Best Estimate Fire Modelling and Uncertainty Analysis using Monte Carlo Simulation

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Presenter

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ENGINEERING RISK SOLUTIONS

Objectives of Presentation

- Describe a flexible tool for evaluating the likelihood of fire progression and suppression with the following benefits:
  - A more realistic estimate of fire risk due to the minimization of conservatism by eliminating need for simplifying/ bounding assumptions
  - Quantitative parameter and modelling uncertainty
  - Understanding of which input uncertainties are most influencing the overall uncertainty on output probabilities or frequencies
  - Prioritization of the need (or not) for further evaluation of critical modelling assumptions and parameters.

Monte Carlo Solution

- Can be based on point estimate spreadsheet model using NUREG 1805 FDT correlations or CFAST model
- Allows any input parameter to be processed as a distribution
- Capability of calculating results in terms of both point estimate and probability distributions using 1D or 2D solutions
- Generates importance in terms of Pearson or Spearman correlation coefficients
- Implementation using for example
  - Oracle's Crystal Ball (EXCEL Add in)
  - INL's Risk Analysis Virtual ENvironment (RAVEN)

Focus here is on Damage State Probability

The CDF and LERF for each fire scenario are given by:

$$\mathrm{CDF} = \sum_{\mathrm{i}} \lambda_i \,.\, \sum_{j} W_{ij} \,.\, \sum_{k} \boxed{(SF.P_{ns})_{ijk}} \,.\, CCDP_{ijk}$$

where

λ_i = Scenario ignition source bin frequency

W_{Ij} = Scenario ignition source weighting factor

$(SF{\cdot}P_{ns})_{\mathrm{ijk}}$ = Probability of scenario fire damage state

$CCDP_{\mathrm{ijk}}$ = CCDP for scenario fire damage state

$CLERP_{\mathrm{ijk}}$ = CLERP for scenario fire damage state

Monte Carlo Applications So Far

- Solution of NUREG/CR 6850 Appendix L Main Control Board Model for unique configurations
    - Non standard sized cabinets
    - Raceway Targets located in rear of MCB
- Address error in NUREG/CR 6850 Appendix L model and proposed FAQ incorporating NUREG 2178 Peak HRRs & NUREG 2169 Mean Suppression rate
    - Error identified by comparison of MC results with reported Analytical results
    - Sensitivity Analyses to address impact of errors and mitigating factors
    - Corroboration of revised Appendix L model documented in NEI Task Force White paper (July 2017)
- Enhanced SF* PNS values for transient fires
- Fire Modelling Uncertainty Analysis and propagation in FPRA for 2 US PWR NFPA Studies (Peer Reviewed – Best Practice)
- Fire Modelling Best Estimate and Uncertainty Analysis Methodology Development and Demonstration for EPRI (EPRI 3002003188 (draft))

Basics of Point Estimate Analysis

- Uses an ignition source PHRR PD to calculate the probability of the PHRR exceeding a given value to cause damage.
- Selects 1 or 2 peak PHRR ranges and associated probabilities to determine time to target damage.
- Uses the PD for the manual suppression time to calculate the probability of non-suppression within the time to cause damage to a given target based on the maximum PHRR of each range.
- Apart from PHRR and Suppression Rate all other input values and modeling assumptions are conservatively fixed.
- Detection time is often based on the maximum PHRR (which can be non conservative).
- Time to damage after reaching minimum damage threshold often not credited.

Basics of Monte Carlo Simulation

- On each trial,
  - the ignition source PHRR, manual suppression time and the status of detection and automatic suppression systems (working or not working) are selected at random from the defined distributions.

  - the time to detection and suppression is determined based on deterministic simulation of the time to reach conditions resulting in each pre defined **DAMAGE STATE** (assuming no suppression) using the selected PHRR.

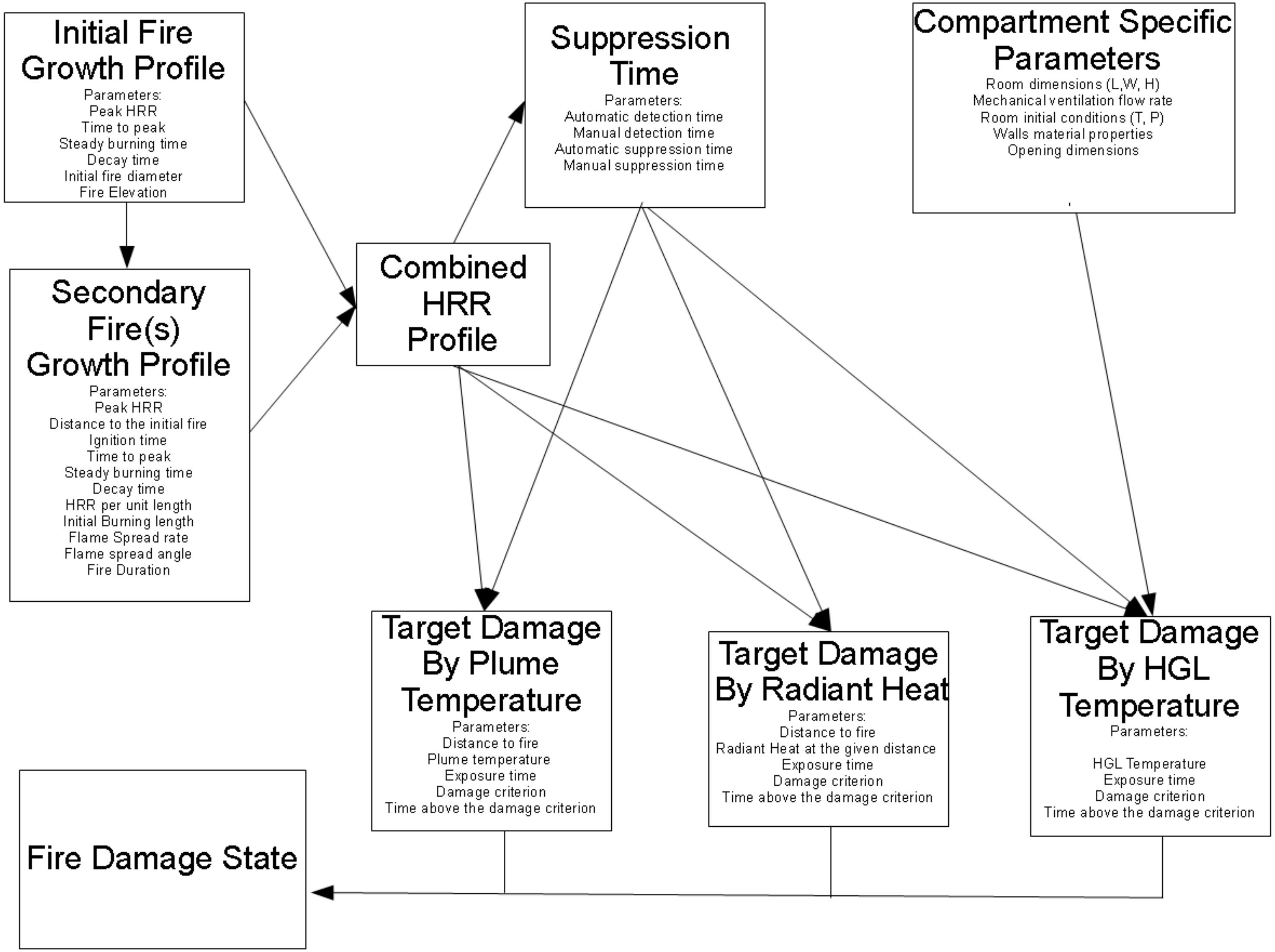
  - a unique **DAMAGE STATE** is then assigned to each trial based on the time to damage relative to time to suppression.

Basics of Monte Carlo Simulation (Cont)

- The probability of any given **DAMAGE STATE** occurring is calculated as the average number of times the damage state occurs over a large number of trials.

- Fire source location can be treated as random
- Detection time is determined for each specific PHRR
- Damage time given exceedance of critical damage criteria can easily be incorporated for each trial

- Distributions representing multiple parameter and modelling inputs can also be sampled



Initial Fire Growth Profile

Parameters:
Peak HRR
Time to peak
Steady burning time
Decay time
Initial fire diameter
Fire Elevation

Secondary Fire(s) Growth Profile

Parameters:
Peak HRR
Distance to the initial fire
Ignition time
Time to peak
Steady burning time
Decay time
HRR per unit length
Initial Burning length
Flame Spread rate
Flame spread angle
Fire Duration

Combined HRR Profile

Suppression Time

Parameters:
Automatic detection time
Manual detection time
Automatic suppression time
Manual suppression time

Compartment Specific Parameters

Room dimensions (L,W, H)
Mechanical ventilation flow rate
Room initial conditions (T, P)
Walls material properties
Opening dimensions

Target Damage By Plume Temperature

Parameters:
Distance to fire
Plume temperature
Exposure time
Damage criterion
Time above the damage criterion

Target Damage By Radiant Heat

Parameters:
Distance to fire
Radiant Heat at the given distance
Exposure time
Damage criterion
Time above the damage criterion

Target Damage By HGL Temperature

Parameters:

HGL Temperature
Exposure time
Damage criterion
Time above the damage criterion

Fire Damage State

Example 1: NUREG/CR 6850 Appendix L Solution

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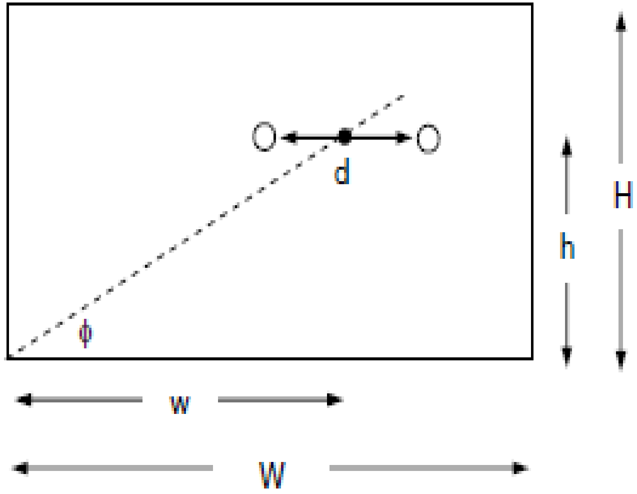


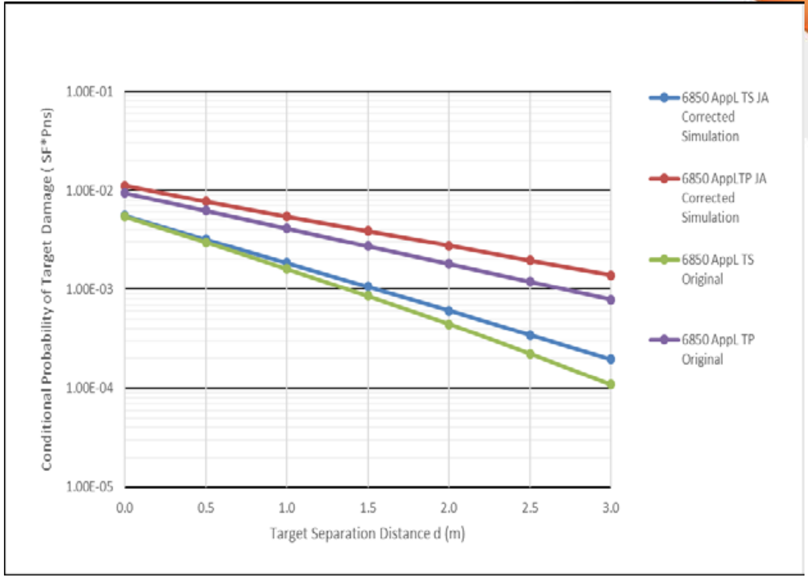
$$r(d,w,h) = \frac{d}{2} + \sqrt{w^2 + h^2}$$

- Target set of two components mounted on the front panel distance (*d)* apart. The mid-point between the two targets has coordinates (*w,h*) and the fire is assumed to be fixed at the origin (*0,0*).
- The term *r*(*d*,*w*,*h*) represents the distance between the origin of the fire and the farthest target
- ZOI of fire based on an axi-symmetric plume model
- A fire starting in a given origin will need to generate a damaging plume temperature a distance *r*(*d*,*w*,*h*) in order for the target set to be considered damaged.

NUREG/CR 6850 Appendix L Solution (Cont)

For a given separation distance (d) conduct a set of MC trials

1. randomly select target location (w, h), PHRR (Q), and manual suppression time (ts)
2. Determine fire – target separation distance (r)
3. Determine if target damage occurs when PHRR is achieved and time to target damage (td)
4. If ts>td damage trial results in damage
5. Repeat steps 1 thru 3 50,000 times
6. $[SF \cdot Pns](d)$ = no of trials resulting in damage/ 500000
7. Repeat steps 1-5 for different values of (d)



- Solution much simpler and less error prone, more flexible than analytical approach (See NEI Task Force White Paper)
- NUREG/CR 6850 underestimates $[SF \cdot Pns](d)$
- However this can be compensated for by resolving using more realistic value of location factor (k=1 instead of 2) and capping PHRR at 98%ile

Example 2- FPRA Uncertainty Analysis

- Uncertainty within any PRA can be described as one of the following three types:
  - Parameter uncertainty
  - Model uncertainty
  - Completeness and Accuracy uncertainty*

* Resolved as far as possible through independent technical/peer reviews (not addressed further here)

Parameter Uncertainty

- Relates to the uncertainty in the value of a parameter used in the PRA model
  - **Epistemic Uncertainty**: imperfect knowledge about model parameters (may be physical parameters in fire models, physical items such as times, parameters in reliability models)

    Expression of “degree of belief” in parameter values
  - **Aleatory uncertainty** - inherent randomness, variability

- Some aspects of model may appear to have both characteristics. But still possible to separate into epistemic and aleatory categories
  - **Example:** suppression probability may use a constant recovery rate model
    - means that suppression time is aleatory (random, variable suppression time)
    - distribution of suppression times is controlled by suppression rate parameter. This parameter is subject to Epistemic Uncertainty.

Model Uncertainty

- Model uncertainty is a choice of model that is not conservatively or optimistically biased.
- Relates to:
    - the assumptions made in the analysis (e.g. source elevation)
    - the validity of models used.
        - **Examples** include the choice of correlation to predict
            - fire plume temperature
            - Radiant flux.
- Model uncertainties may be addressed by:
    - sensitivity studies
    - in some cases may be parameterized and propagated
        - e.g. NUREG 1934 Plume, Radiant and HGL uncertainty factors

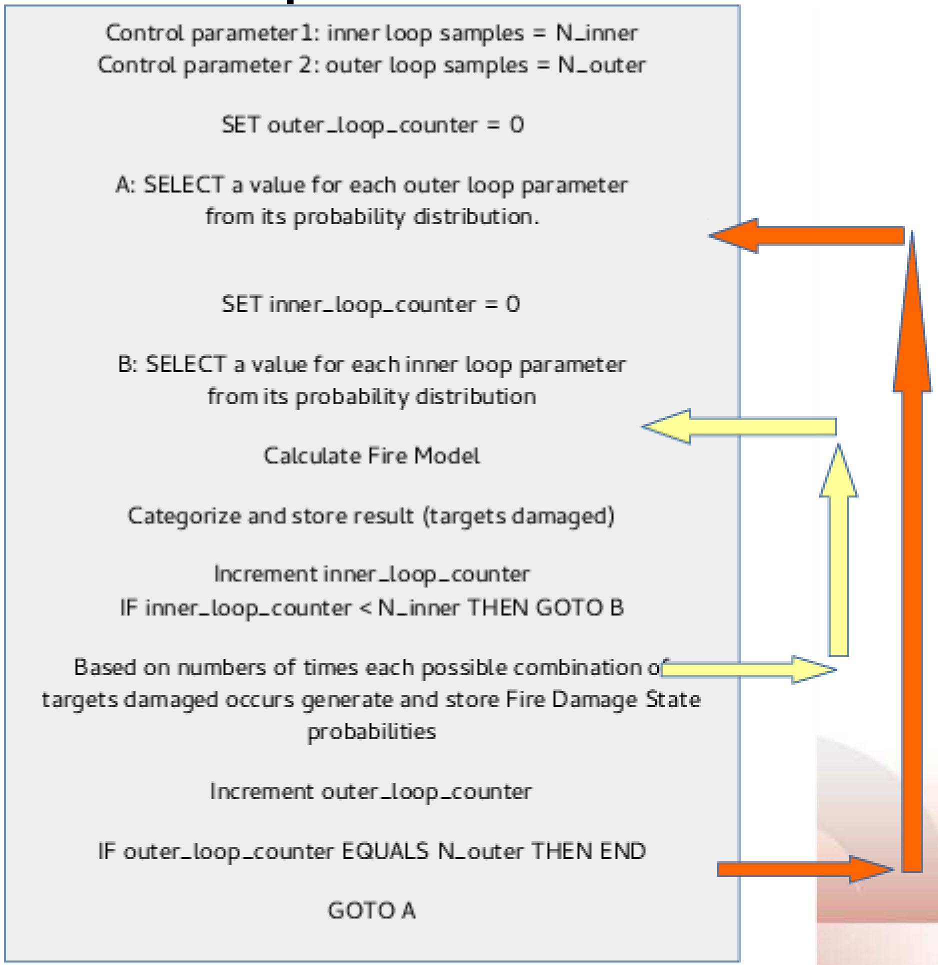
Parameter and Model Uncertainty Examples

- **ALEATORY**
- Peak Heat Release Rate [kW]
- Time to Peak [min]
- Steady Burning Phase [min.]
- Decay Time [min.]
- Cable Tray HRRPUA [kW/m^2]
- Cable Tray Initial Burning Length [m]
- Manual Suppression Time [min.]
- Smoke Detector Failure
- Room Ambient Temperature [°C]
- **EPISTEMIC**
- Manual Suppression Rate [min.$^{-1}$]
- Smoke Detector Unavailability
- Flame Spread Angle
- Error in Dist. to Closest Target [m]
- Error in Dist. to Closest Combustible [m]
- Error in Fire Elevation [m]
- Vent. Opening Height [m]
- Vent. Opening Area [m^2]
- Convective HRR Fraction
- Fire Diameter [m]
- Fire Elevation [m]
- Model Uncertainty HGL Temp.
- Model Uncertainty Plume Temp.
- Model Uncertainty Radiant Heat
- Damaging Temperature (TP) [°C]
- Damaging Temperature (TS) [°C]
- TP Burning Rate [m/min]
- TS Burning Rate [m/min]

Fire Damage States Uncertainty Calculation

- **Single Loop (1D) Monte Carlo Fire Model**
  - All uncertainties treated equally
  - Produces point estimate
- **Double loop (2D) Monte Carlo Fire Model**
  - Aleatory Parameters are sampled in the inner loop
  - Epistemic Parameters are sampled in the outer loop
  - Every inner loop is processed like a single loop Monte Carlo Fire Model
  - The results from the inner loop FDS probabilities are accumulated and processed at the end of the outer loop simulation resulting in a probability distribution for each FDS

FPRA Uncertainty Analysis
Two Loop Monte Carlo



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Control parameter1: inner loop samples = N_inner
Control parameter 2: outer loop samples = N_outer

SET outer_loop_counter = 0

A: SELECT a value for each outer loop parameter
from its probability distribution.

SET inner_loop_counter = 0

B: SELECT a value for each inner loop parameter
from its probability distribution

Calculate Fire Model

Categorize and store result (targets damaged)

Increment inner_loop_counter
IF inner_loop_counter < N_inner THEN GOTO B

Based on numbers of times each possible combination of
targets damaged occurs generate and store Fire Damage State
probabilities

Increment outer_loop_counter

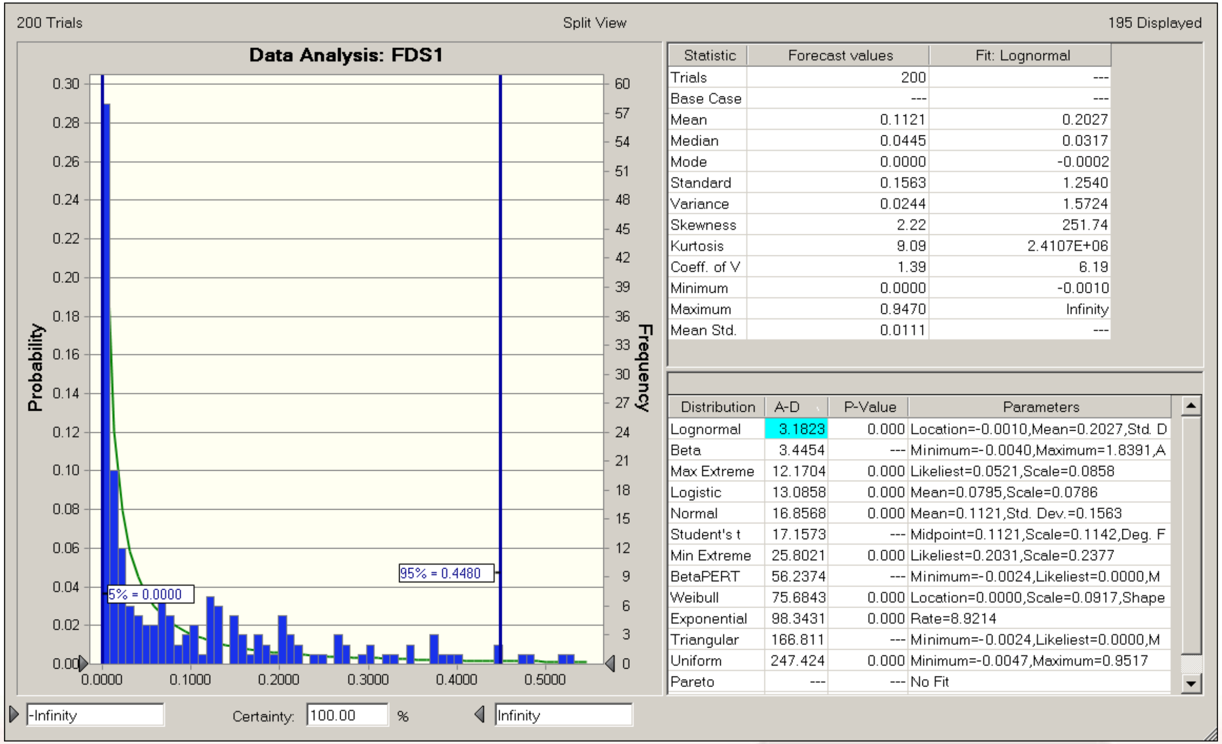
IF outer_loop_counter EQUALS N_outer THEN END

GOTO A
```

Monte Carlo Model 1D Simulation
Mean Value vs Point Estimate

Fire Damage State	**Case 0.1:** **Base Case Calculated FIDS Probabilities**	**Case 0.2:** **Monte Carlo Model Validation**	**Case 1: Fixed Epistemic/ Varying Aleatory Parameters**	**Case 2: Varying all Uncertainty Parameters /Fixed Fire Elevation**	**Case 3: Varying all Uncertainty Parameters**	**Case 4: Varying Uncertainty Parameters /FEAHRR**
FDS0	0.301	0.286	0.582	0.473	0.829	0.952
FDS1	0.406	0.416	0.273	0.344	0.108	0.028
FDS2/5	0.073	0.084	0.066	0.044	0.017	0.005
FDS3/6	0.089	0.102	0.032	0.059	0.016	0.006
FDS4	0.130	0.113	0.047	0.080	0.031	0.008
Total	1.0	1.0	1.0	1.0	1.0	1.0

Example of the FDS Probability Distribution Results



200 Trials

Split View

195 Displayed

Statistic	Forecast values	Fit: Lognormal
Trials	200	---
Base Case	---	---
Mean	0.1121	0.2027
Median	0.0445	0.0317
Mode	0.0000	-0.0002
Standard	0.1563	1.2540
Variance	0.0244	1.5724
Skewness	2.22	251.74
Kurtosis	9.09	2.4107E+06
Coeff. of V	1.39	6.19
Minimum	0.0000	-0.0010
Maximum	0.9470	Infinity
Mean Std.	0.0111	---

Distribution	A-D	P-Value	Parameters
Lognormal	3.1823	0.000	Location=-0.0010,Mean=0.2027,Std. D
Beta	3.4454	---	Minimum=-0.0040,Maximum=1.8391,A
Max Extreme	12.1704	0.000	Likeliest=0.0521,Scale=0.0858
Logistic	13.0858	0.000	Mean=0.0795,Scale=0.0786
Normal	16.8568	0.000	Mean=0.1121,Std. Dev.=0.1563
Student's t	17.1573	---	Midpoint=0.1121,Scale=0.1142,Deg. F
Min Extreme	25.8021	0.000	Likeliest=0.2031,Scale=0.2377
BetaPERT	56.2374	---	Minimum=-0.0024,Likeliest=0.0000,M
Weibull	75.6843	0.000	Location=0.0000,Scale=0.0917,Shape
Exponential	98.3431	0.000	Rate=8.9214
Triangular	166.811	---	Minimum=-0.0024,Likeliest=0.0000,M
Uniform	247.424	0.000	Minimum=-0.0047,Maximum=0.9517
Pareto	---	---	No Fit

-Infinity

Certainty: 100.00 %

Infinity

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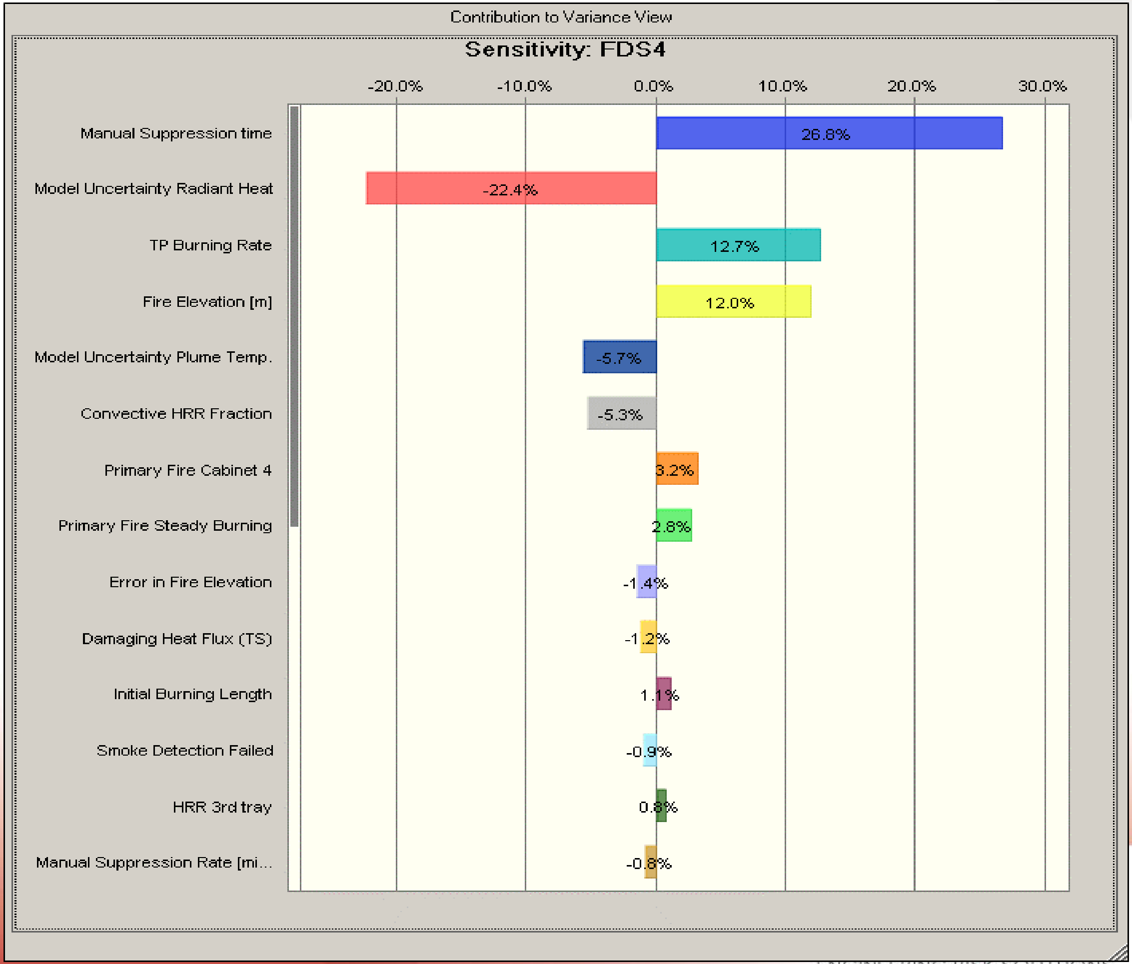
Ranking Importance of Uncertainties

- Pearsons’ product moment correlation
  - Preferred measure of uncertainty importance
  - When multiplied by itself is referred to as the contribution to variance
  - When multiplied by 100 provides a measure of the percentage of the variance in an output variable that can be explained by the variance of the input variable.
  - Related to the Fussell-Vesely importance measure, but additionally takes account of the ratio between the widths (standard deviations) of input and output uncertainty distributions.
  - Tornado charts are a way to present uncertainties ranked by their importance, based on the contribution to variance
    - Shows positive or negative effects

Ranking Importance of Uncertainties (Cont.)

Example of Tornado Chart



Ranking Importance of Uncertainties

- For a particular case in question, principal Contributions to Variance across all fire damage states were:
  - Ignition Source PHRR (Aleatory)
  - Plume Temperature Model Uncertainty (Epistemic)
  - Radiant Heat Model Uncertainty (Epistemic)
  - Fire Elevation (Epistemic)
  - Manual Suppression Time (Aleatory)
  - Ventilation Rate/ Area (Epistemic)

– Insights may be used to suggest where further effort may be used to refine/confirm the validity of certain assumptions as well as where to focus plant improvements to reduce uncertainties

Final Remarks

- NUREG 6850 Appendix L
    - Complex geometries can be evaluated
    - Simplistic axi-symmetric plume model can be replaced
    - Can address variability of SF* PNS according to specific target set locations within MCB
    - Can address MCB internal barriers accounting for dependencies
- FPRA Uncertainty Analysis
    - Monte Carlo Approach offers significant benefits
        - Best estimate results
        - Insights
    - Resource commitment is high
    - Possibility of developing a library of cases to cover a wide range of typical scenarios

- Further information http://www2.jacobsen-analytics.com/

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