Fire Risk Modeling - Sensitivity and Uncertainty Analysis

EPRI – NRC
UNCERTAINTY
WORKSHOP

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Objectives

- Demonstrate benefits of uncertainty analysis in general
  - Confidence that decision criteria have been met
  - Contribution of individual inputs to overall risk variance
  - More realistic prediction of best estimate risk

- Demonstrate fire risk sensitivity and uncertainty approach using Monte Carlo Simulation
  - With focus on fire growth and suppression modeling

Overall Sources of Uncertainty

- Generic uncertainty issues summarized in NUREG/CR-6850 Appendix V for each FPRA task.
- Expanded to list ~ 157 separate issues

Task 1: 2	Task 5: 5	Task 9: 4
Task 2: 14	Task 6: 20	Task10: 3
Task 3: 4	Task 7: 1	Task 11: 74
Task 4: 1	Task 8: 17	Task 12: 12

Overall Risk

The CDF associated with each fire source

$$CDF = \lambda_{IS} \cdot W_{IS} \cdot \sum_i \left(SF \cdot P_{ns}\right)_i \cdot CCDP_i$$

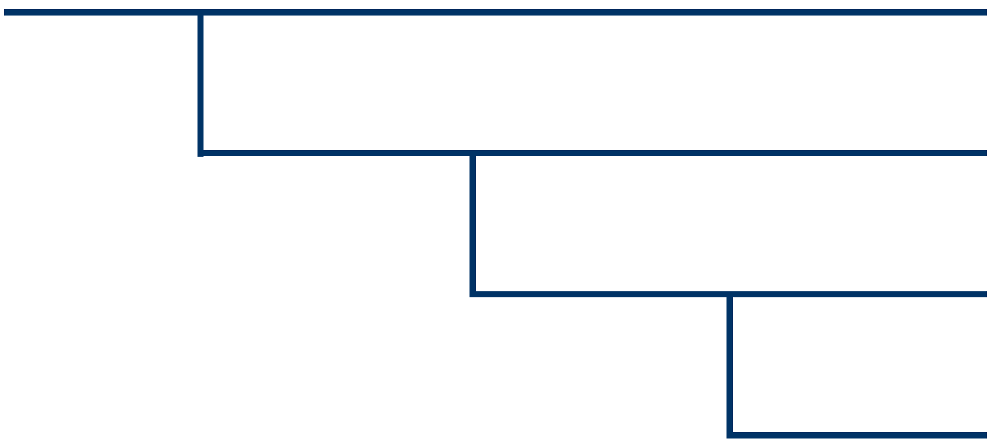
λ_{IS}	= *Scenario ignition source bin frequency*
W_{IS}	= *Scenario ignition source weighting factor*
$(SF \cdot P_{ns})_i$	= *Probability of scenario fire damage state 'i'*
$CCDP_i$	= *CCDP for scenario fire damage state 'i'*

Detailed Fire Modeling
(NUREG/CR- 6850 Task 11)

- Identify & Characterize Ignition Sources
  - Location in compartment
  - Peak heat release rate (HRR) , Fire growth profile
  - Frequency
- Identify Targets
  - Distance from ignition source, Damage criteria
- Identify & Characterize Fire Detection & Suppression Provisions
  - Manual, Automatic
- Calculate Damage State Probability/ Scenario Frequencies

Fire Growth Event Tree

Fire Ignition	Fire suppressed before damage to closest target	Fire suppressed before damage to closest combustible	Fire suppressed before damage to whole room	Fire Damage State



Fire suppressed before damage to closest target

Fire damages closest target but is suppressed before damage to closest combustible

Fire damages closest combustible but is suppressed before damage to whole room

Fire damages whole room

Detailed Fire Modeling (NUREG/CR- 6850 Task 11)

- Probability of Fire Damage State (Manual suppression only)
  - Calculate Severity Factor
    SF = Probability of target damage at time, t
  - Calculate Probability of Manual Non Suppression

$$P_{ns} = e^{-\lambda t}$$

λ = Suppression rate
t = Time to target damage
(would account for detector response time and unavailability)

- P(SF * Pns) = Probability that time to suppress fire exceeds time to damage

Uncertainties in Detailed Fire Modeling

- Aleatory (Inherent Randomness)
  - Manual suppression time
  - Ignition source peak HRR
  - Fire growth profile (i.e. time to peak HRR, steady burning time, decay time)
  - Etc.
- Epistemic (State of Knowledge)
  - Cable damage temperature (target in plume, ceiling jet, hot gas layer)
  - Cable damage radiant heat flux (target not in plume, ceiling jet or HGL).
  - Time to damage vs exposure severity
  - HGL, Ceiling Jet, Plume Fire Models (Not included in example)
  - Etc

Distribution Examples used in the Fire Damage Calculation Uncertainty Analysis

Data Item	Type of Distribution	Distribution Parameters	Comments
Room Ambient Temp ^{O}C	Triangular	Minimum 20 Maximum 30 Likeliest 25	Distribution assumed triangular to reflect central tendency to mean value 25ºC.
Ventilation opening area m^2	Uniform	Minimum 0.0113 Maximum 3.75	Opening area assumed to vary between single closed door (with 0.5" leakage path below the opening as recommended in Ref. 2 Section F.2) and double doors fully open.
Fire Elevation (in)	Uniform	Minimum 0 Maximum 36	Distribution assumed uniform with minimum at floor level and maximum based on engineering judgment.
Manual suppression rate (Electrical fires) (min^{-1})	Lognormal	Median 0.102 95% 0.122	Distribution assumed lognormal with median value of 0.102 from FAQ 08-0050 and uncertainty bounds based on error factor from data in NUREG/CR 6850 Table P-2.

Distribution Examples used in the Fire Damage Calculation Uncertainty Analysis

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SCIENTECH

Data Item	Type of Distribution	Distribution Parameters	Comments
Peak HRR for vertical cabinet with qualified cable, fire in more than one cable bundle (kW)	Gamma	Shape (α) 0.70 Scale (β) 216.0	Distribution/parameters from (Ref. 2) Table G-1. The peak HRR is an aleatory uncertainty, which is modeled directly in the detailed fire models.
Time to reach peak HRR (Transient fire) (min)	Lognormal	Location 0 Mean 9.25 S.D. 2.28	Distribution assumed lognormal with same mean and S.D. as test data in FAQ 08-0052 (Ref. 26).
Cable damage threshold temperature (Thermoset cable) (^{o}C)	Weibull	5% 330 95% 390 Shape 3.25	Distribution assumed Weibull assuming point estimate value given in (Ref. 2) is 5th percentile with 95th percentile based on test results given in (Ref. 2) Tables H-3 and H-4. Shape factor chosen to make distribution symmetrical.
Error in measurement of distance to closest target (in)	Uniform	Minimum -3.0 Maximum +3.0	Distribution conservatively assumed to be uniform with range based on recommendation from plant personnel.

Monte Carlo Simulation

- Sample from Input Probability Distributions
  - Detection/Suppression system states
  - Detection/Suppression time parameters
  - Ignition source peak HRR
  - Time to peak HRR, etc.
- Calculate:
  - Detection Time / Suppression Time
  - Maximum HRR at time of suppression
  - Local target impact
    - Plume temperature
    - Radiant heat flux
    - Time to failure
  - Whole room impact
    - Ceiling jet
    - Hot gas layer
    - Time to failure
  - Damage States
    - Local Target(s) failed (1 or 0)?
    - Thermo plastic cable targets damaged (1 or 0)?
    - Whole room damage (1 or 0) ?
- Repeat 1000's of times to estimate damage state mean values:
  - Local target FDS failure probabilities & Wide-spread FDS failure probability

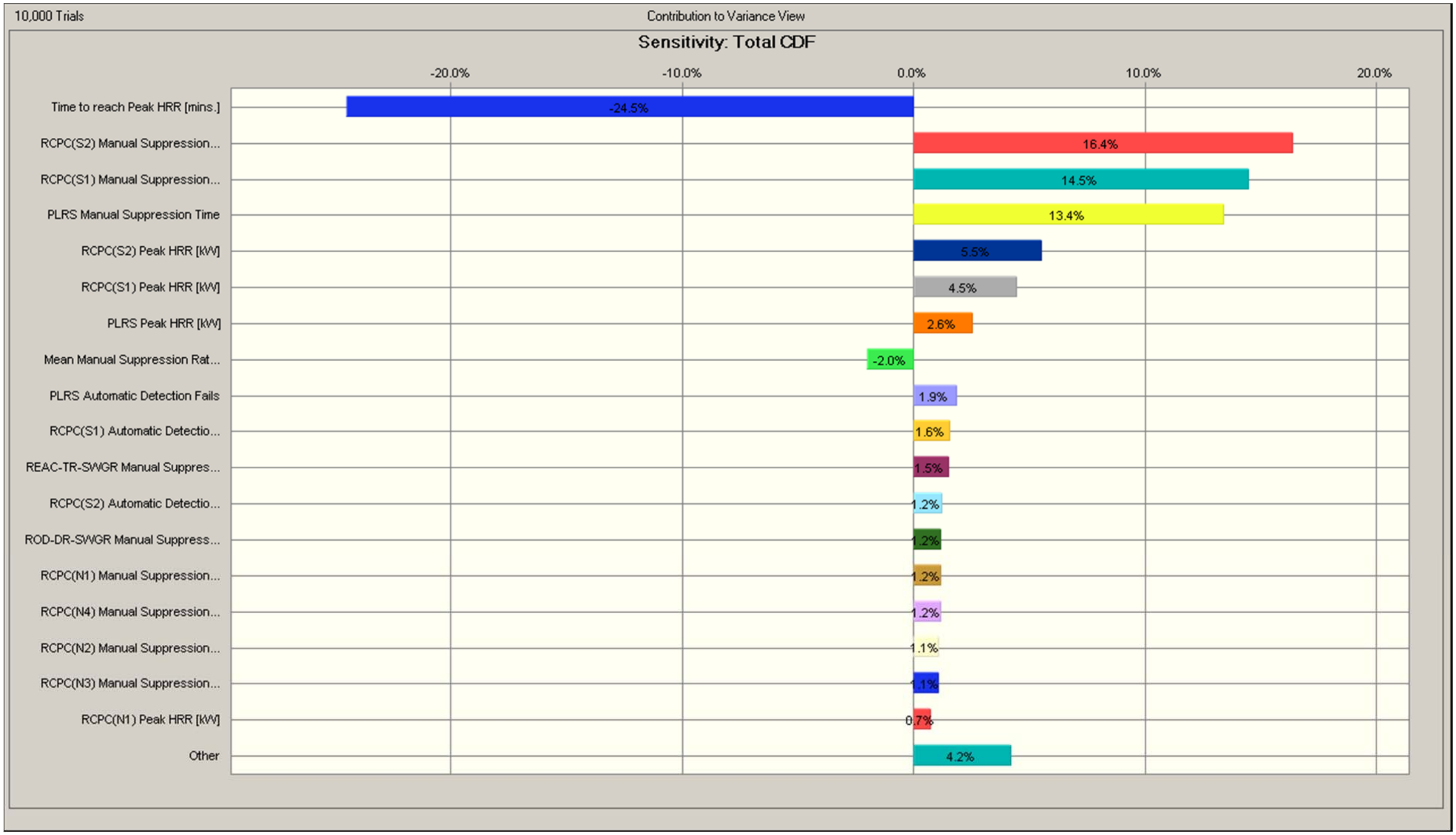
Comparison of Results with Point Estimate Methodology

Fire Damage State	Point Estimates (CDF per yr)	MC Simulation (CDF per yr)	
		With P.E. Assumptions	Without P.E. Assumptions
Fire suppressed before damage to closest target	2.08E-09	2.08E-09	2.76E-09
Fire damages closest target but is suppressed before damage to closest combustible	3.13E-08	3.13E-08	1.58E-08
Fire damages closest combustible but is suppressed before damage to whole room	3.45E-07	3.45E-07	2.27E-07
Fire damages whole room	5.62E-07	5.15E-07	6.71E-08
Total CDF	9.41E-07	8.94E-07	3.13E-07

Sensitivity Analysis

- Crystal Ball© 1D Simulation
- Sensitivity of Outputs to Variations in Inputs
- Contribution to Variance depends on:
  - Variance in input values
  - Sensitivity of outputs to changes in inputs
- High Sensitivity
  - High variance in input value and/or
  - High sensitivity of output to input value

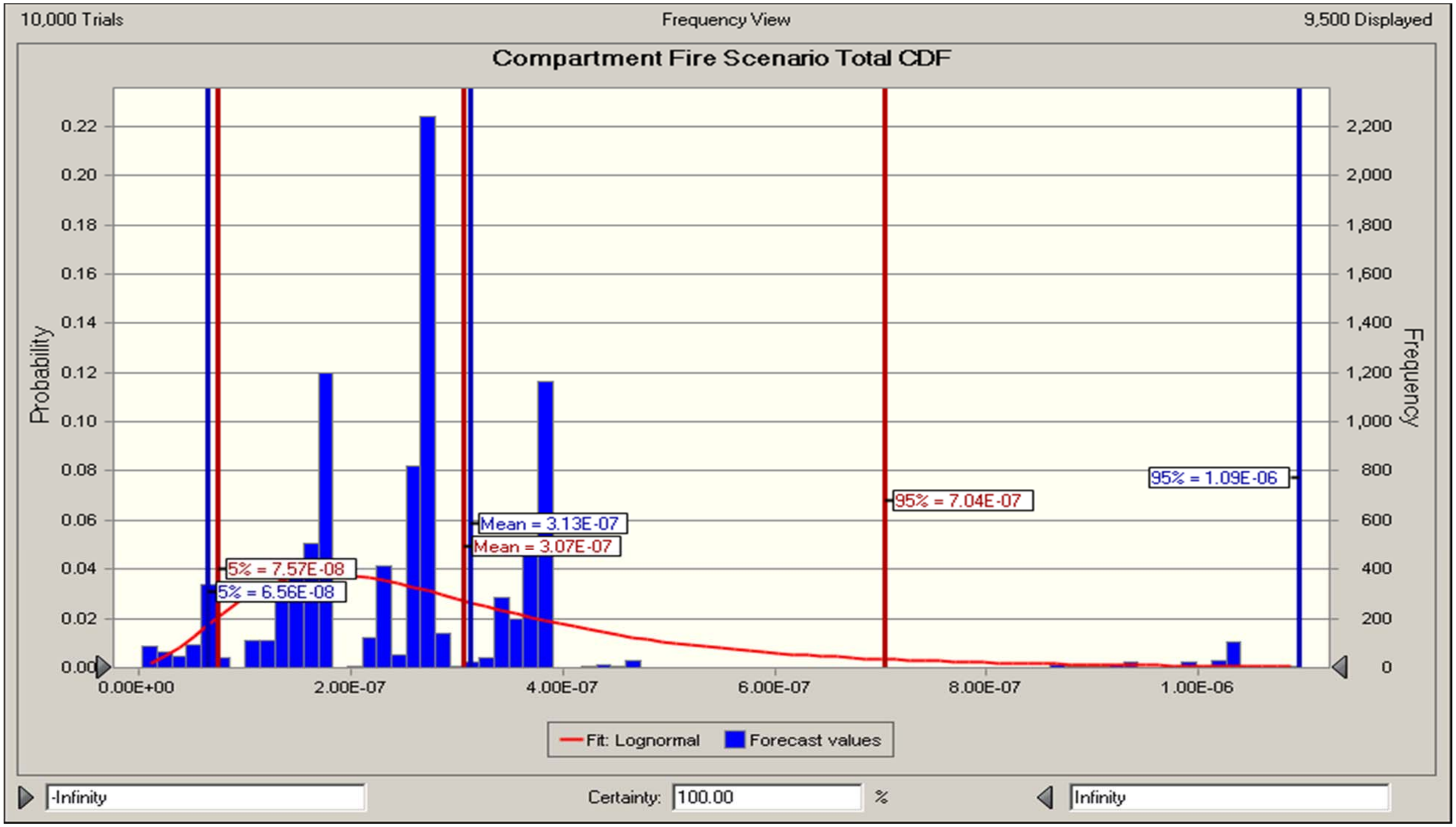
Sensitivity Analysis Results



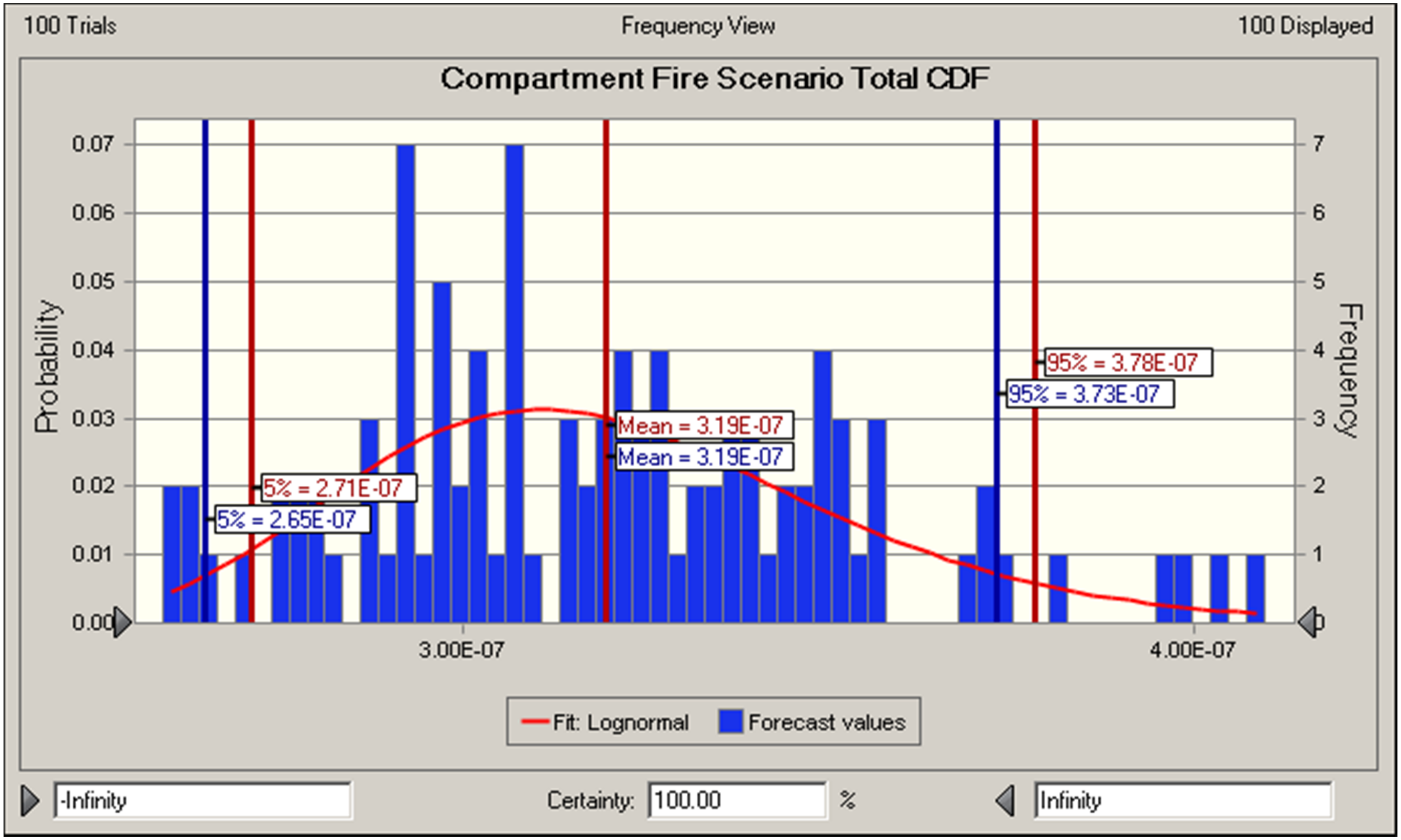
Uncertainty Analysis

- Crystal Ball© 2D Simulation
  - Inner loop for “variables” (aleatory uncertainties)
  - Outer loop for “uncertainties” (epistemic)
- Outer loop
  - Samples values (“Assumptions”) for epistemic uncertainties
  - Repeated typically 100 times
- Inner loops
  - Forecasts scenario probability based on outer loop assumptions
  - Repeated typically 10,000 times

Uncertainty Analysis Results
Fire CDF Overall Uncertainty



Uncertainty Analysis Results
Fire CDF Epistemic Uncertainty



Advantages of Simulation over Point Estimate Methodologies

- Mininizes conservatism by eliminating need for simplifying/bounding assumptions
- More flexible and easy to extend with more detailed/accurate modeling
- Computer code does Sensitivity & Uncertainty Analysis automatically
  - Prioritizes need (or not) for further evaluation of critical modeling assumptions and parameters

Future Improvements to be Addressed

- Comprehensive identification and treatment of modeling uncertainty issues
- Incorporation of CFAST modeling
- Integration of PRA model and fire damage models to fully account for correlation between fire growth and accident mitigating system / human performance related uncertainties
- Identification of uncertainty characteristics associated with generic scenario types (e.g. HGL vs plume damage) to simplify application