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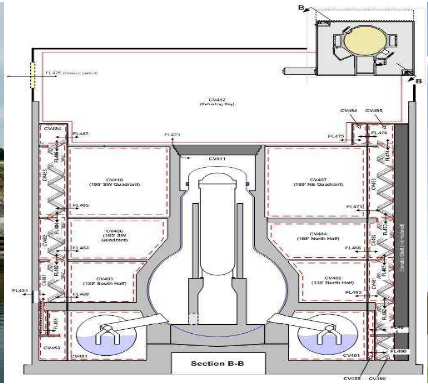

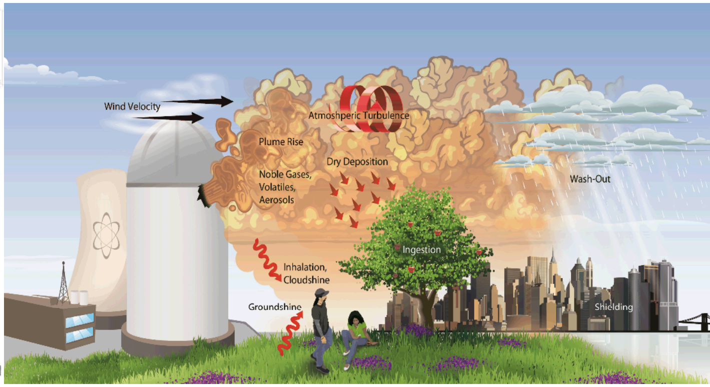

SOARCA project uncertainty Analysis

Application of techniques to SOARCA

Presented by C. Sallaberry (6224)

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Overview of first part

- Background
- Uncertainty characterization for Peach Bottom SOARCA-UA
- UA for Peach Bottom SOARCA-UA
- SA for Peach Bottom SOARCA-UA

Peach Bottom 10 and 20 mile analysis areas

SOARCA Uncertainty Analysis Objectives

1. Identify the uncertainty in the input and parameters used in the SOARCA deterministic “best estimate,” and

2. Develop insight into the overall sensitivity of the SOARCA results to uncertainty in key modeling inputs
   - Assess key MELCOR and MACCS2 modeling uncertainties in an integrated fashion to quantify of the relative importance of each uncertain input on the potential consequences

SOARCA Uncertainty Analysis description

- Focus is on epistemic (state-of-knowledge) uncertainty in input parameter values
  - Model uncertainty addressed to the extent that some parameters represent or capture alternate model effects or in separate sensitivity analyses
  - Aleatory (random) uncertainty due to weather is handled in the same way as the SOARCA study
- Peach Bottom unmitigated, long-term station blackout scenario selected
- Scenario definition not changed after Fukushima
  - A separate qualitative discussion was included in an appendix
- Looking at uncertainty in key model inputs
  - MELCOR parameters
  - MACCS2 parameters

Determination of outputs and inputs

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Determination of Metrics (SOARCA)

- Analysis of source term releases including Cesium and Iodine release over time
- Latent cancer fatality risk and prompt fatality risk using LNT dose-response model

Key uncertain input parameters were identified

- Description of most influential uncertain parameters in study
- Guidance solicited from peer reviewers on chosen parameters and distributions; feedback from Advisory Committee on Reactor Safeguards

Probability distribution construction

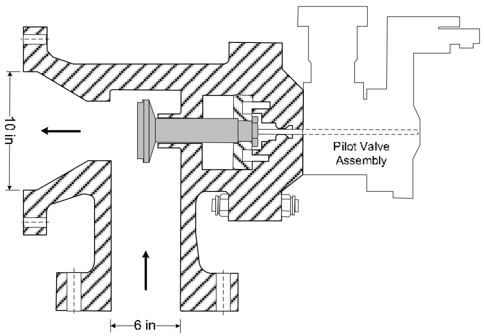
- Core team of staff from SNL and NRC with expertise in probability and statistics, uncertainty analysis, and MELCOR and MACCS2 modeling for SOARCA
- Subject matter experts (SMEs) provided support in reviews of data and parameters
- Focus on confirming that the parameter representations appropriately reflect key sources of uncertainty, are reasonable, and have a defensible technical basis
- Attempt to obtain contribution from uncertainty across the spectrum of phenomena operative in the analyses, through a balanced depth and breadth of coverage
- **Different approach has been developed and used for Surry SOARCA-UA**

SOARCA Uncertainty Inputs

MELCOR	MACCS2
Epistemic Uncertainty (21 variables)	**Epistemic Uncertainty (350 variables)**
Sequence Issues	**Deposition**
SRV stochastic failure to reclose (SRVLAM)	Wet deposition model (CWASH1)
Battery Duration (BATTDUR)	Dry deposition velocities (VEDPOS)
In-Vessel Accident Progression Parameters	**Shielding Factors**
Zircaloy melt breakout temperature (SC1131(2))	Shielding factors (CSFACT, GSFAC, PROTIN)
Molten clad drainage rate (SC1141(2))	**Early Health Effects**
SRV thermal seizure criterion (SRVFAILT)	Early health effects (EFFACA, EFFACB, EFFTHR)
SRV open area fraction (SRVOAFRAC)	**Latent health effects**
Main Steam line creep rupture area fraction (SLCRFRAC)	Groundshine (GSHFAC)
Fuel failure criterion (FFC)	Dose and dose rate effectiveness factor (DDREFA)
Radial debris relocation time constants (RDMTC, RDSTC)	Mortality risk coefficient (CFRISK)
Ex-Vessel Accident Progression Parameters	Inhalation dose coefficients (radionuclide specific)
Debris lateral relocation – cavity spillover and spreading rate (DHEADSOL, DHEADLIQ)	**Dispersion Parameters**
Containment Behavior Parameters	Crosswind dispersion coefficients (CYSIGA)
Drywell liner failure flow area (FL904A)	Vertical dispersion coefficients (CZSIGA)
Hydrogen ignition criteria (H2IGNC)	**Relocation Parameters**
Railroad door open fraction (RRIDRFAC, RRODRFAC)	Hotspot relocation (DOSHOT, TIMHOT)
Drywell head flange leakage (K, E, δ)	Normal relocation (DOSNRM, TIMNRM)
Chemical Forms of Iodine and Cesium	**Evacuation Parameters**
Iodine and Cesium fraction (CHEMFORM)	Evacuation delay (DLTEVA)
Aerosol Deposition	Evacuation speed (ESPEED)
Particle Density (RHONOM)	**Aleatory Uncertainty (984 weather trials)**
865 MELCOR source terms developed	Weather Trials

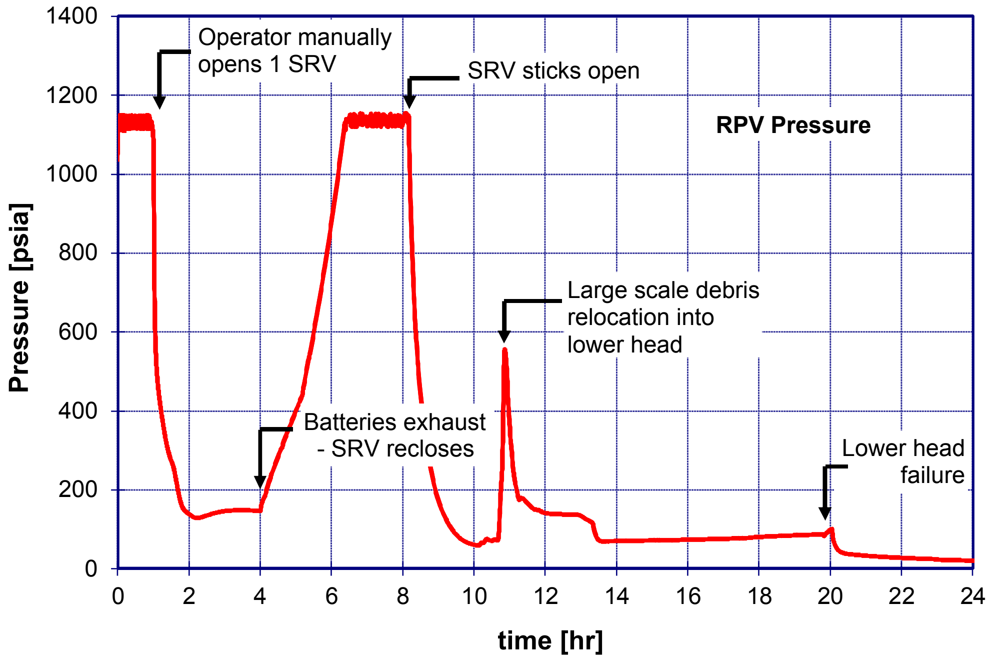
Distribution Construction examples (MELCOR)

1 - BWR SRV Seizure Modeling



Modes of Valve Seizure

- Excessive cycling
- Differential thermal expansion
- Material deformation



In severe accident conditions, high temperature gases well exceed design conditions:

T_{op} ~ 600K

T_{SA} > 800 to 1100K

cycles for hours

Seizure in stuck open eventually occurs:

excessive cycling

thermal deformation

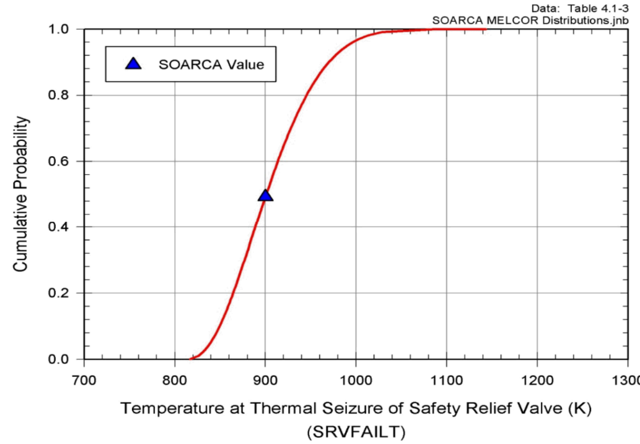
partial or full open

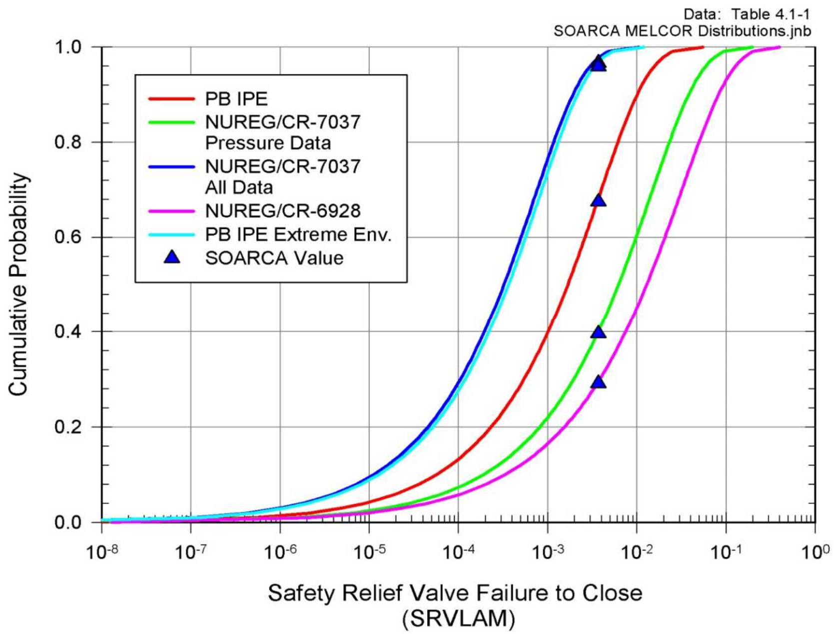
Valve behavior important to accident progression

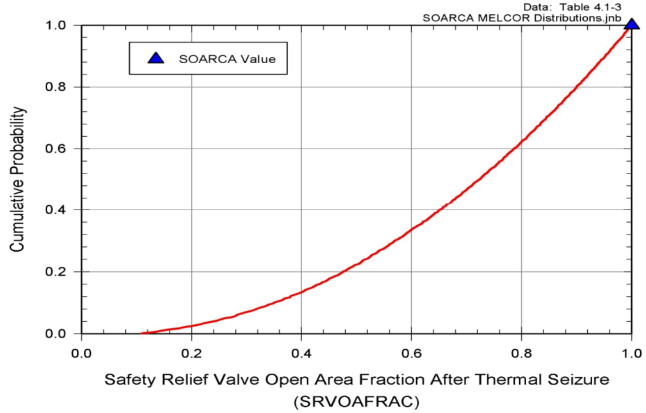
Distribution Construction examples (MELCOR)

2 – SRV Failure

- SRV stochastic failure to reclose (SRVLAM)
  - Beta distribution was fit for the mean value from the Peach Bottom IPE (the SOARCA value) using the methodology in NUREG/CR-7037
- SRV thermal seizure criterion (SRVFAILT)
- SRV open area fraction (SRVOAFRAC)



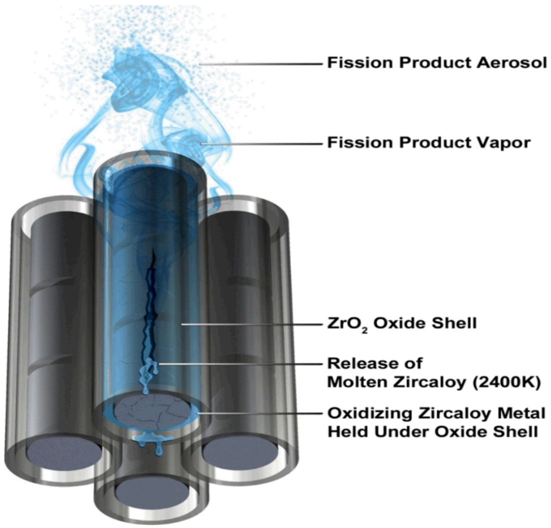


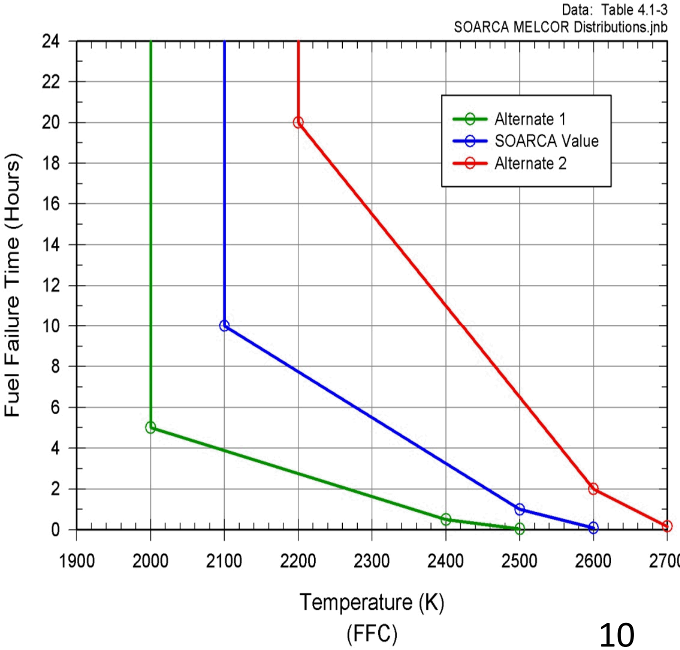


Distribution Construction examples (MELCOR)

3 –Fuel Failure Criterion

- MELCOR lacks a deterministic model for evaluating fuel mechanical response to the effects of clad oxidation, material interactions (i.e., eutectic formation), zircaloy melting, fuel swelling and other processes that occur at very high temperatures
  - In lieu of detailed models in these areas a simple temperature-based criterion is used to define the threshold beyond which normal ("intact") fuel rod geometry can no longer be maintained, and the core materials at a particular location collapse into particulate debris
- Time-at-temperature criterion
  - The time endurance of the upright, cylindrical configuration of fuel rod bundles which decreases with increasing temperature
  - Alternative one is derived from the best estimate by reducing its temperatures by 100 K and dividing its time intervals by two
  - Alternative two is derived from the best estimate by increasing its temperatures by 100 K and multiplying its time intervals by two





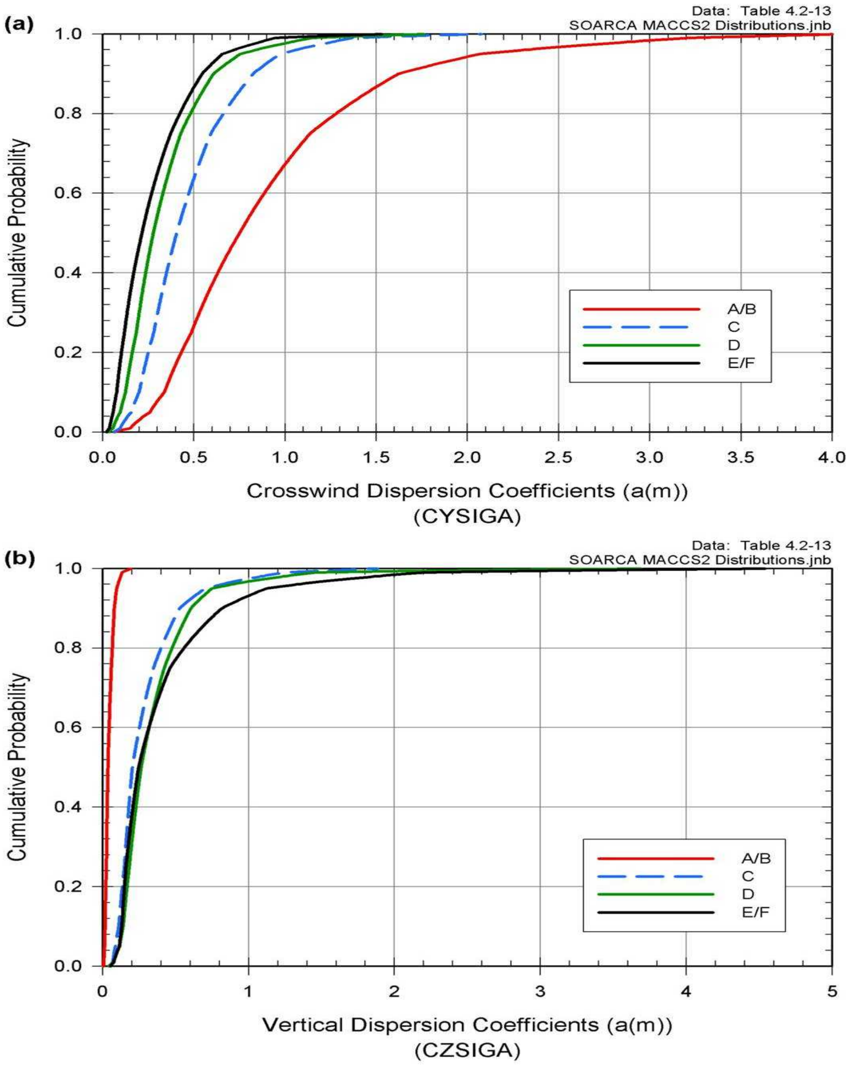
Distribution Construction examples (MELCOR)
3 –*CHEMFORM*

Chemical Forms of Iodine and Cesium

- Iodine and Cesium fraction (CHEMFORM)

Parameter			Distribution		
CHEMFORM **Five alternative combinations of RN classes 2, 4, 16, and 17** **($CsOH$, I_2, CsI, and Cs_2MoO_4)**			Discrete distribution		
			Combination #1 = 0.125		
			Combination #2 = 0.125		
			Combination #3 = 0.125		
			Combination #4 = 0.125		
			Combination #5 = 0.500		
Five Alternatives			**Species (MELCOR RN Class)**		
		CsOH (2)	**I_2 (4)**	**CsI (16)**	**Cs_2MO_4 (17)**
Combination #1	fraction iodine	--	0.03	0.97	--
	fraction cesium	1	--	--	0
Combination #2	fraction iodine	--	0.002	0.998	
	fraction cesium	0.5	--	--	0.5
Combination #3	fraction iodine	--	0.00298	0.99702	--
	fraction cesium	0	--	--	1
Combination #4	fraction iodine	--	0.0757	0.9243	--
	fraction cesium	0.5	--	--	0.5
Combination #5	fraction iodine	--	0.0277	0.9723	--
	fraction cesium	0	--	--	1
Best estimate	Fraction iodine	--	0.0	1.0	--
	Fraction cesium	0.0	--	--	1.0

Distribution Construction examples (MACCS2)
1 –Dispersion Parameters



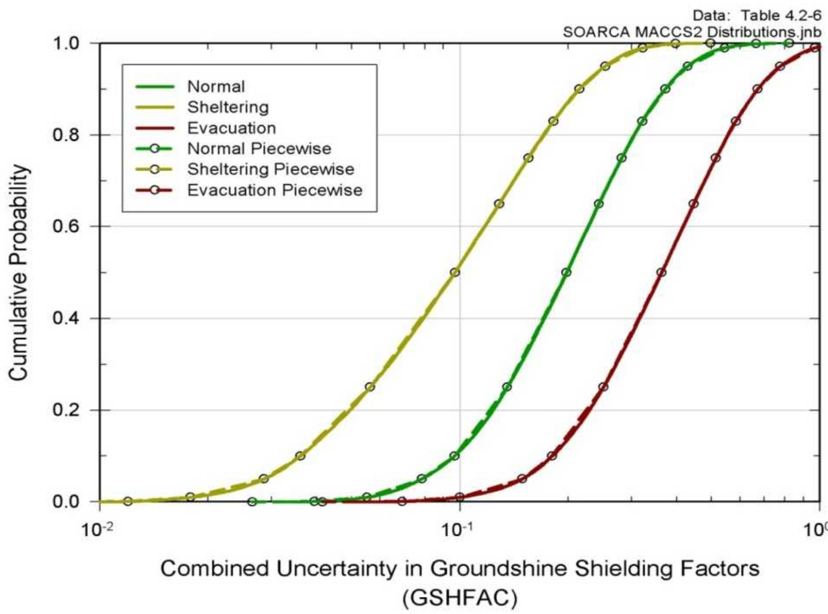
Dispersion Parameters:

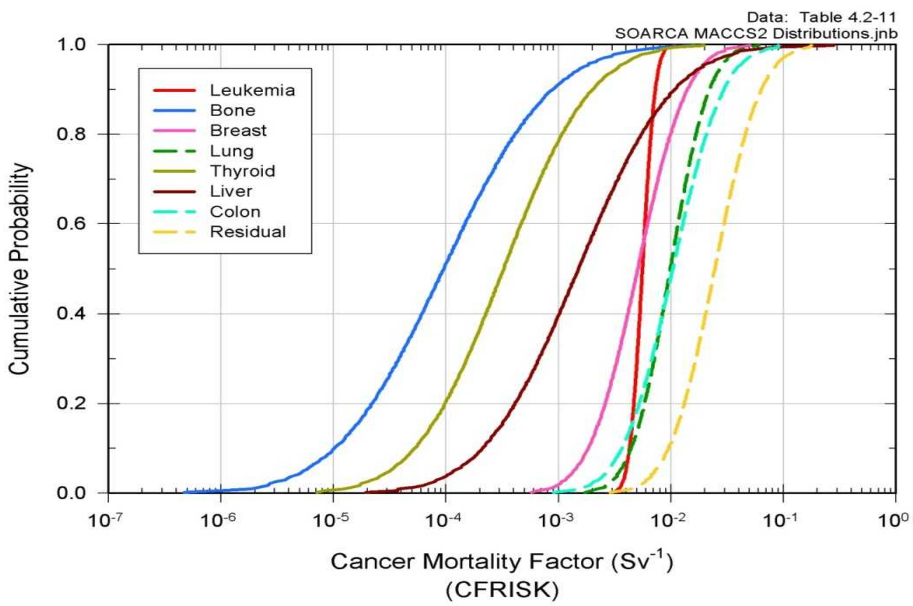
- Linear, crosswind dispersion coefficients (CYSIGA)
- Linear, vertical dispersion coefficients (CZSIGA)
- Parameter Correlation

Distribution Construction examples (MACCS2)
2 –Latent Health Effects

Latent health effects:

- Groundshine (GSHFAC)
- Dose and dose rate effectiveness factor (DDREFA)
- Mortality risk coefficient (CFRISK)
- Inhalation dose coefficients





Generation of input sample and uncertainty propagation

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- Uncertainty in inputs parameters propagated in two steps:
  - A set of source terms generated using MELCOR model using **3** Simple Random Sampling of original size 300.
  - A distribution of consequence results generated using MACCS2 model via LHS sample of size matching the number of converged runs from MELCOR. Finally another LHS run of size matching the sum of the MELCOR converging results has been created for a more accurate distribution of consequence results.
- Simple Random Sampling was preferred to LHS for MELCOR results for two reasons
  - having a valid sample when non converged results are not included
  - having the possibility to increase the sample size if the statistics where unstable.

Uncertainty Analysis

MELCOR RESULTS

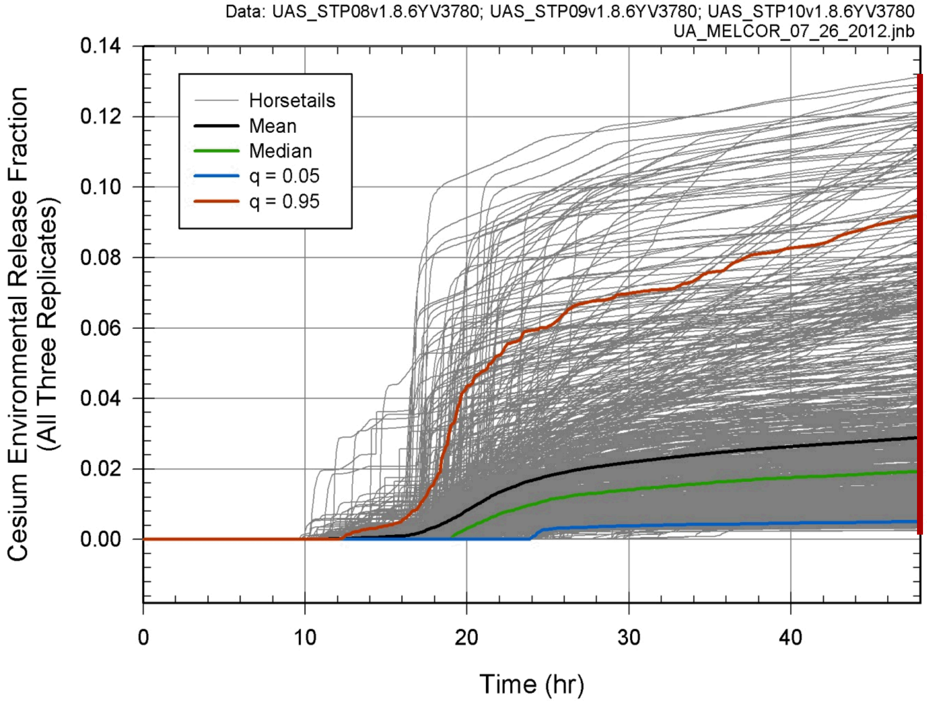
- Representation of Horsetail for MELCOR output (including statistics such as mean and selected quantiles).
- Selection of representative time (48H) to plot CDF of results, including confidence interval over statistics to inform about (statistical) stability of the technique
- Examples follow for Cesium and Iodine releases as well as hydrogen production

MACCS2 RESULTS

- Representation of CCDF of risk (latent cancer fatality or prompt fatality) at different radius level.
- Mean and quantiles for different replicates added to inform about (statistical) stability of the technique
- Examples follow for Prompt fatality

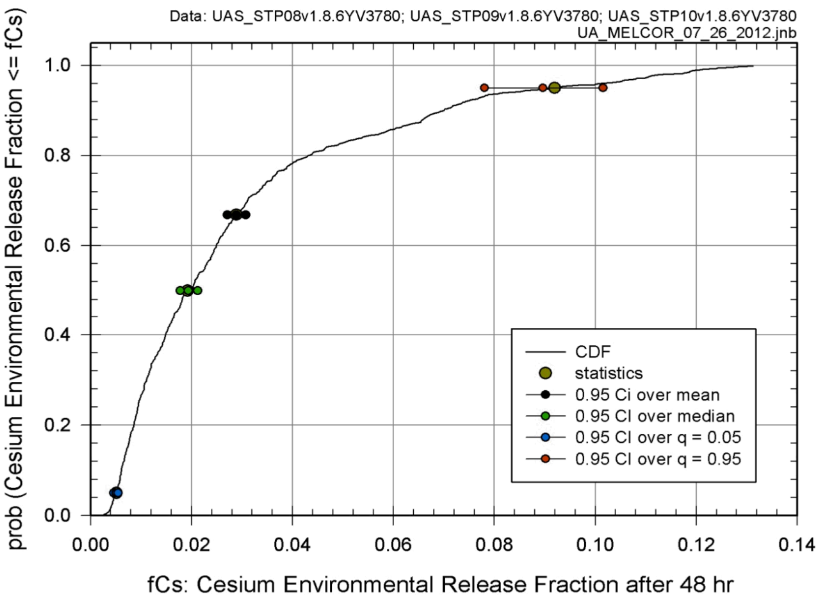
Uncertainty Analysis for MELCOR Results

1. Cesium release fraction



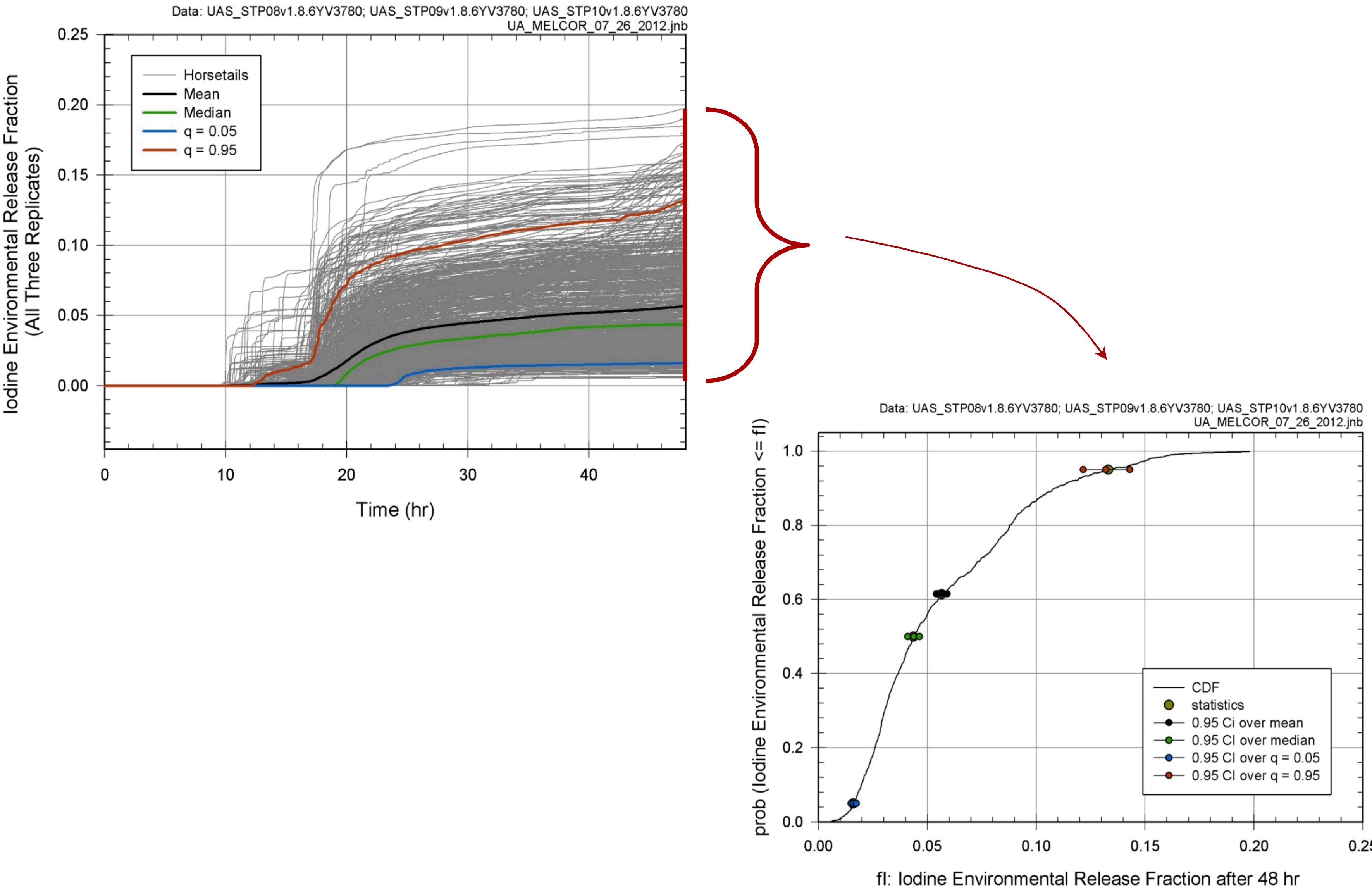
Time-dependent horsetails for 800 realizations with selected statistics superimposed

CDF representation at selected time with confidence interval over statistics (using bootstrap)



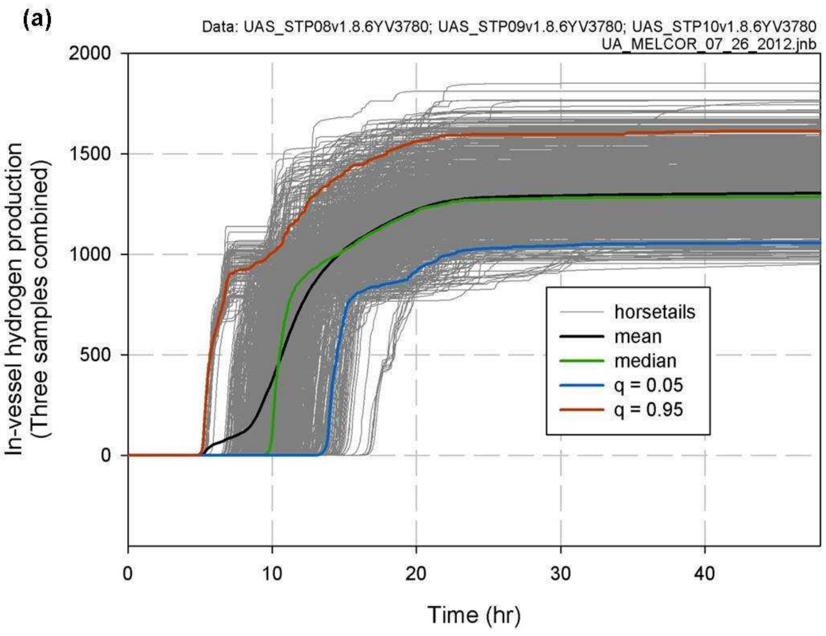
Uncertainty Analysis for MELCOR Results

1. Iodine release fraction

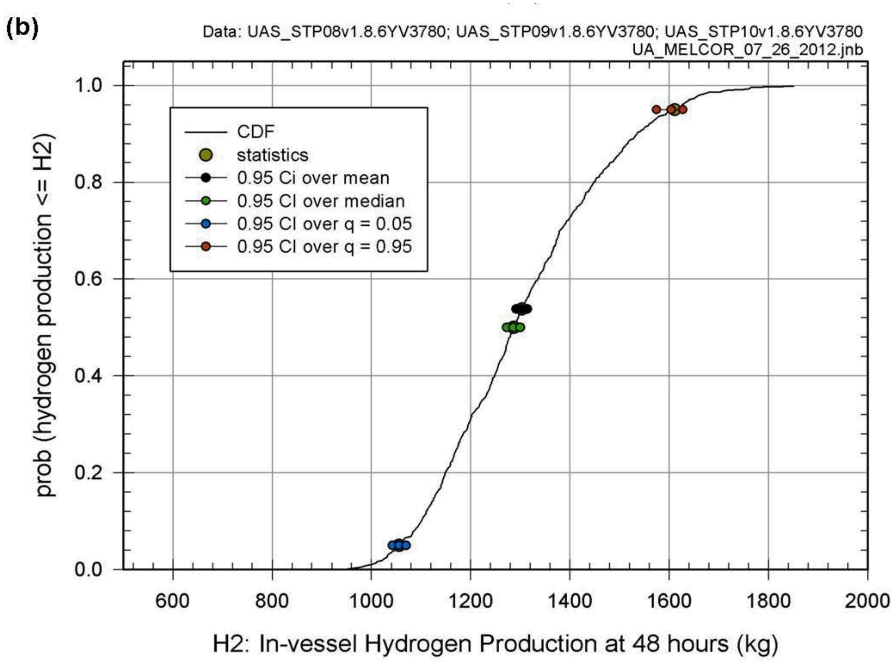


Uncertainty Analysis for MELCOR Results

3. Hydrogen production



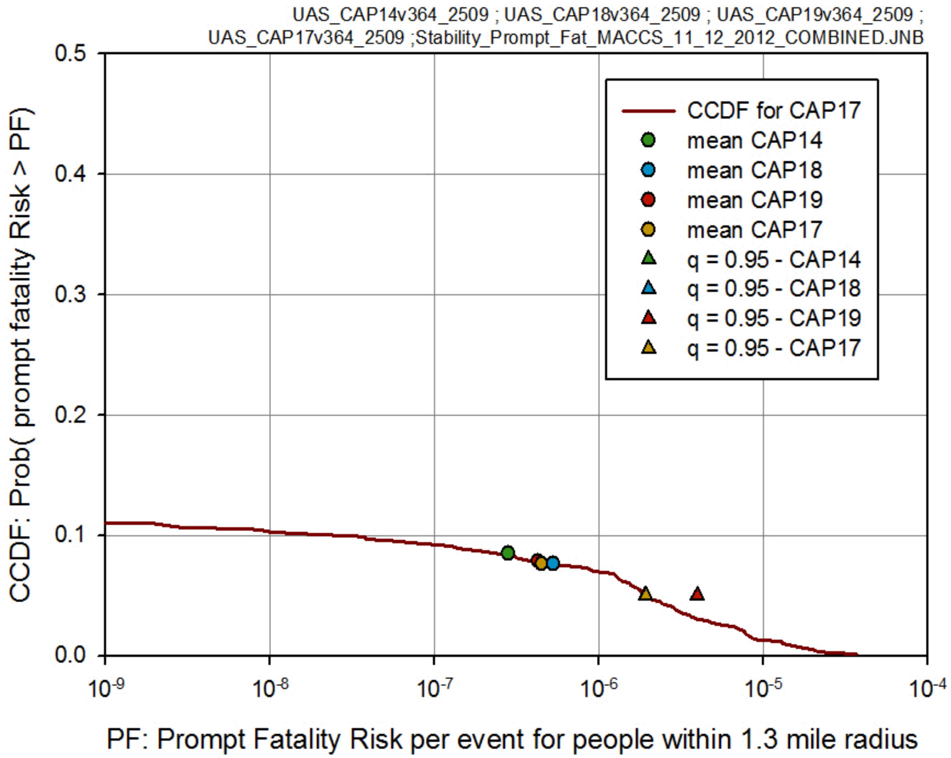
Time-dependent fraction of in-vessel hydrogen production over 48 hours based on combined (i.e., 865) results, with the mean, median and quantiles *q* = 0.05 and *q* = 0.95



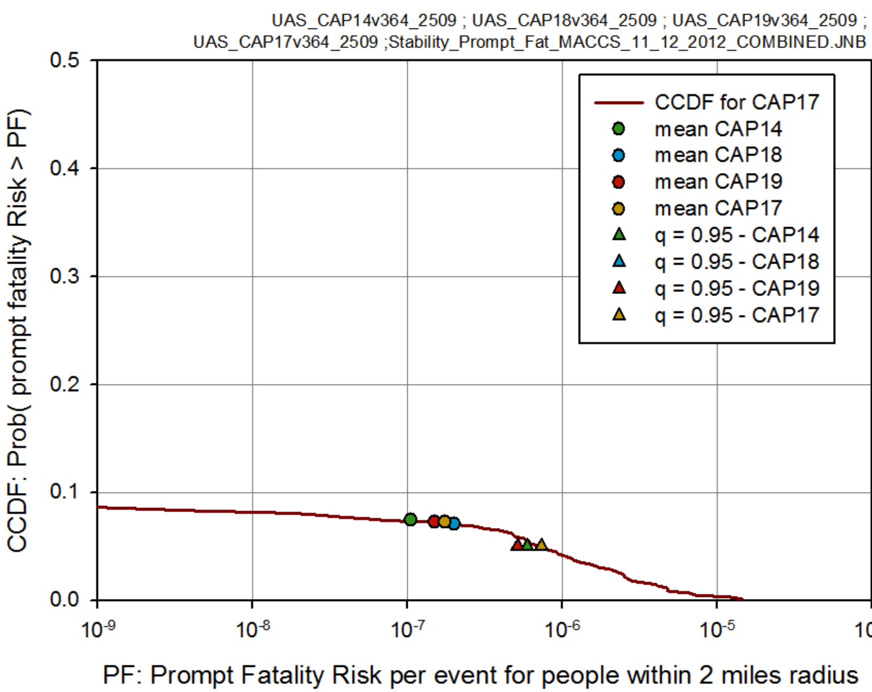
Cumulative distribution function of in-vessel hydrogen production at 48 hours, with 95% confidence interval over mean, median and quantiles *q* = 0.05 and *q* = 0.95

Uncertainty Analysis for MACCS2 Results

Prompt fatality CCDF



Note: Bootstrap technique not used for Confidence Intervals because LHS technique used in generating sample



Sensitivity Analysis Techniques (1/4)

- **Stepwise Regression**
  - Stepwise linear regression is performed on the rank of the values
  - Informs on the monotonic influence of the input parameter towards the output in consideration
  - **Advantage:** Reduces the impact of outliers since it is non parametric
  - **Limitations:** Does not capture non monotonic influence and it is additive so it captures only the influence of each parameter separately and not conjoint influence
  - Three measures are reported:
    - **Standardized Rank Regression Coefficient (SRRC):** Informs of the strength of the monotonic relation and varies between -1.0 (perfect negative relation) and 1.0 (perfect positive relation). The sign indicates whether the input parameter has a “positive” (i.e., high values of the input data lead to high values of the output) or “negative” (i.e., low values of the input data lead to high values of the output) influence
    - **Total R^2 :** Amount of variance explained by the regression model up to the variable in consideration. This value varies between 0 and 1. The closer is the total R^2 to 1, the better is the regression (the more of the variance of the output is explained)
    - **R^2 cont.:** Contribution of the particular variable into the regression model for the output of interest. The higher R^2 cont. is, the more influential the input

Sensitivity Analysis Techniques (2/4)

- **Non monotonic/non additive methods**
  - All other methods used capture non monotonic and conjoint influence
  - Methods first fit a regression model and estimates the quality of the regression (final R^2). The regression model is then use to generate a large number of runs and estimate the importance of the input data on the output of interest via a Sobol variance decomposition
  - Each method has different strengths and weaknesses, justifying the use of all of them, so they can complement each others
  - Three measures are then reported for each method:
    - ***S_i* (first order sensitivity index):** Contribution to the output variance of the input parameter *i* by itself
    - ***T_i* (total order sensitivity index):** Contribution to the output variance of the input parameter *i* and all its interaction. By definition it has to be at least equal to S_i (if no interaction occurs)
    - **p-value:** Estimates the probability for T_i to be equal to 0.0 (meaning that the input parameter has no influence at all, either by itself of conjointly). A p-value close to 0.0 indicates that it is unlikely (and therefore the parameter is likely to have some influence) while a p-value close to 1.0 indicates that there is good chances that this input has no influence at all

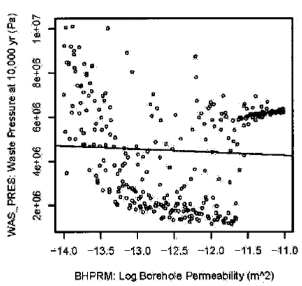
Sensitivity Analysis Techniques (3/4)

- Quadratic regression
  - A stepwise regression with all parameters (x_i), their square values (x_i^2) and any first order interaction ($x_i.x_j$)
  - **Advantages:** Captures some non-monotonic influence as long as they are close to quadratic, and also allows simple interaction for linear conjoint influence
  - **Limitations:** Method has difficulties finding more complex relation or conjoint influence, and this method is parametric and results can be affected by outliers
- Recursive partitioning
  - A decision tree is used to split the input data into area of influence. The method allow multiple splits and 2 parameters interactions. Order 0 polynomial response (i.e., constant) is generated in each defined region
  - **Advantage:** As for any decision tree analysis, the strong point of the method is to capture change in the output due to trigger points (if one variable is higher than a threshold and/or another variable is between two values) which could not be captured easily with other techniques
  - **Limitation:** The method may have a tendency to find relations where none exists, especially when the number of input variables is large compared to the sample size
- Multivariate adaptive regression splines (MARS)
  - This method is a combination of (linear) spline regression, stepwise model fitting and recursive partitioning
  - **Advantage:** The method leans towards the same flexibility as recursive partitioning with the robustness of rank regression in order to avoid over fitting
  - **Limitation:** Because of the use of spline, its efficiency is limited when used over discrete variables, especially if the number of discrete states is small (2 or 3 values). In such cases, it may completely miss the parameter's influence or underestimate it

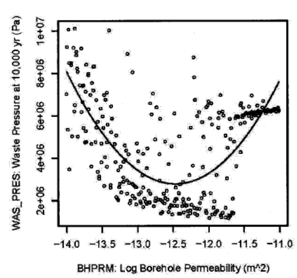
Sensitivity Analysis Techniques (4/4)

- A: stepwise rank regression will capture monotonic influence and may not be sufficient in case of more complex relationship between input and output. However, this method is usually enough 75% to 80% of the cases. The fact is that even in complex analyses, most of the input influences are monotonic.
- B: quadratic regression allows the capture of (simple) non monotonic influence and **conjoint influence** (in the sense of X1 × X2).
- C: Recursive partitioning (aka Tree regression) will split the input space according to the value of the output (high, medium, low …)
- D: splines (such as used in the MARS technique) will consider the influence of input parameters as piecewise, considering smoothness in the local area.

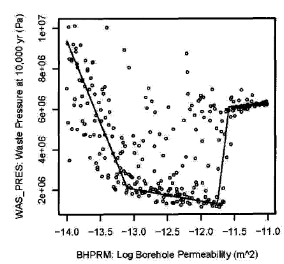
A



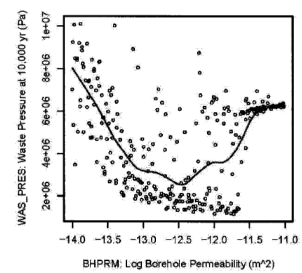
B



C



D



Sensitivity Analysis for MELCOR Results

1. Iodine release fraction after 48 hours

** Inputs are ranked according to the Rank Regression analysis and is not necessarily the order of importance in the uncertainty analysis*

Iodine Release at 48 hours	Rank Regression			Quadratic			Recursive Partitioning			MARS		
Final R^2	0.69			0.76			0.93			0.80		
Input name*	**R^2 inc.**	**R^2 cont.**	**SRRC**	**S_i**	**T_i**	**p-val**	**S_i**	**T_i**	**p-val**	**S_i**	**T_i**	**p-val**
SRVLAM	0.49	0.49	-0.72	0.46	0.68	0.00	0.55	0.78	0.00	0.64	0.70	0.00
CHEMFORM	0.58	0.09	0.30	0.10	0.16	0.00	0.07	0.22	0.00	0.09	0.12	0.00
FL904A	0.64	0.06	0.26	0.05	0.06	0.22	0.02	0.12	0.00	0.05	0.08	0.00
RRDOOR	0.67	0.03	0.28	0.01	0.06	0.03	0.04	0.07	0.00	---	---	---
SRVOAFRAC	0.69	0.02	-0.12	0.06	0.13	0.00	0.05	0.20	0.00	0.06	0.16	0.00
FFC	0.69	0.00	0.06	0.03	0.03	0.17	---	---	---	0.02	0.00	1.00

Example of (small) non monotonic influence not captured by Rank Regression

Example of conjoint influence not captured by additive regression

Sensitivity Analysis for MACCS2 Results

Prompt fatality

	Rank Regression			Quadratic			Recursive Partitioning			MARS		
Final R^2	0.24			0.61			0.60			0.60		
Input	R^2 inc.	R^2 cont.	SRRC	S_i	T_i	p-val	S_i	T_i	p-val	S_i	T_i	p-val
CYSIGA.1..	0.04	0.04	-0.11	0.00	0.03	0.56	0.00	0.00	1.00	0.05	0.17	0.14
EFFTHR.1..	0.08	0.04	-0.11	0.06	0.13	0.26	0.06	0.09	0.23	0.00	0.48	0.00
GSHFAC.2..	0.11	0.03	0.11	0.01	0.24	0.02	0.00	0.13	0.04	0.02	0.11	0.25
SRVLAMB	0.13	0.03	-0.09	0.00	0.30	0.00	0.12	0.36	0.00	0.01	0.26	0.02
CWASH1	0.16	0.03	0.08	0.00	0.86	0.00	0.26	0.91	0.00	0.13	0.34	0.14
SRVOAFRAC	0.18	0.02	-0.07	0.01	0.00	1.00	---	---	---	0.06	0.16	0.62
RRDOOR	0.19	0.01	0.10	0.00	0.00	1.00	---	---	---	0.01	0.32	0.00
PROTIN.2..	0.20	0.01	0.05	---	---	---	0.00	0.00	1.00	0.02	0.43	0.00
EFFTHR.2..	0.21	0.01	-0.05	---	---	---	0.00	0.30	0.00	0.02	0.00	1.00
CSFACT.3..	0.22	0.01	0.04	---	---	---	---	---	---	0.00	0.10	0.26
EIFACB.3..	0.22	0.01	-0.04	---	---	---	---	---	---	---	---	---
SC1131_2	0.23	0.01	0.03	---	---	---	0.03	0.15	0.05	0.00	0.20	0.03
DLTEVA.12..	0.23	0.01	-0.04	0.04	0.46	0.00	---	---	---	---	---	---
SRVFAILT	0.23	0.00	0.03	0.00	0.00	1.00	0.00	0.00	1.00	---	---	---
EITHRE.3..	0.24	0.00	-0.03	0.00	0.00	1.00	---	---	---	0.00	0.20	0.03
DLTEVA_5.2..	---	---	---	0.00	0.24	0.01	---	---	---	---	---	---
CSFACT.2..	---	---	---	0.00	0.27	0.09	0.00	0.48	0.00	0.02	0.02	0.56
PROTIN.3..	---	---	---	0.00	0.07	0.32	0.00	0.00	1.00	---	---	---
PROTIN.1..	---	---	---	0.01	0.00	1.00	---	---	---	0.01	0.00	1.00
VDEPOS.1..	---	---	---	0.00	0.00	1.00	0.04	0.09	0.07	---	---	---
DLTEVA_5.11..	---	---	---	---	---	---	0.02	0.00	1.00	---	---	---
EFFACB.1..	---	---	---	---	---	---	0.01	0.00	1.00	---	---	---
DLTEVA.13..	---	---	---	---	---	---	0.00	0.00	1.00	---	---	---
GSHFAC.3..	---	---	---	---	---	---	---	---	---	0.00	0.00	1.00
	---	---	---	---	---	---	---	---	---	---	---	---
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In this example, the conjoint influence of variable CWASH1 was completely missed by Rank Regression

CWASH1 has also non monotonic influence not captured by rank regression or quadratic

Inputs are ranked according to the Rank Regression analysis and is not necessarily the order of importance in the uncertainty analysis

Conclusion over the methodology used

- Classical sampling based method was appropriate to propagate epistemic uncertainty for the SOARCA-UA analysis
- The initial sample of size 300 was considered acceptable with respect to the stability of selected statistics on the output of interest
- The use of a family of regression techniques makes the analysis a little more complex than when a single stepwise regression technique is used however it seems a more appropriate strategy considering that:
  - Stepwise Linear regression has been shown to be insufficient for some analysis in which the input/output relation was not monotonic and additive
  - The other techniques look only at one aspect of non-monotonicity
  - The more sophisticated the technique is, the more likely it will overfit the data and find non physical relation due to the sample size
- For the same reason the use of replicated analyses (with different random seed) strengthened the confidence the analyst had on both the output distributions and resulting sensitivity analysis.

Perspective over next SOARCA-UA analysis

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- Keeping the same sampling-based approach with Simple Random Sampling technique for MELCOR analysis and LHS for MACCS2 analysis and use of replicated analyses
- Keeping the same approach of combining regression technique for a better understanding of the influence of uncertainty input toward uncertainty output
- Consider new regression techniques that could be more powerful (such as ACOSSO and Gaussian process)
- Extend sensitivity analysis to display influence of parameter as a function of time.