truncated Poisson distributed, $X_i's$ are i.i.d. Bernoulli random variables with the probability p where p is the probability of fatality for each SIF, and *EFfactor* is the equivalent fatality per serious injury.

The rationale for this method is to assume that: (1) the total number of SIFs in a safety incident follows a Zero-Truncated Poisson; and (2) each SIF follow a Bernoulli distribution, with one as fatality and zero as injury with a fixed probability. Because one serious injury is deemed as equivalent to *EFfactor* fatalities, the count of series injuries (i.e., zeros) is multiplied by *EFfactor* and then added to count of fatalities (i.e., ones) to get the total count of EF in the equation for Y.

Note: The correlation between injury and fatality counts turns from negative to positive when the expected value of N increases.

Parameter Specification: Mean is that of the Poisson after truncation, and Probability is the likelihood of fatality for each SIF.

Example:

Using EF = ¼ from PG&E's MAVF, table below shows four random draws from this distribution.

TABLE 2-2 – EXAMPLE OF RANDOM DRAWS FROM PG&E'S MAVF ZERO-TRUNCATED POISSON AND BERNOULLI COMPOUND DISTRIBUTION ADAPTED FOR EQUIVALENT FATALITY DISTRIBUTION

No. of SIFs Given a Risk Event, N	No. of Fatalities, $\sum_{i=1}^{N} X_i$	No. of Serious Injuries, $\sum_{i=1}^{N} (1 - X_i)$	No. of EF, Y
5	4	1	4 + 1/4 = 4.25
4	2	2	2 + 2/4 = 2.50
3	1	2	1 + 2/4 = 1.50
2	0	2	0 + 2/4 = 0.50

Right-Truncated Lognormal and Bernoulli Compound Distribution Adapted for Equivalent Fatality (Rtlognorm_bernoulli_ef)

This distribution is set up similarly to Ztpoisson_bernoulli_ef. The only difference is N now follows a rounded Right-Truncated Lognormal distribution instead of the Zero-Truncated Poisson distribution.

Parameter Specification: Mean and Standard_Dev are those of Lognormal distribution before truncation, Trunc_right is the right truncation point of lognormal, and Probability is the likelihood of fatality for each party involved.

Binomial Distribution Adapted for Equivalent Fatality (Binomial_ef)

This distribution assumes the total number of SIFs per risk event is deterministic and then each fatality given a SIF follow a Bernoulli distribution. In this implementation, the ones of the simulated Bernoulli random variable represent fatalities, and the zeroes represent the serious injuries (0.25 EF). So, the count of zeros also contributes to the value of the random variable.

Parameter Specification: N_Trials is the deterministic total parties involved and Probability is the likelihood of fatality for each SIF.

2.4.3. Bow Tie Input Sheets

The Bow Tie Input Sheets are Tabs 1 through 7 in the Risk Input File and are used to describe the Bow Tie Inputs. These tabs contain the: risk; drivers and sub-drivers; cross-cutting factors; list of outcomes; applicable attribute; tranches; consequence definitions; the distributions and parameters associated with the inputs; information used to extrapolate the inputs over the a specified timeframe; and inputs that describe multipliers which are applied to the extrapolated sub-driver and consequence inputs.

Each Bow Tie sheet is described in detail in Section 3. The way the model uses information contained within these sheets is described in Section 1.

2.4.4. Mitigation Input Sheets

Mitigation Input sheets are Tabs 8 through 11 in the Risk Input File. They are used to describe the mitigation programs applicable to the risk event.[10] These tabs contain

[10] PG&E did include two control programs in its 2020 RAMP Report (Enhanced Inspection control program associated with the Failure of Electric Distribution Overhead Assets risk, Chapter 11, and the Leak Management control program associated with the Loss of Containment on Gas Distribution Main or Service risk, Chapter 8).

program names, effectiveness values, project scope, estimated spend, and performance over time (i.e., degradation of effectiveness).

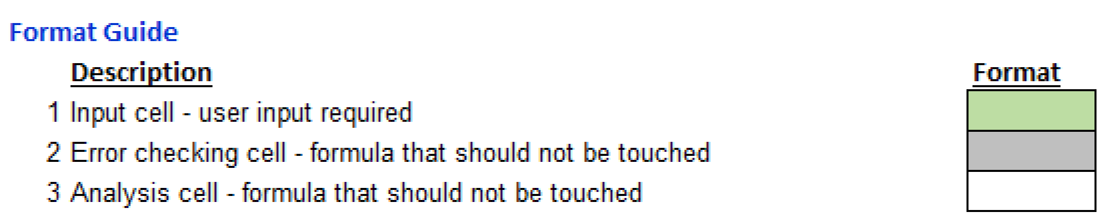
Each of the input sheets addressing the mitigation programs is described in detail in Section 4. The way the model uses information contained within these sheets is described in Section 5.

2.4.5. Reference (REF) Sheets

Each Risk Input File contains some number of tabs that begin with *REF*. These tabs are not parsed by the Python risk model. Rather, they serve as reference tabs within the Risk Input File and primarily include input data from the source data and other modeling workpapers. This information is used to implement calculations primarily to assemble and organize data into a format that can be easily read from the tables in the numbered tabs that are parsed by the Python model.

Within the REF sheets, the following color conventions tend to be used to differentiate data pulled in from external source documents from calculations performed within the risk input sheet itself.

FIGURE 2-8 – COLOR CONVENTION FOR CELLS WITHIN THE REF_ SHEETS



Within the REF sheets, the name of the source document from which the data were pulled are included beside the green-shaded input cells.[11]

[11] PG&E is providing all of the source documents in soft copy that are used in each RAMP risk model. The names of the files correspond to the names of the source files listed on the REF Risk Input File sheets. In addition, PG&E is providing a source document index for each RAMP risk that lists all of the source documents and other information used to generate the risk model outputs.

FIGURE 2-9 – EXAMPLE OF SOURCE NOTATION STRUCTURE (SOURCE REFERS TO THE DOCUMENT NAME WITHIN THE SOURCE DOCUMENT INDEX FOR EACH RISK. SOME REFERENCES INCLUDE SHEET NAMES AND/OR NOTES WHERE NECESSARY)

Source	Sheet	Notes
GO-LOCT-6	pivot	*Filter for Significant, Excluded IO, EF from cause, OP-type event, and malfunction of relief device and ruptured or leaking seal pump from cause_details*

2.5. Risk Model Outputs

Through the calculations and processes outlined in this document, the Model generates a series of outputs, which are then prepared for visualization in the Bow Tie File. The Model produces the Risk Output File with the following sheets, shown in Table 2-2:

TABLE 2-2 – MODEL OUTPUTS WITH DESCRIPTIONS OF EACH WORKSHEET

Sheet	Description
Bow Tie	Bow Tie graphic for Test Year Baseline values which includes: risk exposure; risk score; risk event frequency and percent frequency; percent total frequency and percent total risk by driver; aggregate CoRE, CoRE by outcome, frequency of outcome and percent of total risk per outcome The Bow Tie graphic is included in each RAMP Report risk chapter (Chapters 7-18).
Conseq (Consequences)	Summary table for Test Year Baseline values which includes: outcome-level CoRE, percent frequency, percent risk, event frequency; natural units per event, CoRE, natural units per year, and attribute risk score over all relevant attributes for the risk event. The Summary table is included in each RAMP Report risk chapter (Chapters 7-18).
RSE and Risk Red by Mit (Mitigation)	For the Test Year Baseline, RSEs and net present value (NPV)[a] Risk Reduction for each mitigation in each of the Proposed and Alternative cases, divided into periods from 2020-2022 and 2023-2026
Portfolio	For the Proposed and each Alternative risk mitigation plan, a summary of total expense, total capital spending, NPV of risk reduction, NPV of total spend, and a portfolio-level RSE value.
Risk Scores by Tranche	Tranche-level table summarizing percent exposure, Risk Score by Attribute, and percent of total Risk Score
Risk Scores	Baseline risk score in 2020, Test Year Baseline risk score (2023), Post-Mitigation Risk Score at the end of the evaluation period (2026) and average Risk Scores over 2023-2026 for Test Year Baseline and Post-Mitigation cases
Freq_Driver (Frequency)	Test Year Baseline Frequency by Driver over model years
Freq_Outcome (Frequency)	Test Year Baseline Frequency by Outcome over model years
Input_Exposure	Exposure by Tranche over model years
RiskScore_Outcome	Test Year Baseline Risk Score by Outcome over model years
RiskScore_Tranche	Test Year Baseline Risk Score by Tranche over model years
RiskScore_OutcomeAttribute	Test Year Baseline Risk Score by Outcome and by Consequence Attribute over model years
RiskScore_NU (Natural Units)	Test Year Baseline Natural Unit per Risk Event by Outcome and Attribute over model years
Driver Contrib (Contribution)	Percent contribution to risk across all drivers for the Test Year Baseline scores over model years

(a) Information is presented in terms of Net Present Value (NPV) to account for the discounting of benefits.

3. Bow Tie Inputs

This section of the User Guide describes the process by which the Risk Input File is developed and how the individual sheets and model elements are processed by the Model when calculating risk scores.

The model steps are described in parallel with descriptions and visual representations of the MS Excel tabs on the Risk Input File that inform each step.

3.1. Tab 1-Risk

The *1-Risk* tab describes the risk event modelled by the input file. In addition to describing the risk event itself, there is information regarding the years for which outputs are simulated by the Model.

FIGURE 3-1 – RISK TABLE

Risk Event	Risk Code	Risk Description	Start Year	End Year	Exposure	Test Year
Large Overpressure Event Downstream of M&C Facility	OPDOWN	Loss of containment with or without ignition downstream of an M&C facility	2020	2121	Stations	2023

The Risk Event is used to identify the risk event across the set of output files.

The Start Year and End Year field describe the first and final year for which outputs are simulated. This span of years is referenced in this document as the "analysis horizon."

The Exposure field defines the unit by which 'Exposure' is expressed. In this example, the risk depends on the number of Stations in each tranche.

The Test Year field is the initial year of the rate case. It is used to determine mitigation programs implemented in and after the Start Year but before the Test Year for the purpose of calculating Test Year Baseline Risk Scores. This value must be within the bounds of Start Year to End Year (inclusive).

3.2. Tab 2-BowTie

The *2-BowTie* tab lists the drivers and sub-drivers that comprise the left-hand side of the risk Bow Tie, the outcomes that define the right-hand side of the Bow Tie, and the consequence attributes used to define each outcome.

The information that needs to be completed on Tabs 4 to 7 (the frequency and consequence definition tabs) depends on the lists of drivers, sub-drivers and outcomes specified on this Bow Tie tab.

FIGURE 3-2 – BOW TIE DRIVER, SUB-DRIVER TABLE

Row#	Sub-Driver#	Driver#	Driver	Sub-Driver	Active	Cross Cut
1	1	1	Incorrect Operations	Incorrect Operations	TRUE	
2	2	2	Equipment Related	Equipment Related	TRUE	
3	3	3	CC - SQWF	SQWF	TRUE	SQWF
4	4	4	CC - RIM	RIM	TRUE	RIM

The driver table lists the drivers, the associated sub-drivers, a Boolean flag for whether or not the sub-driver should be considered in the model processing and calculation, and the cross-cutting factor label to which the sub-driver rolls up (if applicable).

The 2-BowTie tab also features a list of Outcomes, which represent different manifestations of the risk event. Within the same tranche, model input parameters may differ between outcomes. Model outputs are generated for each outcome, as well as at an aggregate level across outcomes.

FIGURE 3-3 – OUTCOME TABLE

Outcome#	Outcome
1	Benign
2	LOC
3	LOC and Cyber Attack
4	LOC and IT Asset Failure

The third table on this tab is the Consequence table. The only part of the Consequence Attribute table that needs to be adjusted based on the risk event is the Boolean flag in the Active column. Only those Attributes which are Active will require parameterization in the input sheets that follow. In the example below, there are no Electric Reliability consequences for the Large Overpressure risk event. The total number of active Attributes is 3 (maximum of the activerow# computed column). If an Attribute is not active, it will not show up in any of the downstream tabs (Tabs 6, 7, and 10).

FIGURE 3-4 – BOW TIE CONSEQUENCE ATTRIBUTE AND SUB-ATTRIBUTE TABLE

Row#	Sub-Attribute#	Attribute	Attribute	Sub-Attribute	Active	activerow#
1	1	1	Safety	Safety	TRUE	1
2	2	2	Electric Reliability	Electric Reliability	FALSE	1
3	3	3	Gas Reliability	Gas Reliability	TRUE	2
4	4	4	Financial	Financial	TRUE	3

3.3. Tab 3-Tranche

The population or system to which a risk event applies is segmented into different tranches. The definition and units of exposure for each tranche is defined in the *3-Tranche* tab of the input workbook. The number of tranches impact several Model inputs (e.g., frequency, consequence, mitigation definitions) as each input can be defined differently for each tranche. (As described earlier, Bow Tie of a Risk Event can be conceived as having one Bow Tie per tranche).

Tranches are listed with identifiers and descriptors, a Boolean Active flag, and 7 'Year' fields (denoted Year1 through Year7).

FIGURE 3-5 – LEFT SIDE OF A TRANCHE DEFINITION TABLE ON 3-TRANCHE.

ID	Tranche#	Active	Tranche	Year1	Year2	Year3	Year4	Year5	Year6	Year7
OPDOWN_T1	1	TRUE	MCDS - Transmission Simple	252						
OPDOWN_T2	2	TRUE	MCDS - Distribution District Reg	1330						
OPDOWN_T3	3	TRUE	MCDS - Distribution HPR+FT	2608						
OPDOWN_T4	4	TRUE	MCDS - Transmission Complex	131						
OPDOWN_T5	5	TRUE	MCDS - Transmission LVCR	98						
OPDOWN_T6	6	TRUE	MCDS - Distribution LPR	205						

The values input into the Year fields, shown in Figure 3-5, describe the total units of exposure to which the risk may apply. These values are used with the sub-driver likelihood values (defined in 4-Freq) to compute the Tranche-Sub-Driver-Outcome frequency.

The exposure can vary from year to year, and the Escalation Method and Escalation Parameter fields describe the process by which the initial year's values should be extrapolated over the model's timeframe.

FIGURE 3-6 – RIGHT SIDE OF A TRANCHE DEFINITION TABLE ON 3-TRANCHE

Escalation Method	Escalation Parameter	Tranche Description
esc	0%	Simple Stations on the Transmission System
esc	0%	District Regulators on the Distribution System
esc	0%	High Pressure Regulators on the Distribution System
esc	0%	Complex Stations on the Transmission System
esc	0%	LVCR Stations on the Transmission System
esc	0%	Low Pressure Distribution System

The Escalation Method describes what escalation function should be used (described in Section 2.4.2.2) and how the inputs are scaled year-to-year. The Escalation Method is applied in the first year without exposure values specified. If the exposure for each year is defined, and the analysis horizon is greater than six years, the Escalation Method begins to apply in Year 7.

The Escalation Parameter is the factor that determines by how much the Escalation Method should scale the inputs over the analysis horizon. When left blank, the default value for Escalation Method is “esc,” and the default value for Escalation Parameter is 0 percent.

In the example shown here, since there are no exposure values beyond Year 1 and the escalation rate is 0 percent, the exposure will remain constant over time.

3.4. Tab 4-Freq

The expected likelihood of a risk event (LoRE) for each sub-driver is defined on the *4-Freq* tab. Sub-driver LoRE information is defined at a tranche and outcome level, potentially varying among tranches and/or outcomes.

FIGURE 3-7 – LEFT SIDE OF A FREQUENCY INPUT TABLE

activerow#	Row#	Tranche#	Sub-Driver#	Outcome#	Tranche	Sub-Driver	Outcome	Active Sub-Driver	Active	Driver
1	1	1	1	1	MCDS - Transmission Simple	Incorrect Operations	Benign	TRUE	TRUE	Incorrect Operations
2	2	1	2	1	MCDS - Transmission Simple	Equipment Related	Benign	TRUE	TRUE	Equipment Related
3	3	1	3	1	MCDS - Transmission Simple	SQWF	Benign	TRUE	TRUE	CC - SQWF
4	4	1	4	1	MCDS - Transmission Simple	RIM	Benign	TRUE	TRUE	CC - RIM
5	5	1	1	2	MCDS - Transmission Simple	Incorrect Operations	LOC	TRUE	TRUE	Incorrect Operations
6	6	1	2	2	MCDS - Transmission Simple	Equipment Related	LOC	TRUE	TRUE	Equipment Related
7	7	1	3	2	MCDS - Transmission Simple	SQWF	LOC	TRUE	TRUE	CC - SQWF
8	8	1	4	2	MCDS - Transmission Simple	RIM	LOC	TRUE	TRUE	CC - RIM
9	9	1	1	3	MCDS - Transmission Simple	Incorrect Operations	LOC and Cyber Attack	TRUE	TRUE	Incorrect Operations
10	10	1	2	3	MCDS - Transmission Simple	Equipment Related	LOC and Cyber Attack	TRUE	TRUE	Equipment Related

Figure 3-7 shows the sub-driver identifying information, the tranche and outcome to which that set of distribution information applies, an "Active" Boolean flag, as well as the driver to which the sub-driver rolls up.

The columns on the left side of the worksheet include:

- Activerow# is defined in this table, based on the number of rows with the Active flag set to TRUE. This is referred to in subsequent sheets (5-FreqMult, 10-ProgramFreqEff).
- Row# is defined for this table, and the maximum row number is the product of the number of sub-drivers, tranches, and outcomes.
- Tranche# refers to the number assigned to the active Tranche from *3-Tranche*, and drives the Tranche listed in the Tranche column.
- Sub-Driver# refers to the number assigned to the sub-driver from *2-BowTie,* and drives the sub-driver listed in the Sub-Driver column.
- Outcome# refers to the number assigned to the sub-driver from *2-BowTie,* and drives the sub-driver listed in the Outcome column.
- Driver is the name of the driver to which sub-drivers roll up, and which is displayed in the Bow Tie visual.

FIGURE 3-8 – RIGHT SIDE OF A FREQUENCY INPUT TABLE.

Distribution1	Distribution1_param1	Distribution1_param1_esc_method	Distribution1_param1_esc_param	Distribution1_param2	Distribution1_param2_esc_method	Distribution1_param2_esc_param	Note
Poisson	0.000660796						
Poisson	0.001044739						
Poisson	1.08217E-05						
Poisson	7.46242E-05						
Poisson	3.82541E-05	match	non_cyber_outcome				
Poisson	6.04809E-05	match	non_cyber_outcome				
Poisson	6.2648E-07	match	non_cyber_outcome				
Poisson	4.32006E-06	match	non_cyber_outcome				
Poisson	1.13989E-07	match	cyber_outcome				
Poisson	1.80221E-07	match	cyber_outcome				

Figure 3-8 displays how the distribution is defined.

- The Distribution1 field denotes the statistical distribution that should be used to model the sub-driver LoRE. The number of events for each year is not currently simulated for the calculation of the risk scores, because the Risk Score requires expected value of LoRE.

- The Distribution1_param1 is the expected likelihood of risk event (LoRE), expressed per year and per unit of exposure.

An Escalation Method and Escalation Parameter can be applied to the LoRE values, informing the Model how to scale and shape the LoRE over the timeframe simulated by the Model. These are specified in the fields ending with _esc_method (Escalation Method) and _esc_param (Escalation Parameter). One of the five escalation methods described in Section 2.4.2.2 can be chosen. The escalation method chosen includes a numerical parameter which dictates by how much to escalate and extrapolate the data. For example, the values shown on Figure 3-8 for cyber-related frequencies are escalated using a *match*-type escalation with the parameter named *cyber_outcome* that is defined in in the 12-esc_method tab.

The sub-driver LoREs are read by the model and escalated over the model's analysis horizon according to the specified escalation methodology.

3.5. Tab 5-FreqMult

Some cross-cutting factors, such as Climate Change, may impact how the sub-driver LoREs change over time. These factors are modeled as "frequency multipliers," factors that are applied to the specified sub-driver's frequency.

The *5-FreqMult* tab specifies how multipliers impact sub-driver frequencies at the tranche and outcome level over time, after the multiplier-independent escalation/scaling (defined on the *4-Freq* tab) occurs.

FIGURE 3-9 – FREQUENCY MULTIPLIER TABLE WITH ACTIVE COLUMN EMPTY

Row#_Sheet5	Row#	Tranche#	Sub-Driver#	Outcome#	Tranche	Sub-Driver	Outcome	Active	Escalation Method	Escalation Parameter	Year1	Year2
1	1	1	1	1	MCDS - Tran: Incorrect Operations		Benign					
2	2	1	2	1	MCDS - Tran: Equipment Related		Benign					
3	3	1	3	1	MCDS - Tran: SQWF		Benign					
4	4	1	4	1	MCDS - Tran: RIM		Benign					
5	5	1	1	2	MCDS - Tran: Incorrect Operations		LOC					
6	6	1	2	2	MCDS - Tran: Equipment Related		LOC					

The Frequency Multiplier table in Figure 3-9 lists the sub-drivers, tranches, and outcomes to which the multipliers are applied (along with other identifying information).

- The Row# identifier refers to this table (*5-FreqMult*);

- The Tranche#, Sub-Driver#, and Outcome# identifiers refer to numbers defined on *2-BowTie* and *3-Tranche*.

Each multiplier is defined by a yearly value, specified in 'Year' columns, which can be filled by an escalation method and escalation parameter. The escalation method is applied for the first year of undefined multiplier data over the analysis horizon.

Figure 3-9 shows an example where the Active column is empty, which indicates that the frequency multipliers are not needed. Within the model, Escalation Method is set to **esc** when empty and Escalation Parameter is set to 0 when empty within the Model as default values.

FIGURE 3-10 – EXAMPLE INPUT FILE WITH ESCALATION PARAMETER ACROSS SEVERAL OUTCOMES.

Active	Escalation Method	Escalation Parameter	Year1	Year2	Year3	Year4
TRUE	esc	0.014531316	1			
TRUE	esc	0.014531316	1			
TRUE	esc	0.014531316	1			
TRUE	esc	0.014531316	1			
TRUE	esc	0.014531316	1			
TRUE	esc	0.014531316	1			

A numerical example for a row with Active value TRUE is included in Figure 3-10. The Escalation Method and Escalation Parameter fields are defined as described in Section 2.4.2.2. This example shows that the frequency multipliers are 1 for the first year (Year1). Because there are no values in Year2, Year3 and Year4, the multiplier value of 1 in Year1 is used and is escalated using **esc** method at 1.4531316 percent rate. Therefore, the multipliers are 1.014531316 for Year 2, 1.0145316^2 for Year3, and 1.0145316^3 for Year4, etc.

For example, if a sub-driver LoRE in Year 1 is 0.000660796 (Figure 3-8), the sub-driver LoRE in Year 2 is now set as 0.00067031 (0.000660796 × 1.014531316 = 0.00067031).

The escalated sub-driver data, with multipliers applied, represents the final set of sub-driver inputs that determine the LoREs at sub-driver, outcome and tranche level.

3.6. Tab 6-Conseq

The consequences, expressed as potential results per driver frequency, are provided on Risk Input File tab *6-Conseq*. As with sub-drivers, consequences for each attribute are defined at the tranche and outcome level.

FIGURE 3-11 – LEFT SIDE OF THE CONSEQUENCE DEFINITION TABLE FROM 6-CONSEQ

Row#	activerow#	Tranche#	Outcome#	Sub-Attribute#	Tranche	Outcome	Sub-Attribute	Active	Distribution1 Note	Distribution1
1	0	1	1	1	MCDS - Transmission Simple	Benign	Safety	FALSE	MCDS - Transmissic	
2	0	1	1	2	MCDS - Transmission Simple	Benign	Gas Reliability	FALSE	MCDS - Transmissic	
3	1	1	1	3	MCDS - Transmission Simple	Benign	Financial	TRUE	MCDS - Transmissic	Lognormal
4	2	1	2	1	MCDS - Transmission Simple	LOC	Safety	TRUE	MCDS - Transmissic	Ztpoisson_bernoulli_ef
5	3	1	2	2	MCDS - Transmission Simple	LOC	Gas Reliability	TRUE	MCDS - Transmissic	Lognormal
6	4	1	2	3	MCDS - Transmission Simple	LOC	Financial	TRUE	MCDS - Transmissic	Lognormal
7	5	1	3	1	MCDS - Transmission Simple	LOC and Cyber Att	Safety	TRUE	MCDS - Transmissic	Ztpoisson_bernoulli_ef
8	6	1	3	2	MCDS - Transmission Simple	LOC and Cyber Att	Gas Reliability	TRUE	MCDS - Transmissic	Lognormal
9	7	1	3	3	MCDS - Transmission Simple	LOC and Cyber Att	Financial	TRUE	MCDS - Transmissic	Lognormal
10	8	1	4	1	MCDS - Transmission Simple	LOC and IT Asset F	Safety	TRUE	MCDS - Transmissic	Ztpoisson_bernoulli_ef

The Consequence table in Figure 3-11 lists the Active tranches, outcomes, and Attributes for which consequence distributions need to be defined, along with identifying information.

- The Row# identifier refers to the *6-Conseq* table;
- The activerow# number is defined in the *6-Conseq* table based on the number of active rows within the table; and
- The Tranche#, Sub-Attributer#, and Outcome# identifiers refer to numbers defined on *2-BowTie* and *3-Tranche*.

FIGURE 3-12 – RIGHT SIDE OF THE CONSEQUENCE DISTRIBUTION FROM 6-CONSEQ

Distribution1	Distribution1_Prob	Distribution1_param1	Distribution1_param1_esc_method	Distribution1_param1_esc_param	Distribution1_param2	Distribution1_param2_esc_method	Distribution1_param2_esc_param	Distributions Operator	Distribution2 Note	Distribution2
Lognormal	1	50000			25000					
Ztpoisson_bernoulli_ef	0.019444444	10.42857143			0.123287671					
Lognormal	0.66	46147			88373					
Lognormal	1	787973.106			2186684.372					
Ztpoisson_bernoulli_ef	0.019444444	10.42857143			0.123287671					
Lognormal	0.66	46147			88373					
Lognormal	1	787973.106			2186684.372					
Ztpoisson_bernoulli_ef	0.019444444	10.42857143			0.123287671					

A distribution is selected for each consequence, along with the distribution's parameters, escalation method, and escalation parameter. The distributions that can be included in the distribution fields are listed in Section 2.4.2.3.

In cases where the Active field is identified as FALSE, there is no consequence for that outcome and no consequence definition is needed.

The distribution probability (also called sampling probability) field is unique to the *6-Conseq* tab. This is shown in Figure 3-12 as Distribution1_Prob. The probability field denotes the probability that the consequence actually occurs given the risk event outcome. For example, with Distribution1_Prob of 0.4, the consequence described by Distribution1 is expected to materialize with 40 percent probability and not to materialize (i.e., zero consequence) with 60 percent probability.

The consequences can be described by a variety of distributions. Those distributions can have up to six parameters, which are shown on the *6-Conseq tab* and listed as Distribution1_param1, Distribution1_param2, Distribution1_param3, etc.

The final set of inputs to characterize the distributions are escalation parameters, which use one of the methods described in Section 2.4.2.2. Each of the input parameters for the distributions has an associated escalation method (*e.g.*, Distribution1_param1_esc_method and Distribution1_param1_esc_param). DistributionN_paramN_esc_Method is set to **esc** when empty and DistributionN_paramN_esc_param is set to 0 when empty within the Model as default values.

The Risk Input File enables multiple distributions for defining the consequence for each row on the *6-Conseq* table (the combination of tranche, outcome, and attribute). This is useful when the consequence is either the sum or the product of the two distributions. In this case, Distribution2 parameters can be specified as Distribution1 and the Model either sums or takes the product of those distributions to generate a final Natural Unit for each trial depending on the operator specified: "sum" or "prod" under the Distributions Operator field. If more than two distributions are needed, parameters for Distribution3 and Distribution4 can be specified.

3.6.1. Safety Attribute Distributions

The remainder of this section presents two options for specifying distribution inputs for modeling the Safety consequence which is measured as Equivalent Fatality (EF) count. The Safety attribute consequence of a risk event has three required components, while the other attributes have two.

Safety consequences are characterized by:

1) Distribution probability (probability that outcome has a Safety consequence);
2) Distribution of total serious injuries and fatalities; and
3) Fraction of serious injuries and fatalities that are fatalities.

There are two different options to define the parameters in the Model with based on Items 1 through 3 above.

1) *Option 1:* Define a single Safety distribution to include the three safety consequences characteristics. The three distributions which end in _*ef* are tailored to expect an additional parameter (fraction of fatalities) beyond the standard set of required parameters (distribution probability and distribution parameters).
   This option was implemented in Figure 3-11 and Figure 3-12 (see the Distribution1 field). These distributions are defined in Section 2.4.2.4.1.
2) *Option 2:* Use any parametric distribution for Distribution1, the 'efprod' Distributions Operator, and Distribution2 to specify the fraction of SIFs that are fatalities (which can either be deterministic or not). The random variables from the two distributions are as follows:
   a) The number of SIFs from a safety incident, N, is assumed to follow Distribution1, which can be any positive discrete distributions (e.g., Zero-Truncated Poisson, Discrete); and
   b) The percent of fatality, X, follows Distribution2, which can be any distributions with support in [0, 1] (e.g., Standard uniform distribution, Deterministic distribution with D_Value in [0,1], and Discrete distribution).

   The final EF count, Y, is generated as follows:

$$Y = N \times (X + (1 - X) \times EFfactor)$$

   Notes: The sampling probabilities for the Distribution1 and Distribution2 must be set the same when using *Option 2*.

   Example:

   Assuming *EFfactor* = ¼ (i.e., one serious injury is ¼ fatality), Table 3-1 shows four random draws using this option.

TABLE 3-1 – FOUR RANDOM DRAWS USING OPTION 2

No. of SIFs, N	Percent of Fatality X	No. of EF, Y
5	0.2	5*(0.2 + 0.8/4) = 2.00
4	0.4	4*(0.4 + 0.6/4) = 2.20
3	0.8	3*(0.8 + 0.2/4) = 2.55
2	0.6	2*(0.6 + 0.4/4) = 1.40

Figure 3-13 is an example of how the two options are presented in the *6-Conseq* tab.

FIGURE 3-13 – SUMMARY OF TWO OPTIONS TO CHARACTERIZE SAFETY CONSEQUENCE DISTRIBUTIONS

	Dist1	Dist1_ Prob	Dist1_ param 1	Dist1_ param 2	Dist1_ param 3	Dist1_ param 4	Dists Operator	Dist2	Dist2_ Prob	Dist2_ param 1	Dist2_ param 2
Option 1	Ztpoisson_bernoulli_ef	5%	2	46%					5%		
Option 1	Rtlognorm_bernoulli_ef	100%	26	50	300	50%			100%		
Option 2	Ztpoisson	85%	3				efprod	Uniform	85%	14%	34%
Option 2	Ztpoisson	100%	2				efprod	Deterministic	100%	90%	

3.7. Tab 7-ConseqMult

Consequence multipliers are applied to the Natural Units simulated for each trial from the consequence distribution of each tranche, outcome, attribute and year, based on the specification in *6-Conseq*.

FIGURE 3-14 – CONSEQUENCE MULTIPLIER TABLE

Row#	Row#_Sheet6	Tranche#	Outcome#	Sub-Attribute#	Tranche	Outcome	Sub-Attribute	Active	Cross Cut	Note	Escalation Method	Escalation Parameter	Year1
1	3	1	1	3	MCDS - Transmission Simple	Benign	Financial	TRUE	RIM				101.90%
2	4	1	2	1	MCDS - Transmission Simple	LOC	Safety						
3	5	1	2	2	MCDS - Transmission Simple	LOC	Gas Reliability						
4	6	1	2	3	MCDS - Transmission Simple	LOC	Financial	TRUE	RIM				101.90%
5	7	1	3	1	MCDS - Transmission Simple	LOC and Cyber Attack	Safety	TRUE	CYB				102.25%
6	8	1	3	2	MCDS - Transmission Simple	LOC and Cyber Attack	Gas Reliability	TRUE	CYB				102.50%

Other than the variable to which the multipliers are applied, the fields shown in Figure 3-14 are functionally identical to those on *5-FreqMult*. A user can specify if the multiplier should be active by setting Active as TRUE and can specify an Escalation Method and Escalation Parameter by which to extrapolate the multiplier data over time.

In the example shown in Figure 3-14, the multipliers do not increase with time (implied by the empty Escalation Method and Escalation Parameter columns), so the same multiplier is applied across all simulated years.

3.8. Baseline Risk Score

Using the input data from the Risk Input File Sheets 1 through 7 (defining the drivers, sub-drivers, tranches, risk event frequencies, frequency multipliers, consequences and consequence multipliers) the Model performs a Monte Carlo simulation for the CoRE calculation and calculates baseline risk scores.

An overview of the calculation process is provided in Section 5.1, and a numerical example for the Electric Distribution Network Asset Failure risk calculation is included in workpapers.[12]

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[12] See WP User Guide-1.

4. Mitigation Inputs

Mitigation and Control projects and/or programs are the efforts enacted or proposed in order to reduce overall risk. Risk Controls are programs that are in place that reduce the risk from the Inherent case to the Baseline case. Mitigations represent work that would reduce Baseline risk. Risk Reduction is defined as the difference between the Inherent and Baseline risk scores, as well as the difference between the Baseline and Mitigated risk scores. Values in the Risk Input File, Tabs 2 through 7, represent the Baseline case, or the current state of risk.

Mitigated cases can include the Proposed case or Alternative cases, depending on the group of mitigations considered.

To calculate risk scores for the Inherent and Mitigated cases, the risk Bow Tie inputs stored for each tranche and outcome are transformed to model the effectiveness of the programs. The scale by which the distributions are transformed are a function of the program effectiveness calculations, outlined in Section 5.2 of the User Guide.

4.1. Program Definition Inputs

4.1.1. Tab 8-Program

The programs listed on Tab *8-Program* describe the programs that apply to the risk described in the Risk Input File and can include the proposed mitigations and alternative mitigations developed to address that risk as well as mitigations developed to impact the cross-cutting factors. Tab, *8-Program* shown in Figure 4-1, features descriptive information which determines the numerical values developed for Tabs 9 to 11.

FIGURE 4-1 – MITIGATION AND CONTROL PROGRAM DEFINITION

Row#	LOB/ Cross Cut	Program#	Program	Program Type	Program Description	Case	Scenario	FreqMitigation	ConseqMitigation	active#_freqprogram	active#_conseqprogram
1	GO	1	M3-SCADA Visibility [Transmission] (2020 - 2022)	Mitigation	Additional SCADA infrastructure	Proposed	1	TRUE		1	0
2	GO	2	M3-SCADA Visibility [Transmission] (2023 - 2026)	Mitigation	Additional SCADA infrastructure	Proposed	1	TRUE		2	0
3	GO	3	M4-Station OPP Enhancements [Transmission] (2020	Mitigation	Station OPP	Proposed	1	TRUE		3	0
4	GO	4	M4-Station OPP Enhancements [Transmission] (2023	Mitigation	Station OPP	Proposed	1	TRUE		4	0
5	GO	5	M1-Critical Documents Program (2020 - 2022)	Mitigation	Revision and/or developing new criti	Proposed	1	TRUE	TRUE	5	1
6	GO	6	M1-Critical Documents Program (2023 - 2026)	Mitigation	Revision and/or developing new criti	Proposed	1	TRUE	TRUE	6	2
7	GO	7	M3-SCADA Visibility [RTU] (2020 - 2022)	Mitigation	Additional SCADA infrastructure	Proposed	1	TRUE		7	2
8	GO	8	M3-SCADA Visibility [RTU] (2023 - 2026)	Mitigation	Additional SCADA infrastructure	Proposed	1	TRUE		8	2
9	GO	9	M3-SCADA Visibility [ERX] (2020 - 2022)	Mitigation	Additional SCADA infrastructure	Proposed	1	TRUE		9	2
10	GO	10	M3-SCADA Visibility [ERX] (2023 - 2026)	Mitigation	Additional SCADA infrastructure	Proposed	1	TRUE		10	2

There are four computed data columns in *8-Program*:

- Row# refers to the row number in *8-Program* and serves as an identifier for Tabs 9-11.

- The Program# increases by one number each time a new program is listed in the Program column.
- The final two columns, active#_freqprogram and active#_conseqprogram increase by one number each time there is a new program which affects frequency or consequence, respectively, based on information entered into the FreqMitigation and ConseqMitigation columns. These two columns are referred to in Tabs 10 and 11 where mitigation effectiveness values are specified.

The remaining information is input by the user to describe the programs and includes the Line of Business (LOB) or cross-cutting factor to which the program applies, the program name, the program type (Mitigation or Control), and a description of the program.

The Case column (either *Proposed* or *AlternativeN*) indicates whether the mitigation is part of the Proposed mitigation portfolio or of it is an Alternative mitigation and should be included in one of the Alternative portfolios. The case information is used for portfolio-level RSE calculations. The two Boolean flag columns, indicating FreqMitigation or ConseqMitigation, determine which programs apply to the two program effectiveness definition tabs (*10-ProgramFreqEff and 11-ProgramConseqEff)*.

4.1.2. Tab 9-ProgramExposureSpend

The programs defined on the *8-Program* tab can be applied across the tranches. The units of exposure and tranches to which the programs apply are listed on Tab *9-ProgramExposureSpend*.

FIGURE 4-2 – LEFT SIDE OF THE TABLE DEFINING PROGRAM EXPOSURE AND SPEND AT THE TRANCHE LEVEL

Row#	Row#_Sheet8	active#	Tranche#	Program	Tranche	Index	Active	Spend Type	Scope%	Exposure Year1
1	1	1	1	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Transmission Simple	M3-SCAD	TRUE	capital	9.52%	8
2	1	1	2	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Distribution District Reg	M3-SCAD	FALSE	expense	0.00%	0
3	1	1	3	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Distribution HPR+FT	M3-SCAD	FALSE	expense	0.00%	0
4	1	1	4	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Transmission Complex	M3-SCAD	FALSE	expense	0.00%	0
5	1	1	5	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Transmission LVCR	M3-SCAD	FALSE	expense	0.00%	0
6	1	1	6	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Distribution LPR	M3-SCAD	FALSE	expense	0.00%	0
7	2	2	1	M3-SCADA Visibility [Transmission] (2023 - 2026)	MCDS - Transmission Simple	M3-SCAD	TRUE	capital	12.70%	0
8	2	2	2	M3-SCADA Visibility [Transmission] (2023 - 2026)	MCDS - Distribution District Reg	M3-SCAD	FALSE	expense	0.00%	0
9	2	2	3	M3-SCADA Visibility [Transmission] (2023 - 2026)	MCDS - Distribution HPR+FT	M3-SCAD	FALSE	expense	0.00%	0
10	2	2	4	M3-SCADA Visibility [Transmission] (2023 - 2026)	MCDS - Transmission Complex	M3-SCAD	FALSE	expense	0.00%	0

9-ProgramExposureSpend starts with four numerical identifier data columns:

- Row# refers to the row number within this table.
- The Row#_Sheet8 refers to the identifier from *8-Programs*.
- The active# is computed here and increases by one each time there is a new Active row.
- The Tranche# corresponds to the listed Tranche and is based on the table from *3-BowTie*.

These four columns determine which Programs and Tranches are listed.

FIGURE 4-3 – RIGHT SIDE OF THE PROGRAM EXPOSURE AND SPEND DEFINITION TABLE

Scope%	Exposure Year1	Exposure Year2	Exposure Year3	Exposure Year4	Cap Spend USD Year1	Cap Spend USD Year2	Cap Spend USD Year3	Cap Spend USD Year4	O&M Spend USD Year1	O&M Spend USD Year2	O&M Spend USD Year3	O&M Spend USD Year4	Case	Program Short Name
9.52%	8	8	8	0	3750000	3840000	3936000	0	0	0	0	0	Proposed	M3-SCADA
0.00%	0	0	0	0	0	0	0	0	0	0	0	0	Proposed	M3-SCADA
0.00%	0	0	0	0	0	0	0	0	0	0	0	0	Proposed	M3-SCADA
0.00%	0	0	0	0	0	0	0	0	0	0	0	0	Proposed	M3-SCADA
0.00%	0	0	0	0	0	0	0	0	0	0	0	0	Proposed	M3-SCADA
0.00%	0	0	0	0	0	0	0	0	0	0	0	0	Proposed	M3-SCADA
12.70%	0	0	0	8	0	0	0	4034400	0	0	0	0	Proposed	M3-SCADA
0.00%	0	0	0	0	0	0	0	0	0	0	0	0	Proposed	M3-SCADA
0.00%	0	0	0	0	0	0	0	0	0	0	0	0	Proposed	M3-SCADA
0.00%	0	0	0	0	0	0	0	0	0	0	0	0	Proposed	M3-SCADA

Note: The number of years has been condensed in this graphic so the table can fit on this page.

As shown in Figure 4-3, the columns on the right side of the table include the program scope, amount of exposure and estimated program costs.

- The Scope % field is computed as a ratio of the total exposure of all years relative to the Tranche exposure; it may be greater than 100 percent.
- Exposure Year1, Exposure Year2, Exposure Year3, etc., fields, denotes the units of exposure per Program-Tranche combination per year. These values must be less than or equal to the total units of exposure for the tranche in the specified year.
- The Cap Spend USD Year1, etc., and O&M Spend USD Year1, etc., fields list the estimated cost for the amount of work done relative to those units of exposure in each tranche. The spend values entered on *9-ProgramExposureSpend* will be used to calculate a Risk Spend Efficiency (RSE) for each program.
- The Program Short Name is simply an abbreviation of the program without the duration (either 2020-2022 or 2023-2026).

4.2. Program Effectiveness Inputs

Tabs 10-ProgramFreqEff and *11-ProgramConseqEff* describe the mitigation effectiveness impact at the sub-driver and consequence distributions levels.

A mitigation or control program's effectiveness is a measure (described as a percentage) of how much the mitigation or control reduces the frequency or consequence of a risk event. Given that the program is applied only to a portion of the tranche in this input sheet, the effectiveness input is adjusted by the Model to determine the average effectiveness for the whole tranche by multiplying a ratio of program exposure to the tranche exposure. The Model also calculates the effectiveness for the years beyond the program implementation year when the program's benefit lasts longer than one year. The average effectiveness of mitigations in a Portfolio is then aggregated into the overall Portfolio effectiveness.

The Proposed case shows the impact that implementing the Proposed mitigations has on the baseline risk score. As such, the Proposed risk score will be less than the baseline risk. The final mitigation effectiveness factor, is defined as 1 – [overall mitigation effectiveness], expressed as a percentage. For example: the effectiveness of a given portfolio of mitigations may be 20 percent. The expected baseline frequency of an outcome is 0.7 events per year. After the portfolio of mitigations is implemented, the mitigated frequency would be 0.56 (= [1 – 0.2] × 0.7).

Controls represent risk mitigation programs that are already in place. The Inherent case represents the risk absent the Control program. The risk score for the Inherent case will be greater than the results from the baseline case. Whereas the scaling factor from the mitigations are represented as [1 – program effectiveness] for mitigations, the scaling factor for controls is represented as [1 + program effectiveness] where the effectiveness of a Control is defined as the percentage increase expected if the Control is removed.

Sections 4.2.1 and 0 outline how the program effectiveness values are derived and applied to sub-drivers and consequences.

4.2.1. Tab 10-ProgramFreqEff

At the tranche level and outcome level, programs are described by a series of identifier fields, fields describing the "Active" status of the program, and fields describing the effectiveness of program application. Shown in Figure 4-4, the set of identifier fields includes only the set of tranches, sub-drivers and outcomes that are Active in *4-Freq* (identified with Row#_Sheet4) and includes only Programs identified as applicable to Frequency mitigation (identified with Row#_Sheet8).

FIGURE 4-4 – PROGRAM DEFINITON SECTION (LEFT SIDE) OF THE PROGRAM EFFECTIVENESS TABLE

Row#	Row#_Sheet4	Tranche#	Sub-Driver#	Outcome#	Row#_Sheet8	Program#	Program	Tranche	Sub-Driver	Outcome	Program Active On Tranche	Category
1	1	1	1	1	1	1	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Transmission Simple	Incorrect Operations	Benign	TRUE	Incorrect Operations
2	2	1	2	1	1	1	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Transmission Simple	Equipment Related	Benign	TRUE	Equipment Related
3	3	1	3	1	1	1	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Transmission Simple	SQWF	Benign	TRUE	CC - SQWF
4	4	1	4	1	1	1	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Transmission Simple	RIM	Benign	TRUE	CC - RIM
5	5	1	1	2	1	1	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Transmission Simple	Incorrect Operations	LOC	TRUE	Incorrect Operations
6	6	1	2	2	1	1	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Transmission Simple	Equipment Related	LOC	TRUE	Equipment Related
7	7	1	3	2	1	1	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Transmission Simple	SQWF	LOC	TRUE	CC - SQWF
8	8	1	4	2	1	1	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Transmission Simple	RIM	LOC	TRUE	CC - RIM
9	9	1	1	3	1	1	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Transmission Simple	Incorrect Operations	LOC and Cyber Attack	TRUE	Incorrect Operations
10	10	1	2	3	1	1	M3-SCADA Visibility [Transmission] (2020 - 2022)	MCDS - Transmission Simple	Equipment Related	LOC and Cyber Attack	TRUE	Equipment Related

- The program identification fields include the program, the tranche to which it applies, and the outcome to which it applies.
- The Category field includes the Driver to which Sub-drivers map.
- The Program Active on Tranche field denotes if the program should be applied and calculated for that tranche in the Model.
- The Active field denotes if the program should be applied and calculated for the specified sub-driver in the outcome.

FIGURE 4-5 – LEFT SIDE OF THE PROGRAM EFFECTIVENESS TABLE, INCLUDING NUMERICAL PROGRAM DEFINITIONS

Effectiveness	Re-mitigation Impact on Effectiveness	Annual Degradation Rate During Period 1	Number of years for period 1	Escalation Method for Period 1	Program Short Name
50.00%		0.00%	15		M3-SCADA
15.00%		0.00%	15		M3-SCADA
50.00%		0.00%	15		M3-SCADA
50.00%		0.00%	15		M3-SCADA
50.00%		0.00%	15		M3-SCADA
15.00%		0.00%	15		M3-SCADA
50.00%		0.00%	15		M3-SCADA
50.00%		0.00%	15		M3-SCADA
50.00%		0.00%	15		M3-SCADA
15.00%		0.00%	15		M3-SCADA

The effectiveness of the mitigation or control program is described using the numerical fields in Figure 4-5. The Effectiveness field denotes the percentage reduction to the sub-driver parameter per unit of program exposure for the specified tranche and outcome, independent of historical program application to the same exposure. When blank, the "Effectiveness" field defaults to 0.

Programs can have a diminishing marginal effectiveness. If the same program is applied to the same exposure, the application of the program will not yield the same level of effectiveness.[13]

The effectiveness of a mitigation can degrade over time. In the *10-ProgramFreqEff* input sheet, this degradation can be specified using one or two periods. The periods are defined as two sets of yearly degradation, where in the first period, the effectiveness may decrease by one set of values, and in the second period, a different set of degradation values apply.[14] A user can also specify a custom escalation curve using the "match" method in the *12-esc* input sheet. Effectiveness degradation for programs are defined using the following fields:

- Annual Degradation Rate During Period 1: Represents the yearly rate by which the effectiveness of the program degrades. When left black, the default value is zero.
- Number of years for Period 1: Represents the number of years the degradation rate outlined for Period 1 should apply. When left blank, the default value is the full analysis horizon of the model.
- Escalation Method for Period 1: Using the escalation functions outlined for other variable escalation and extrapolation, this is the chosen method for the Period 1 degradation rate escalation. When left blank, the default value is "esc."

The degradation rate is escalated and applied to the effectiveness value for the years specified in each period.

Different mitigations can impact the same sub-driver of the same tranche in a given year. To derive the combined program effectiveness impact to a sub-driver, the product of effectiveness factors for all mitigation programs are used as a final effectiveness factor. For example, in Year 1, if the effectiveness of Mitigation A is 0.5, the effectiveness of Mitigation B is 0.8, and the effectiveness of Mitigation C is 0.75, the overall effectiveness for mitigations A, B and C for the particular sub-driver is calculated as:

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13 This re-mitigation impact capability was not utilized in the RAMP risk models, but, is available for future use.

14 None of the 12 RAMP risks use different degradation rates over two different periods of time.

$$1 - (1 - 0.5) \times (1 - 0.8) \times (1 - 0.75).$$

4.2.2. Tab 11-ProgramConseqEff

Functionally, the *11-ProgramConseqEff tab* is identical to the 10-ProgramFreqEff. Effectiveness values are calculated the same way, except they applied to the simulated consequence in Natural Units, rather than the Drivers and Sub-Drivers.

5. Calculations: Baseline Risk Score and Mitigation Analysis

5.1. Baseline Risk Score Calculation

This section provides an overview of the process for calculating the Baseline Risk Score. A numerical example for the Electric Distribution Network Asset Failure risk calculation is included in workpapers.[15] The name of the tab from the sample calculation workpaper (WP) corresponding to each step described below is included at the end of each step.

Steps for using completed model to calculating Risk Scores and RSEs:

1) Exposure: Obtain annual exposure for each Tranche, apply escalation factors, as necessary, using inputs specified in *3-Tranche*. (WP Tab: Input_Exposure.)
2) LoRE: Given the likelihood of the risk event occurring at each Tranche-Sub-Driver-Outcome combination in year 1, apply escalation factors (as necessary) to those values to compute future-year LoRE values. Apply any frequency multipliers (cross-cutting factor impacts) to these annual LoRE values. LoRE has units of expected number of events/unit exposure/year, or can be interpreted as the probability of having an event per unit of exposure per year when the unit of exposure is small enough.[16] (WP Tab: Input_LoRE.)
3) Frequency: Compute as the product of tranche exposure and LoRE for each Tranche-Sub-Driver-Year combination. Frequency has units of expected number of events per year. (WP Tab: Frequency.)
4) CoRE: Using the conditional distributions of consequence specified for each Tranche-Outcome-Attribute, simulate Natural Units per Tranche-Outcome-Attribute. (WP Tab: ExpectedNaturalUnitPerEvent.)
    a) Apply distribution parameter escalation methods. (Not relevant to this risk.)
    b) Simulate sufficient number of iterations to ensure mean convergence within 2 percent for each conditional distribution for each analysis year. (WP Tab: Sim_Distribution.)
    c. Apply Consequence multipliers to simulated Natural Unit values. (Not relevant to this risk.)

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15 See the workpaper WP-User Guide-1.

16 Within the model, the number of risk events is not simulated. The mean of the Poisson distribution specified in Distribution1_param1 in 4-Freq tab is used as the expected number of events per unit exposure each year.

d) For each consequence distribution for the Tranche-Outcome-Attribute with multiple distributions specified with operator for combining, simulate Bernoulli Random Variable with conditional sampling probability, which is sampling probability for the distribution divided by the maximum sampling probability across distributions for the same Tranche-Outcome-Attribute. The maximum of the conditional sampling probabilities for the consequence distributions of same Tranche-Outcome-Attribute would be equal to 1. If there is just one consequence distribution defined for a Tranche-Outcome-Attribute combination, the conditional sampling probability would be equal to 1, so there is no need to simulate Bernoulli random variables. (WP Tab: Sim_CondProbability.)

e) Multiply values from 4.c. to 4.d. element-wise so trials with realized outcome corresponds to conditional sampling probability, and then add them element-wise over the same Tranche-Outcome-Attribute. (WP Tab: Sim_DistMultiplyCondProb.)

f) Compute total natural units over all distributions for each event (defined at the Tranche-Outcome-Attribute level). (WP Tab: Sim_CondNaturalUnitPerEvent.)

g) Transform the simulated natural units per risk event for each Tranche-Outcome-Attribute using MAVF to get Trial CoRE conditional on the Attribute consequence occurring given the Risk Event. (WP Tab: Sim_CondCoRE.)

h) Compute CoRE per Tranche-Outcome-Attribute by taking the mean over all conditional Trial CoRE and multiplying it by the maximum sampling probability. (WP Tab: CoRE.)

5) Multiply Frequency at tranche/outcome by the corresponding (Multi-Attribute) CoRE to get Risk Score per tranche/outcome. (WP Tab: RiskScore.)

6) Sum Baseline Risk Scores by tranche over all tranches to get Baseline Risk Score. (WP Tab: Summary.)

5.1.1. Frequency Calculation

The LoRE values from *4-Freq* for each sub-driver are escalated over the analysis horizon using the method specified in the input sheet and detailed in *12-esc_method*. The frequency multipliers are also escalated, also using the method specified in *12-esc method and* applied to the escalated LoRE. This is multiplied to the tranche exposure obtained from *3-Tranche* sheet, to derive Frequency by tranche and outcome for each year over the analysis horizon. Note that in the formulas below, the year dimension is not included in the subscripts since it applies to all variables.

$$Frequency_{tr,o} = Exposure_{tr} \times LoRE_{tr,o}$$

Where:

$Exposure_{tr}$ is the exposure for tranche tr.

$LoRE_{tr,o}$ is the LoRE of outcome o in tranche tr, and is obtained by summing over the sub-drivers leading to the outcome as shown below:

$$LoRE_{tr,o} = \sum_{d} LoRE_{tr,d,o}$$

5.1.2. CoRE Calculation

If an attribute has more than one distribution and not all the distribution (or sampling) probabilities are the same, the distribution's sampling probability conditional on at least one of the distributions occurs is obtained as its sampling probability divided by the largest sampling probability of all distributions. The distribution's conditional sampling probability is used to simulate Bernoulli random variates to determine whether the part of consequence following that distribution occurs given the consequence materializes.

$$p_{tr,o,a}^{max} = Max\{p_{1,a,tr,o}, \dots, p_{M,a,tr,o}\}$$

$$P_{m,a,tr,o}^{cond} = \frac{p_{m,a,tr,o}}{p_{tr,o,a}^{max}}, \quad \forall m = 1, \dots, M$$

Where:

M is the number of distributions that characterize consequence of a given tranche, outcome and attribute.

$p_{m,a,tr,o}$ is the sampling probability of the nth distribution for the given tranche, outcome and attribute.

$p_{tr,o,a}^{max}$ is the maximum sampling probability across all $p_{m,a,tr,o}$, with m = 1…M.

CoRE is the weighted sum of Scaled Units of four Attributes (Safety, Financial, Reliability Electric, Reliability Gas), multiplied by 1,000. The Scaled Unit of each

Attribute varies from 0 to 100, consistent with its definition in the S-MAP Settlement Agreement and is the output of applying the MAVF's Range and Scaling Function to the Attribute Levels.

$$CORE_{tr,o} = \sum_{a} CoRE_{tr,o,a}$$

Attribute CoRE for tranche tr, outcome *o* and attribute a is calculated as follows:

$$Attribute\ CORE_{tr,o,a} = \frac{1}{\#\ trials} \times \sum_{n=1}^{\#\ trials} Trial\ CoRE_{tr,o,a,n}$$

Where:

$$Trial\ CORE_{tr,o,a,n} = scaler \times w_a \times p_{tr,o,a}^{max} \times f\left(\sum_{m=1}^{\#\ dists} I_{n,m,a,tr,o} \times NU_{n,m,a,tr,o}\right)$$

$NU_{n,m,a,tr,o}$ is Natural Unit simulated in trial n for distribution m of attribute a of outcome o for tranche tr, conditional on distribution m of attribute a materializes given risk event.

$I_{n,m,a,tr,o}$ is Bernoulli variate based on conditional sampling probability for distribution m simulated in trial n of attribute a of outcome o for tranche tr. $I_{n,m,a,tr,o}$ is only applicable when there are multiple distributions needed to characterize the given attribute.

$f(.)$ is the scaling function for converting natural units into scaled unit ranged from 0 to 100.

$p_{tr,o,a}^{max}$ is the maximum sampling probability across distributions for attribute a of outcome o for tranche tr.

w_a is the MAVF weight of attribute a.

$scaler$ is an MAVF scaler of 1,000.

5.1.3. Baseline Risk Score Formula

<u>*Risk Score by Tranche and Outcome*</u> is calculated as the product of Exposure, Likelihood of Risk Event (LoRE) and Consequence of Risk Event (CoRE), and can be expressed formulaically as follows:

$$Risk\ Score_{tr,o} = Exposure_{tr} \times LoRE_{tr,o} \times CoRE_{tr,o} = Frequency_{tr,o} \times CoRE_{tr,o}$$

Where:

Risk Score by Tranche, Sub-Driver and Outcome is proportioned by the frequency as follows:

$$Risk\ Score_{tr,d,o} = Risk\ Score_{tr,o}\ \times \frac{LoRE_{tr,d,o}}{LoRE_{tr,o}}$$

Total Risk Score is the sum of the Risk Scores over all tranches and outcomes

$$Risk\ Score = \sum_{tr,o} Risk\ Score_{tr,o}$$

5.2. Mitigation Analysis

The risk score for the Proposed/Inherent case is obtained by applying control/mitigation effectiveness to specified sub-driver-outcome-tranche frequencies or outcome-tranche-Attribute simulated natural unit values.

1) For mitigated risk scores:
    a) Apply mitigation effectiveness to specified sub-driver-outcome-tranche frequencies or outcome-tranche simulated natural unit values.
    b) Recalculate Risk Score given mitigated exposure for each year.
    c) Compute risk reduction allocation factor.
2) Compute program cost NPV.
3) Compute risk reduction NPV.
4) Compute RSE.

These program related inputs are defined in Tabs *8-Program*, *9-ProgramExposureSpend*, *10-ProgramFreqEff*, and *11-ProgramConseqEff* in the Risk Input File.

The following sections include numerical examples as to how these calculations are performed.

5.2.1. Overall Effectiveness Calculation

There are two overall effectiveness calculations: Overall Effectiveness on Frequency and Overall Effectiveness on Consequence.

Overall Effectiveness on Frequency:

Overall Mitigation Factor by Tranche, Sub-Driver and Outcome is the percentage risk remaining after all mitigation programs are implemented.

$$Overall\ Mitigation\ Factor_{tr,d,o} = 1 - \ Overall\ Effectiveness\ Factor_{tr,d,o}$$

Where the *Overall Effectiveness Factor* is the overall percentage reduction of frequency due to all mitigation programs (subscript m) proposed.

$$Overall\ Effectiveness\ Factor_{tr,d,o} = 1 - \prod_{m} Mitigation\ Factor_{tr,d,o,m}$$
$$= 1 - \prod_{m} \left(1 - Effectiveness\ Factor_{tr,d,o,m}\right)$$

$Mitigation\ Factor_{tr,d,o,m}$ is the percentage remaining risk post mitigation program m, which is one minus the percentage risk reduction due to program m, $Effectiveness\ Factor_{tr,d,o,m}$, as derived below:

$$Effectiveness\ Factor_{tr,d,o,m} = \ Scope_{tr,m} \times Effectiveness_{tr,d,o,m}$$

$Scope_{tr,m}$ is the percentage exposure of tranche tr to mitigation program m.

$Effectiveness_{tr,d,o,m}$ is the percentage reduction of frequency for applicable scope from mitigation program m.

Overall Effectiveness on Consequence:

The formulas for the overall mitigation factor for Attribute a are developed by simply replacing the subscript d with a.

5.2.2. Test Year Baseline Risk Scores

The Test Year Baseline risk score is the product of the Test Year Baseline Frequency and Test Year Baseline CoRE over the set of modeled years.

5.2.2.1. Test Year Baseline Frequency

The Test Year Baseline Frequency is the product of the Baseline frequency and the overall mitigation effectiveness factor for all Frequency mitigation programs implemented before the Test Year.

5.2.2.2. Test Year Baseline CoRE

The Test Year Baseline CoRE is the product of the Baseline CoRE and the overall mitigation effectiveness factor for all Consequence mitigation programs implemented before the Test Year.

5.2.3. Mitigated Risk Scores[17]

Mitigation programs which act to reduce the Frequency but have no impact on CoRE are simply a function of the difference in the *Baseline and Mitigated Risk Scores* in LoRE and hence Frequency.

$$\begin{aligned} Baseline\ Risk\ Score_{tr,d,o} &= Exposure_{tr} \times Baseline\ LoRE_{tr,d,o} \times Baseline\ CoRE_{tr,o} \\ &= Baseline\ Frequency_{tr,d,o} \times Baseline\ CoRE_{tr,o} \end{aligned}$$

$$\begin{aligned} Mitigated\ Risk\ Score_{tr,d,o} &= Exposure_{tr} \times Mitigated\ LoRE_{tr,d,o} \times Mitigated\ CoRE_{tr,o} \\ &= Mitigated\ Frequency_{tr,d,o} \times Mitigated\ CoRE_{tr,o} \end{aligned}$$

The mitigated LoRE for a specific tranche, sub-driver and outcome combination is expressed as follows:

$$Mitigated\ LoRE_{tr,d,o} = Baseline\ LoRE_{tr,d,o} \times Overall\ Mitigation\ Factor_{tr,d,o}$$

The mitigated CoRE for a specific tranche, sub-driver and outcome is expressed as follows:[18]

$$Mitigated\ Trial\ CoRE_{tr,o,a,n} = Scaler \times w_a \times f\left(Overall\ Mit\ Factor_{a,tr,o} \times NU_{n,a,tr,o}\right)$$

The Mitigated Trial CoRE is used to compute the Mitigated CoRE as follows:

$$Mitigated\ CORE_{tr,o} = \sum_a \frac{1}{\#\ trials} \sum_{n=1}^{\#\ trials} Mitigated\ Trial\ CoRE_{tr,o,a,n}$$

5.2.4. Risk Reduction Scores

Total Risk Reduction is the reduction in the overall Risk Score due to the mitigation programs. The two possible formulations are follows, with the first applying to a mitigation and the second to a control program:

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17 Mitigated Risk Scores mean the post-Mitigation Risk Scores.

18 This formula assumed the case where the sampling probability equal to one and there is one distribution specified for tranche-outcome-attribute. Otherwise, the same adjustments are made in the formula similarly as described in Section 4.2.

$$Total\ Risk\ Reduction = Baseline\ Risk\ Score - Mitigated\ Risk\ Score$$
$$Total\ Risk\ Reduction = Inherent\ Risk\ Score - Baseline\ Risk\ Score$$

Baseline Risk Score is the pre-mitigation risk score.

Mitigated Risk Score is the post-mitigation risk score.

The above expression is also applicable at specific tranche (subscript tr), sub-driver (subscript d), and outcome (subscript o) levels.

The formula below shows how MARS is calculated in general.

$$Total\ Risk\ Reduction_{tr,d,o} = Baseline\ Risk\ Score_{tr,d,o} - Mitigated\ Risk\ Score_{tr,d,o}$$

5.2.5. Risk Reduction Allocation to Mitigation/Control Programs

Because multiple programs can impact a sub-driver or consequence, it is difficult to discern the risk reduction derived from an individual program simply by looking at the risk reduction outputs by consequence.

This section outlines the process by which overall risk reduction is allocated to each active program.

The allocation of risk reduction attributable to each mitigation is done based on the marginal effectiveness of each mitigation to the portfolio of mitigations for a given Tranche, Outcome, and Sub-Driver/Attribute.

For example:

- Mitigation A has an effectiveness of 0.2 for a given Tranche-Outcome-Sub-Driver/Attribute.
- Mitigation B has an effectiveness of 0.6 for the same Tranche-Outcome-Sub-Driver/Attribute.
- Overall program effectiveness for the Tranche-Outcome-Sub-Driver/Attribute is 68 percent (= 1 - (1 - 0.2) × (1 - 0.6)).
- If we remove Mitigation A from the portfolio, then the overall effectiveness is 60 percent (from Mitigation B). Thus, marginal effectiveness of Mitigation A is 8 percent (= 68% - 60%).
- If we remove Mitigation B from the portfolio, then the overall effectiveness is 20 percent (from Mitigation A). Thus, marginal effectiveness of Mitigation B is 48 percent (= 68% - 20%).
- Risk Reduction Allocation factor for Mitigation A is set to 8%/(8% + 48%) = 14% for this Tranche-Outcome-Sub-Driver/Attribute.

- Risk Reduction Allocation factor for Mitigation B is set to 48%/ (8% + 48%) = 86% for this Tranche-Outcome-Sub-Driver/Attribute.

After the risk reduction attributable to consequence reduction and attributable to frequency reduction have been allocated to each program, the risk reduction can be aggregated at the mitigation program level. Mitigation program risk reduction allocation is calculated at the yearly level for each tranche in the Model.

5.3. Risk Spend Efficiency (RSE) Calculation

Using the allocated program-level risk reduction values, the Model can then calculate the risk spend efficiency for each mitigation program using the spend data entered for the program on the *9-ProgramExposureSpend* tab, shown in Figure 4-3.

The risk spend efficiency represents a program's risk reduction per million dollars spent. Using the estimated cost of the mitigation (or control) and the 7.1 percent discount rate, the Model calculates a discounted yearly spend.

TABLE 5-1 – DISCOUNTED CAPITAL SPEND EXAMPLE | BEFORE DISCOUNT RATE APPLICATION

Program	Tranche	Cap Spend USD Year1	Cap Spend USD Year2	Cap Spend USD Year3	Cap Spend USD Year4	Cap Spend USD Year5	Cap Spend USD Year6	Cap Spend USD Year7
Critical Documentation	Tranche 1	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000	$20,000

TABLE 5-2 – DISCOUNTED CAPITAL SPEND EXAMPLE | AFTER DISCOUNT RATE APPLICATION

Program	Tranche	Cap Spend USD Year1	Cap Spend USD Year2	Cap Spend USD Year3	Cap Spend USD Year4	Cap Spend USD Year5	Cap Spend USD Year6	Cap Spend USD Year7
Critical Documentation	Tranche 1	$20,000	$18,674	$17,436	$16,280	$15,201	$14,193	$13,252

Using the discounted spend data, the model then calculates the RSE at the tranche level as:

$$\text{RSE} = \frac{\text{NPV(Risk Reduction Scores)}}{\text{NPV(Yearly Spend)}} \times 10^6$$