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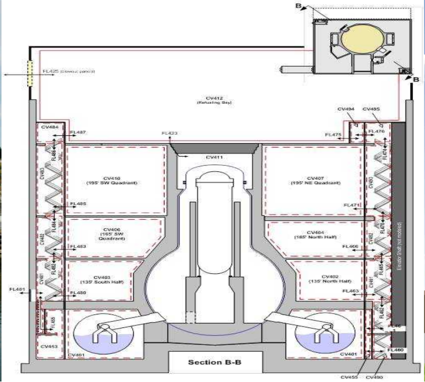

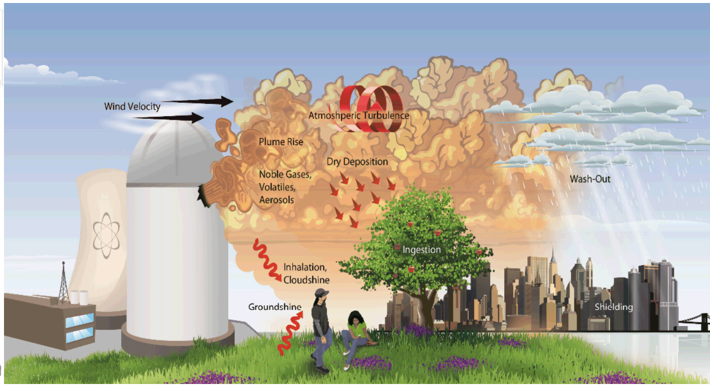

State-of-the-Art Reactor Consequence Analyses Project

Uncertainty Analysis of the Unmitigated Long-Term Station Blackout of the Peach Bottom Atomic Power Station

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Overview

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- Background
- Methodology
- Parameter Selection
- Source Term Analysis
- Environmental Consequence Analysis
- Sensitivity Analyses
- Conclusions

Peach Bottom 10 and 20 mile analysis areas

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Background

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

SOAR CA Uncertainty Analysis

- 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

Treatment of Uncertainty

The analysis of a complex system typically involves answering the following three questions about the system and one additional question about the analysis itself:

1. What can happen?
2. How likely is it to happen?
3. What are the consequences if it happens?
4. How much confidence exists in the answers to the first three questions?

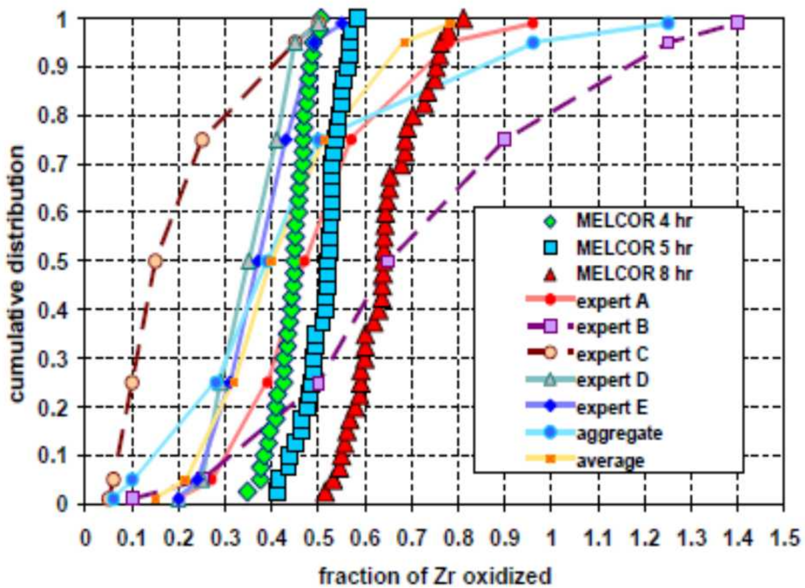
- The answers to questions one and two involve the characterization of aleatory uncertainty

- The answer to question three typically involves numerical modeling of the system conditional on specific realizations of aleatory and epistemic uncertainty
  - The posing and answering of questions one through three gives rise to what is often referred to as the Kaplan/Garrick ordered triple representation for risk

- The answer to question four involves the characterization and assessment of epistemic uncertainty, which is the objective of this analysis

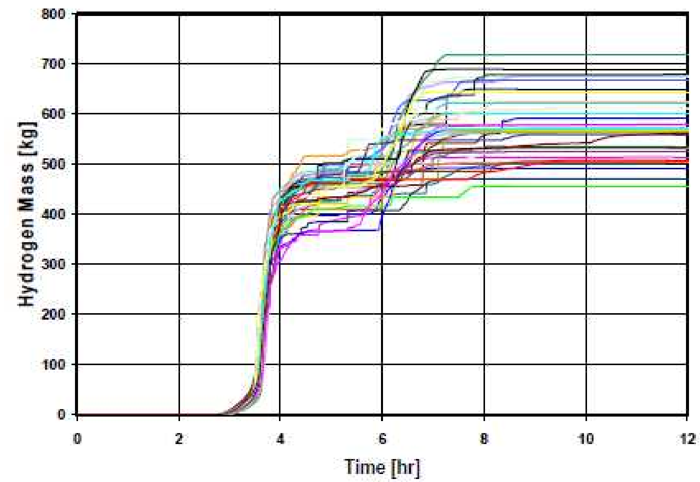
Deterministic versus Probabilistic

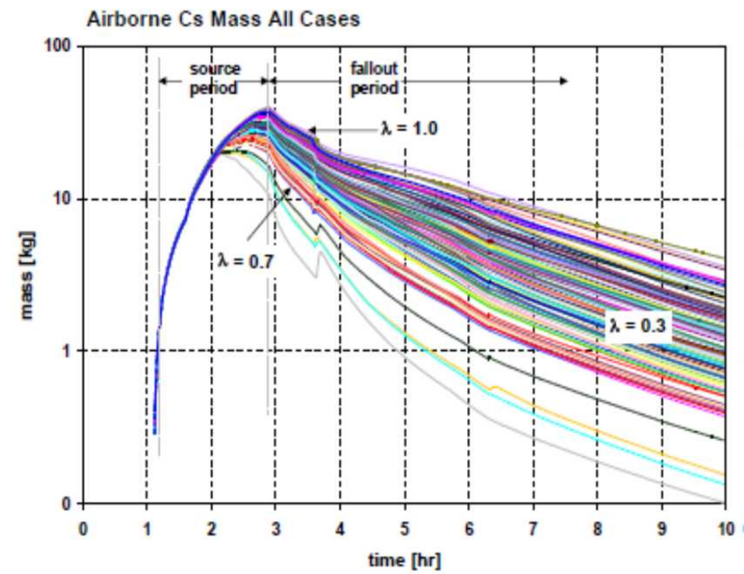
- Traditional safety analyses
  - Deterministic methods
  - ‘Conservative’ input assumptions
    - SRV setpoint drift
  - Produce defensible bounding analyses
  - Can be overly conservative
    - Excessive regulatory burden
- Expert elicitation
  - Only as good as experience of experts
- Objective Uncertainty Analysis
  - Quantification of uncertainty
  - Doesn’t combine unrealistically all worst case parameters
  - Characterizes safety margins
    - What is likely and expected vs. regulatory boundaries
    - Simple set of sensitivity cases or ‘one-offs’



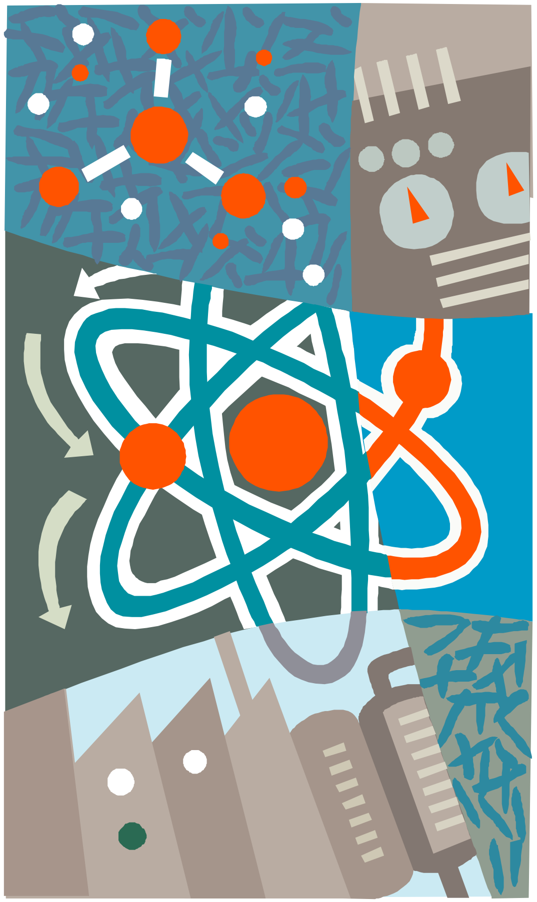
Applications of Uncertainty Analysis

- Hydrogen uncertainty analysis
  - Motivated by Hydrogen Rulemaking (10CFR50.44)
  - Provided estimate of range of in-vessel hydrogen expected from SBO
  - Specific focus: Requirements for backup power for hydrogen igniters
  - Issue for Ice Condenser and Mark III plants
- Containment Analysis
  - Examination of aerosol fallout behavior
  - Detailed RCS & Containment model of AP1000 3BE accident provided TH boundary conditions





Methodology

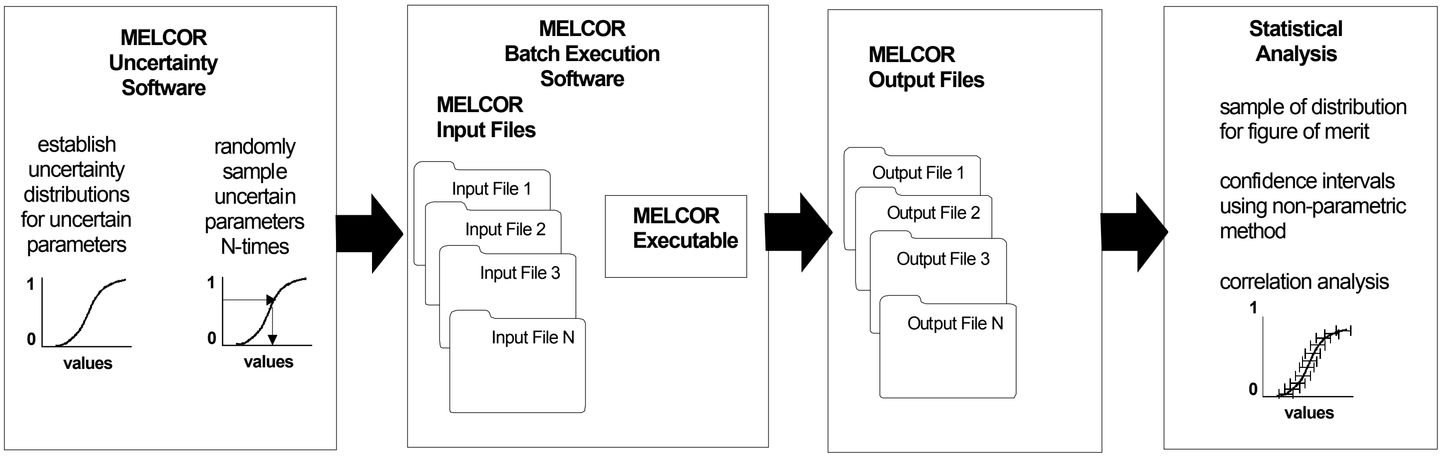


Uncertainty Analysis Methodology

- Method used follow classical sampling based method:
  1. Selection of uncertain parameters (definition of vector $\boldsymbol{x}$)
  2. Characterization of uncertainty in $\boldsymbol{x}$ (i.e., definition of $D_1,D_2,\ldots,D_{nX}$)
  3. Generation of sample from $\boldsymbol{x}$ (i.e., generation of $\boldsymbol{x}_k$, $k = 1,2,\ldots,nS$, in consistency with $D_1,D_2,\ldots,D_{nX}$)
  4. Selection of metrics or figures of merit from the output data ($\boldsymbol{y}$)
  5. Propagation of sample through analysis (i.e., generation of mapping $[\boldsymbol{x}_k, \boldsymbol{y}(\boldsymbol{x}_k)]$, $k = 1,2,\ldots,nS$)
  6. Presentation of uncertainty analysis results (i.e., approximations to the distributions of the elements of $\boldsymbol{y}$ obtained from $\boldsymbol{y}(\boldsymbol{x}_k)$, ($k = 1,2,\ldots,nS$)
  7. Determination of sensitivity analysis results (i.e., exploration of the mapping $[\boldsymbol{x}_k, \boldsymbol{y}(\boldsymbol{x}_k)]$, ($k = 1,2,\ldots,nS$)

- Alternate tools are available
  - DAKOTA – open-source toolkit developed at Sandia National Labs
    - Interfaces with SNAP & MELCOR
      - SNAP can be used to select input parameters, assign probability distributions, generate random variates and input files
    - Caution - little experience in using MELCOR/SNAP/DAKOTA

MELCOR Uncertainty Analysis Methodology



- Define uncertain parameter distributions
- MELCOR Uncertainty software samples distributions
- MELCOR Uncertainty software incorporates “n” sets of sampled parameters into “n” MELCOR input files

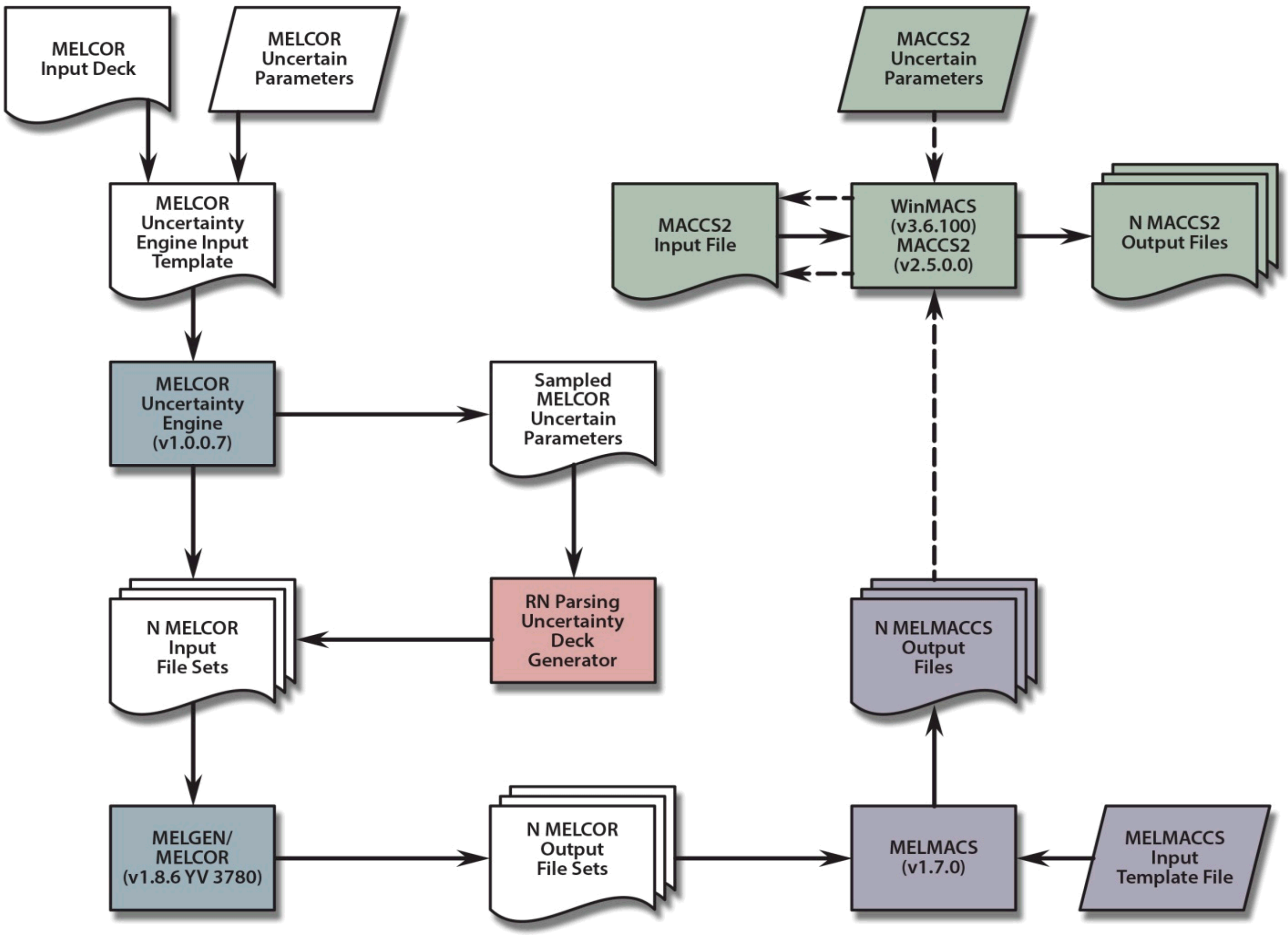
- Batch Execution software (DEF_Admin) runs “n” MELCOR input files on server system

- MELCOR output files are manually retrieved from server system

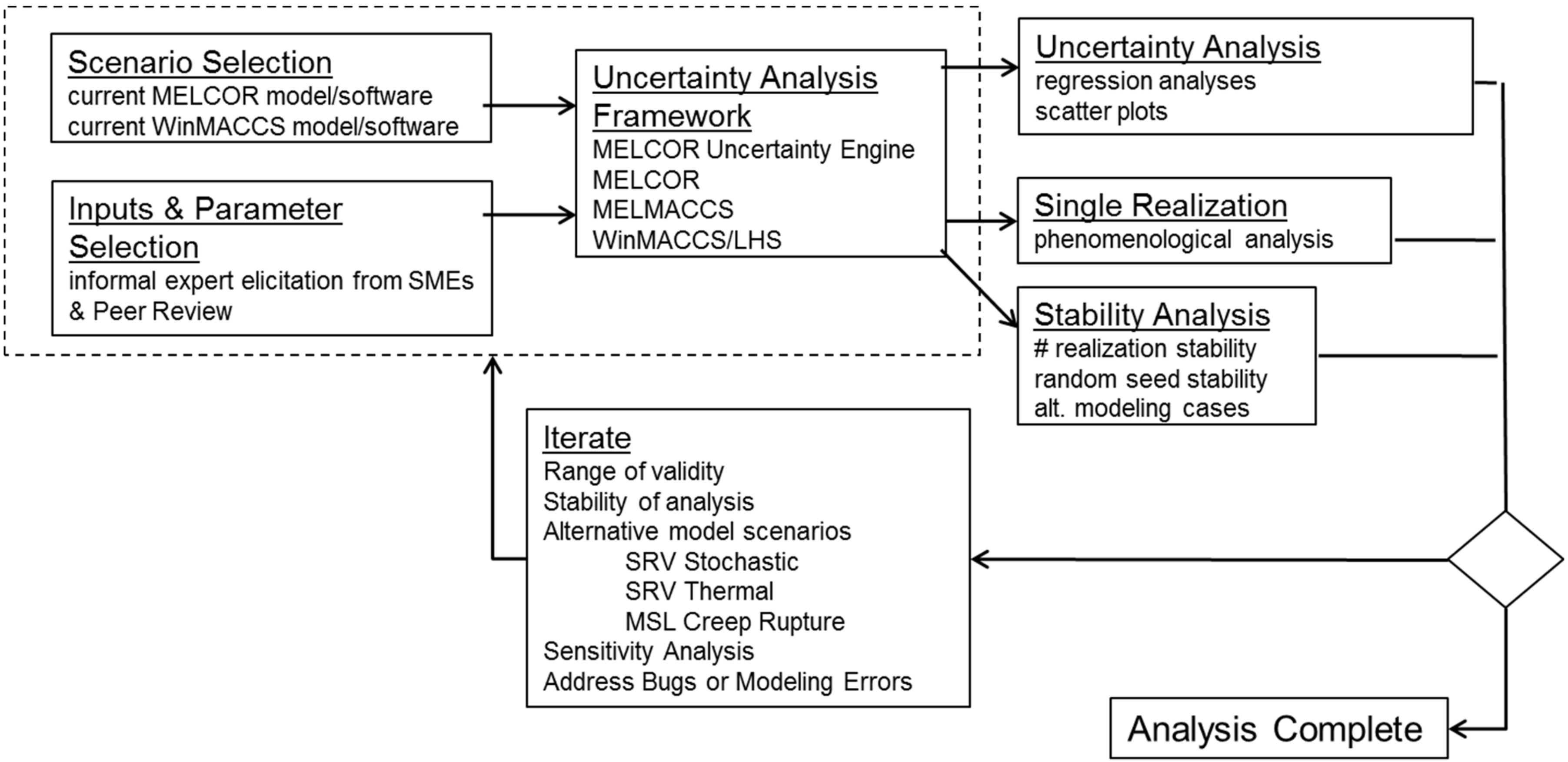
- MELCOR output files are post processed

SOARCA Uncertainty Analysis

Information Flow



Uncertainty Analysis is an Iterative Process

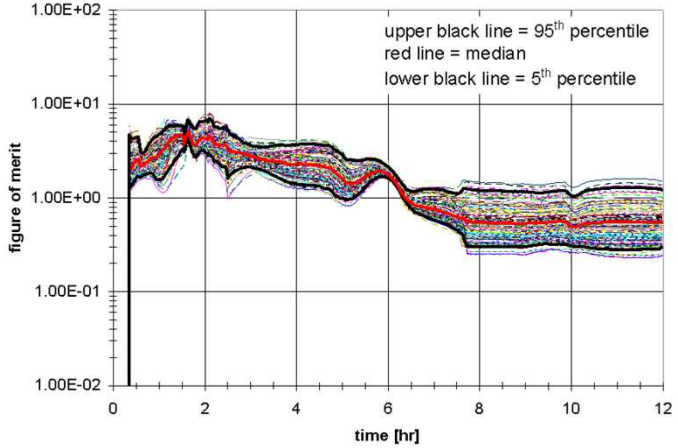


Uncertainty Analysis Post Processing

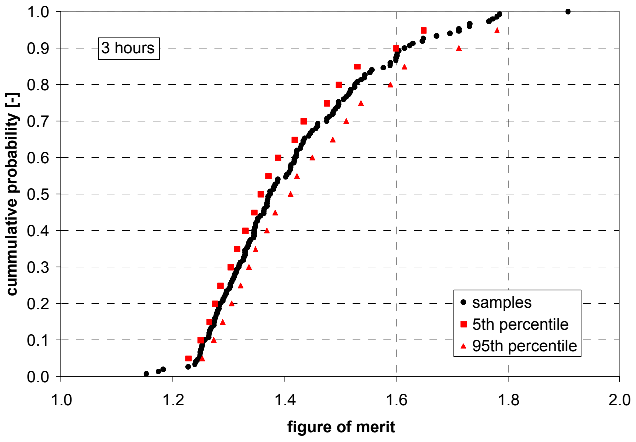
- Determination of Metrics (SOARCA)
  - Analysis of source term releases including Cesium and Iodine release over time
  - Latent cancer fatality risk and prompt fatality risk using LNT dose-response model
  - Description of most influential uncertain parameters in study

- Analysis of Output Metrics:
  - Statistical regression
  - plot of all realizations vs. time (horse-tail plot) including median, mean, 5th and 95th percentiles
  - CDFs (at selected times) and CCDFs with confidence bounds
  - Phenomenological investigation of individual realizations of interest

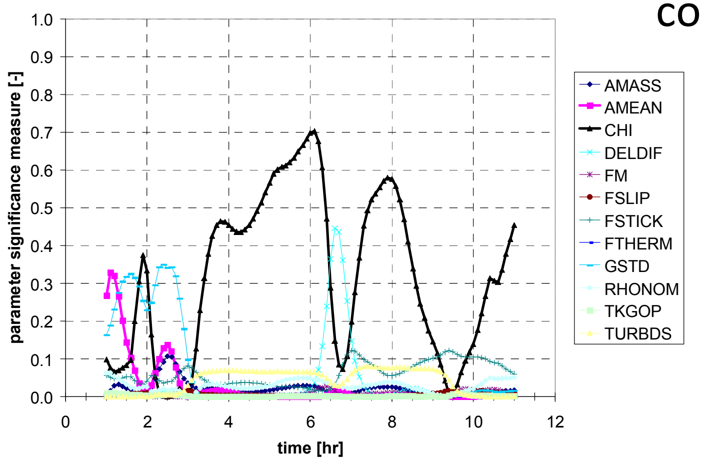
Uncertainty Analysis Post Processing *(continued)*



horse-tail plot with percentiles



CDF at a given time with confidence bounds



regression coefficients

Uncertainty Analysis Regression Techniques

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- **Rank 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

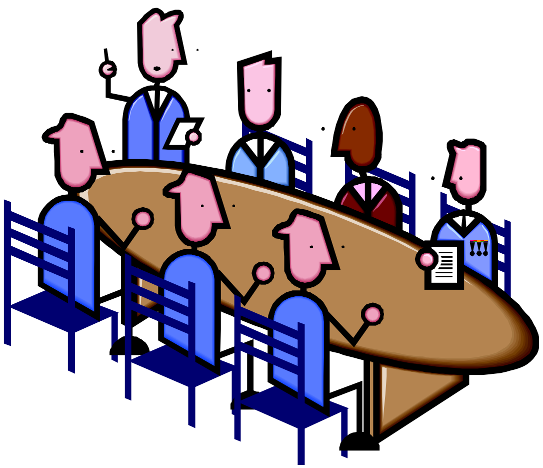
Uncertainty Analysis Regression Techniques *(continued – 1)*

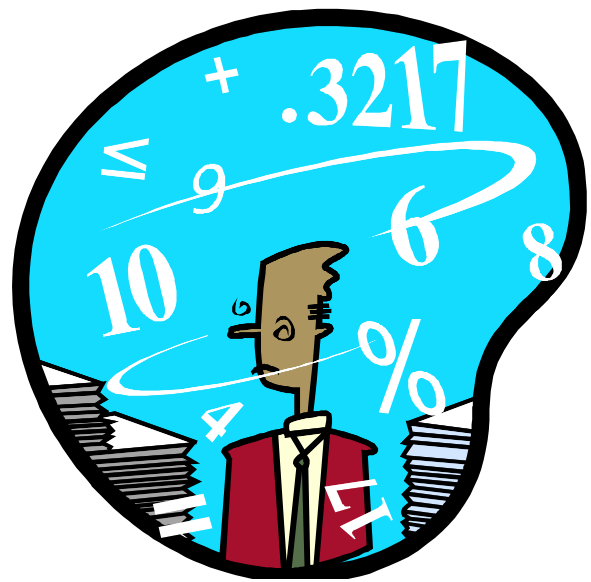
- **Non monotonic/non additive methods**
  - All other methods used capture non monotonic and conjoint influence
  - Methods first fit a regression model and estimates the quality of the regression (final R^2). The regression model is then use to generate a large number of runs and estimate the importance 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 Ti 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

Uncertainty Analysis Regression Techniques *(continued – 2)*

- 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

Parameter Selection





Uncertain Parameters SOARCA Approach

- Key uncertain input parameters were identified
  - Guidance solicited from peer reviewers on chosen parameters and distributions; feedback from Advisory Committee on Reactor Safeguards
- Uncertainty in these parameters propagated in two steps using Monte Carlo and Latin Hypercube (LHS) sampling:
  - A set of source terms generated using MELCOR model
  - A distribution of consequence results generated using MACCS2 model
- Epistemic sample sets of 300 generated to complete a corresponding number of individual code runs (Monte Carlo "realizations") to evaluate the influence of the uncertainty on the estimated outcome

Process for Choosing Parameters and Distributions

- 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
- Approach is based on a formalized PIRT (phenomena identification, and ranking table) process
- 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

SOARCA Uncertainty Inputs

MELCOR

Epistemic Uncertainty (21 variables)

Sequence Issues

SRV stochastic failure to reclose (SRVLAM)
Battery Duration (BATTDUR)

In-Vessel Accident Progression Parameters

Zircaloy melt breakout temperature (SC1131(2))
Molten clad drainage rate (SC1141(2))
SRV thermal seizure criterion (SRVFAILT)
SRV open area fraction (SRVOAFRAC)
Main Steam line creep rupture area fraction (SLCRFRAC)
Fuel failure criterion (FFC)
Radial debris relocation time constants (RDMTC, RDSTC)

Ex-Vessel Accident Progression Parameters

Debris lateral relocation – cavity spillover and spreading rate (DHEADSOL, DHEADLIQ)

Containment Behavior Parameters

Drywell liner failure flow area (FL904A)
Hydrogen ignition criteria (H2IGNC)
Railroad door open fraction (RRIDRFAC, RRODRFAC)
Drywell head flange leakage (K, E, δ)

Chemical Forms of Iodine and Cesium

Iodine and Cesium fraction (CHEMFORM)

Aerosol Deposition

Particle Density (RHONOM)

865 MELCOR source terms developed

MACCS2

Epistemic Uncertainty (350 variables)

Deposition

Wet deposition model (CWASH1)
Dry deposition velocities (VEDPOS)

Shielding Factors

Shielding factors (CSFACT, GSFAC, PROTIN)

Early Health Effects

Early health effects (EFFACA, EFFACB, EFFTHR)

Latent health effects

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

Dispersion Parameters

Crosswind dispersion coefficients (CYSIGA)
Vertical dispersion coefficients (CZSIGA)

Relocation Parameters

Hotspot relocation (DOSHOT, TIMHOT)
Normal relocation (DOSNRM, TIMNRM)

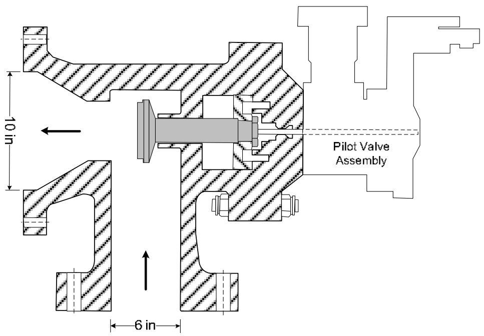
Evacuation Parameters

Evacuation delay (DLTEVA)
Evacuation speed (ESPEED)

Aleatory Uncertainty (984 weather trials)

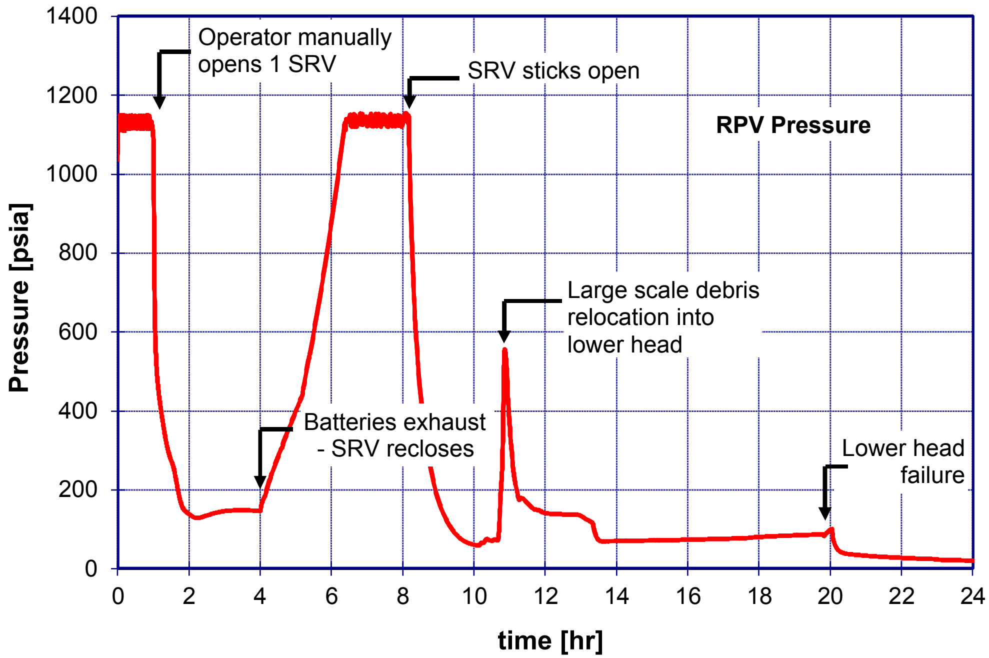
Weather Trials

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

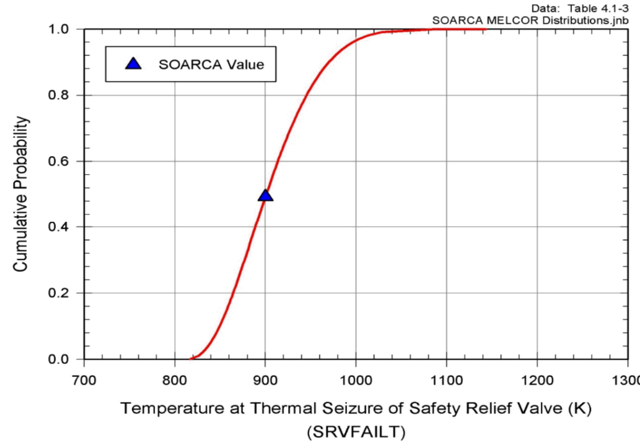
Seizure in stuck open eventually occurs:

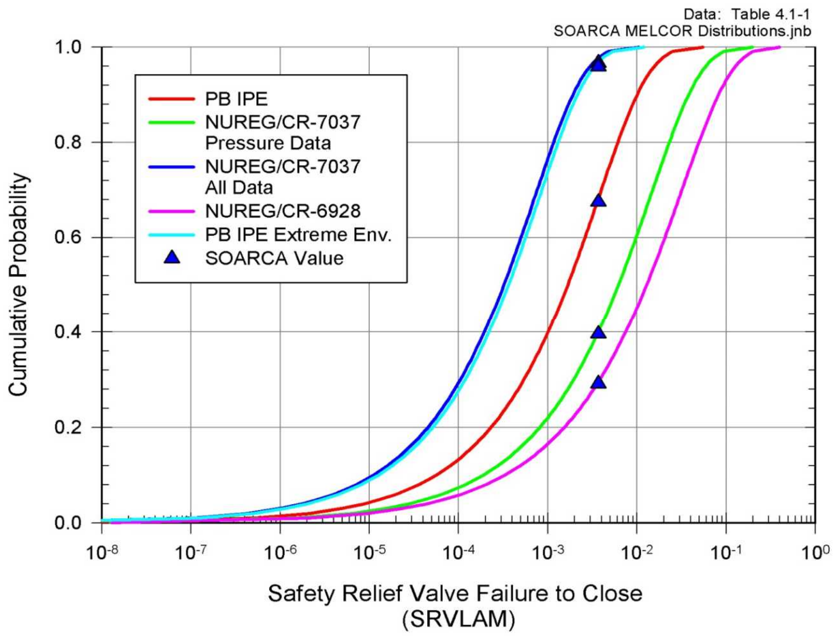
excessive cycling
thermal deformation
partial or full open

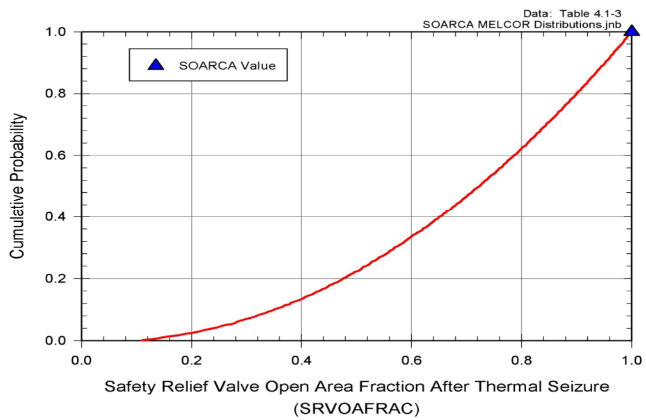
Valve behavior important to accident progression

Uncertainty Analysis Parameter
SRV failure

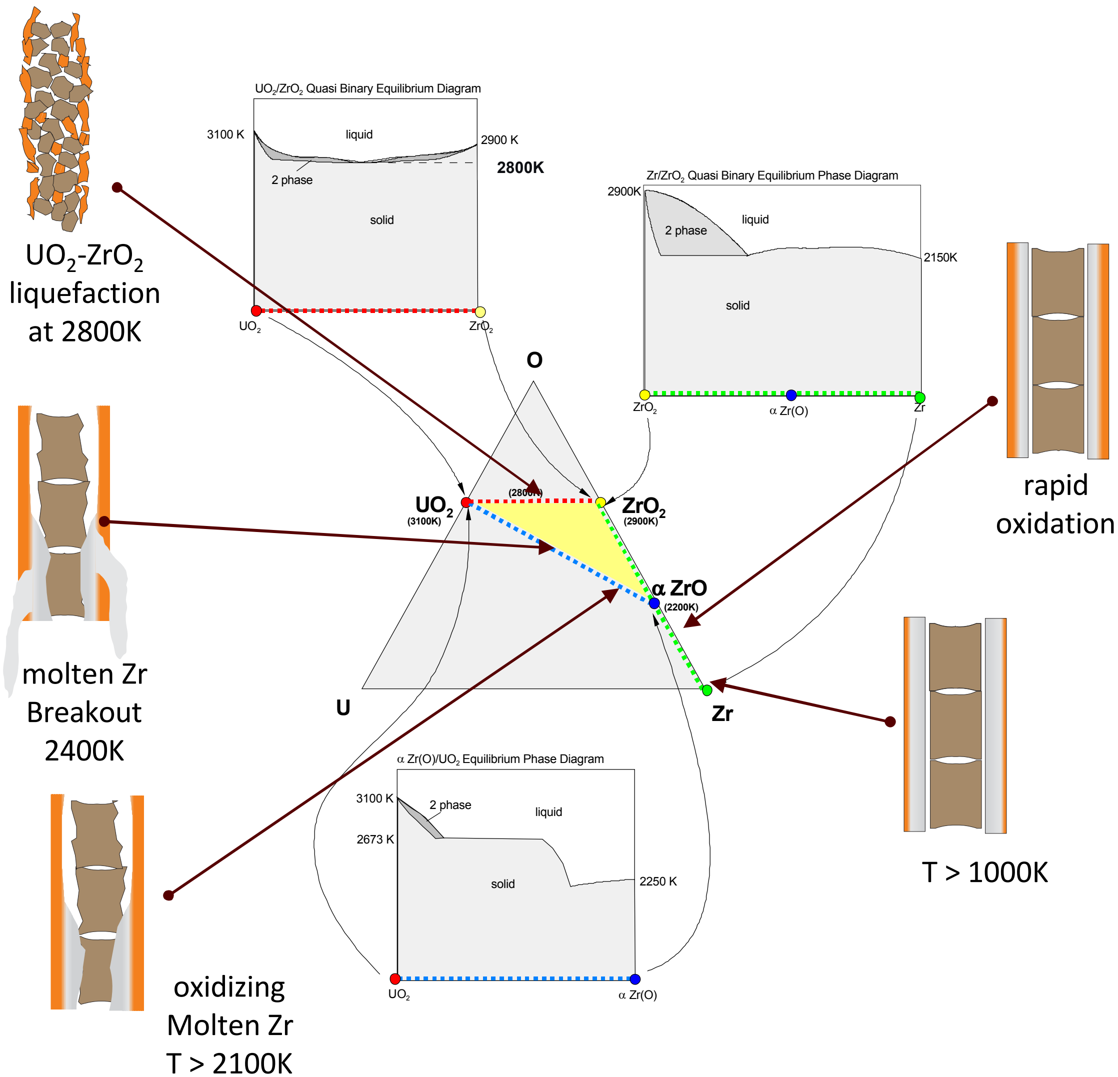
- SRV stochastic failure to reclose (SRVLAM)
  - Beta distribution was fit for the mean value from the Peach Bottom IPE (the SOARCA value) using the methodology in NUREG/CR-7037
- SRV thermal seizure criterion (SRVFAILT)
- SRV open area fraction (SRVOAFRAC)







Modeling Melt Progression Stages



Zr metal melt at 2150K

UO$_2$ dissolution in Zr metal ~20%

Zr melt breakout ~2400K

Loss of rod geometry ~2600K

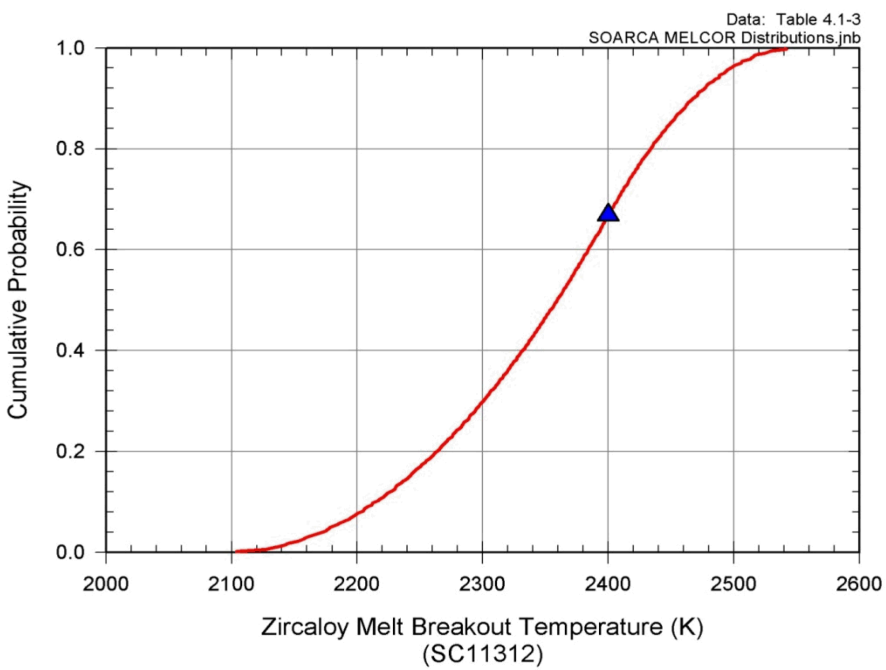
UO$_2$-ZrO$_2$ liquefaction ~2800K

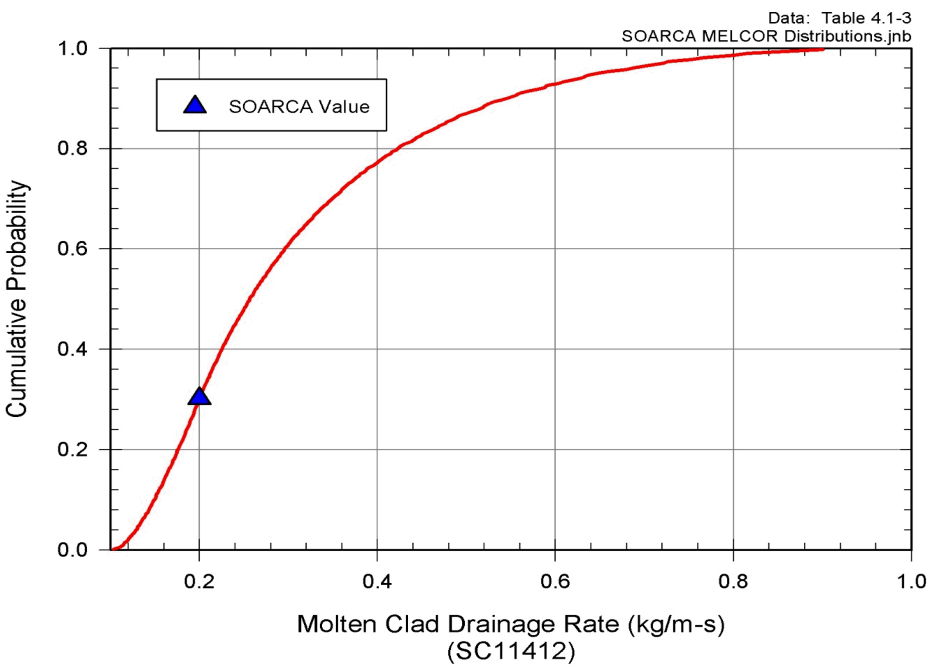
- Parameters are uncertain

Uncertainty Analysis Parameter

In-Vessel Accident Progression Parameters

- Zircaloy melt breakout temperature (SC1131(2))
- Molten clad drainage rate (SC1141(2))

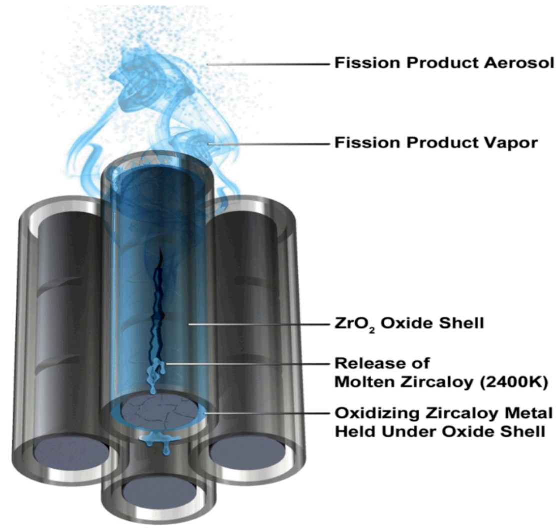


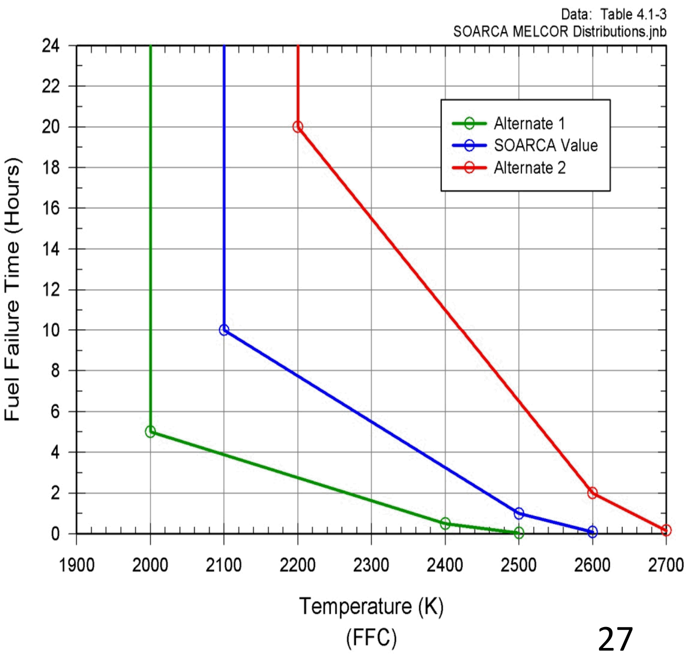


Uncertainty Analysis Parameter

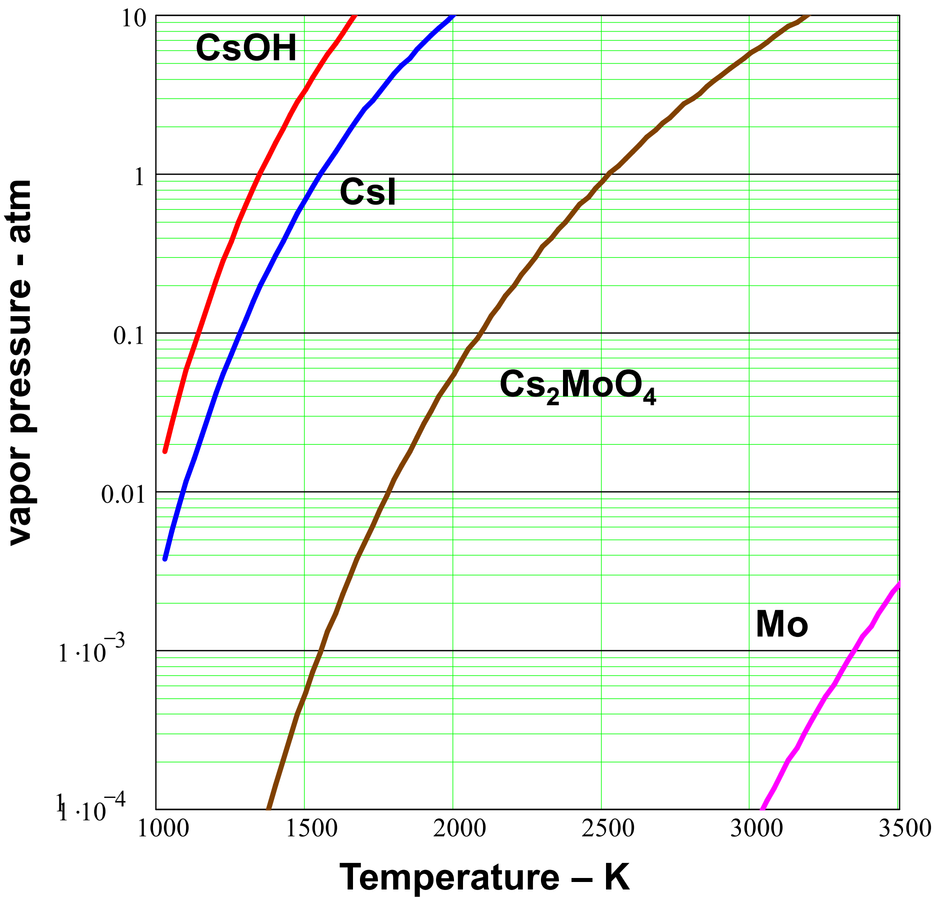
Fuel Failure Criterion

- 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





Speciation of Cesium and Iodine



- Based on Phebus Program Findings
  - Iodine treated as CsI
  - Cs treated as CsI and Cs_2MoO_4
- Cs_2MoO_4 considerably less volatile than CsOH or CsI
  - Affects retention in RCS and long term revaporization
- Uncertainty Study explored alternative balance of speciation
  - I_2, CsOH, CsI and Cs_2MoO_4

Uncertainty Analysis Parameter

CHEMFORM

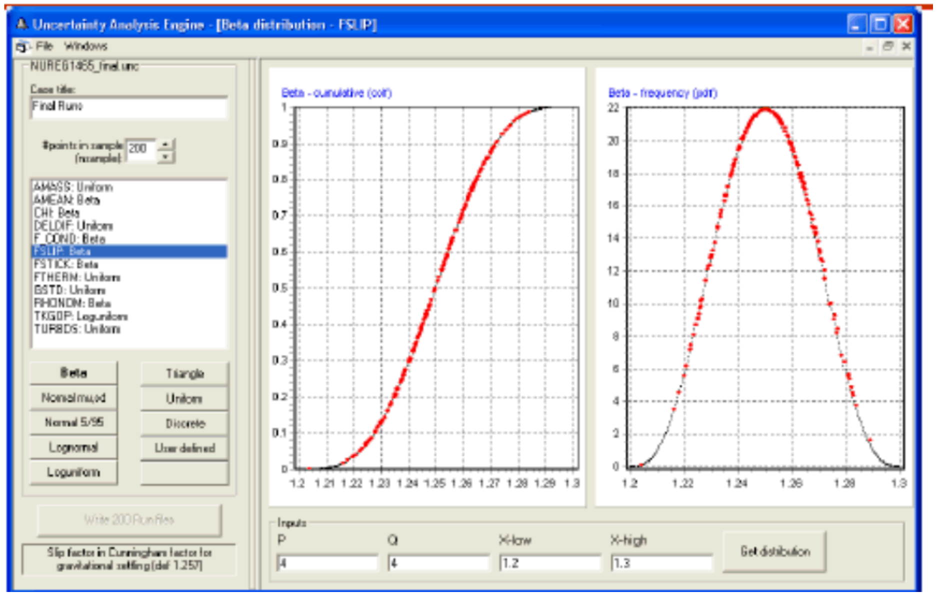
Chemical Forms of Iodine and Cesium

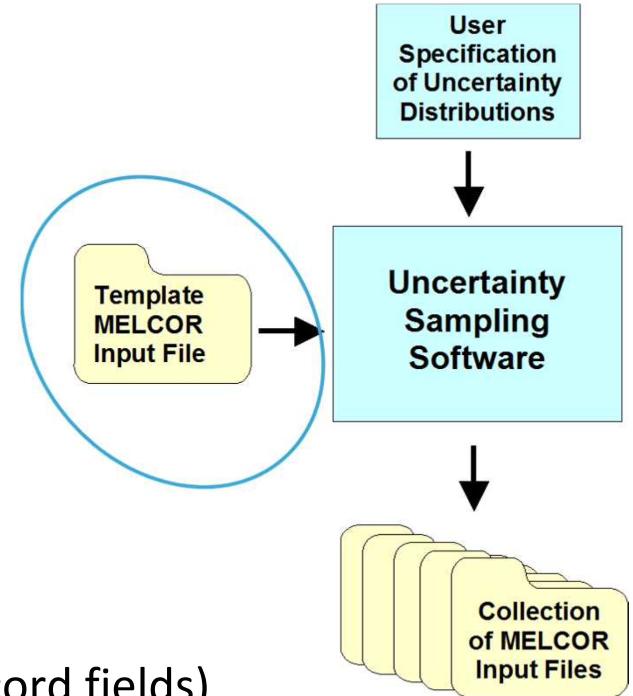
- Iodine and Cesium fraction (CHEMFORM)

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

MELCOR Uncertainty Engine

Parameter Sampling

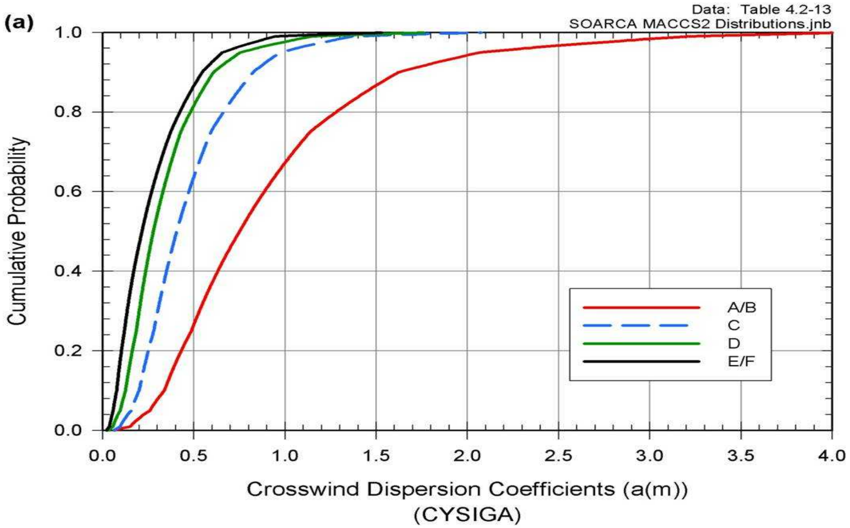


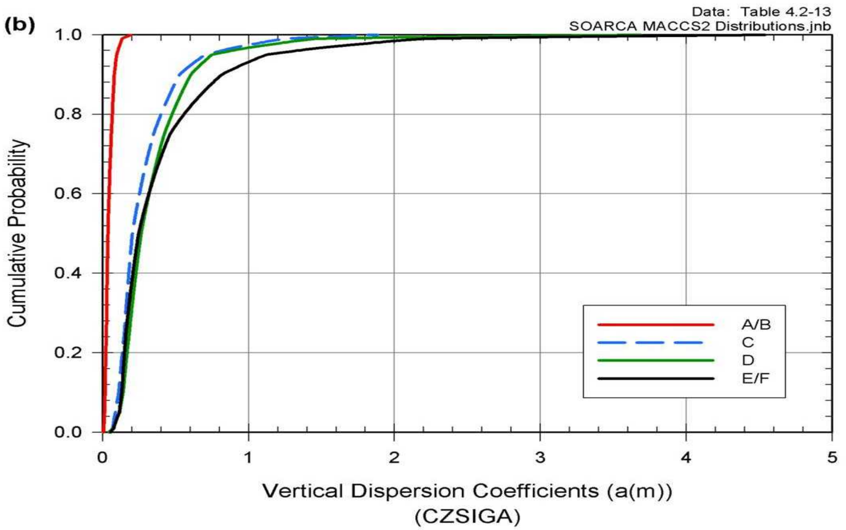


- User Specifies:
  - Uncertain parameters (sensitivity coefficients, record fields)
    - User specifies input files and records containing uncertain parameters
  - Uncertainty distribution for parameters
    - Wide range of available distributions
  - Number of realizations
- Software produces:
  - A collection of MELCOR decks by sampling distributions

Uncertainty Analysis Parameter

Dispersion Parameters





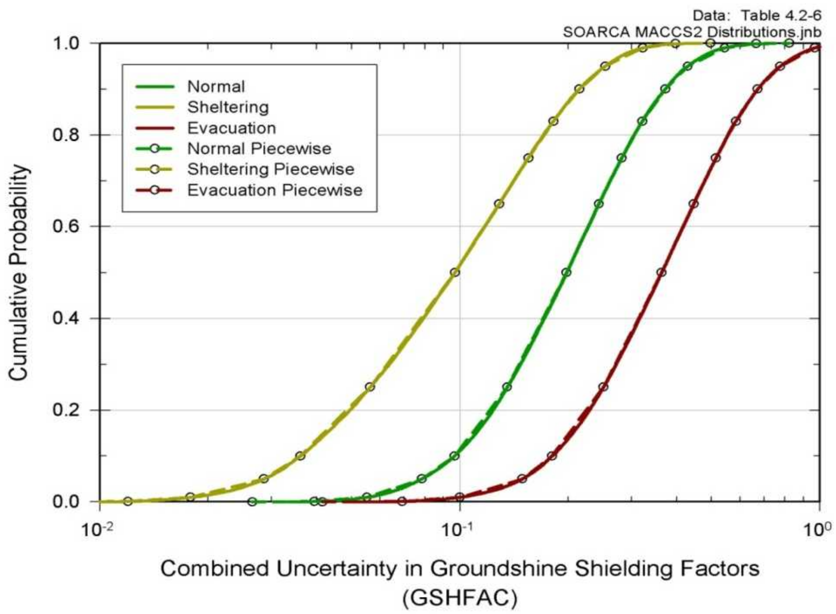
Dispersion Parameters:

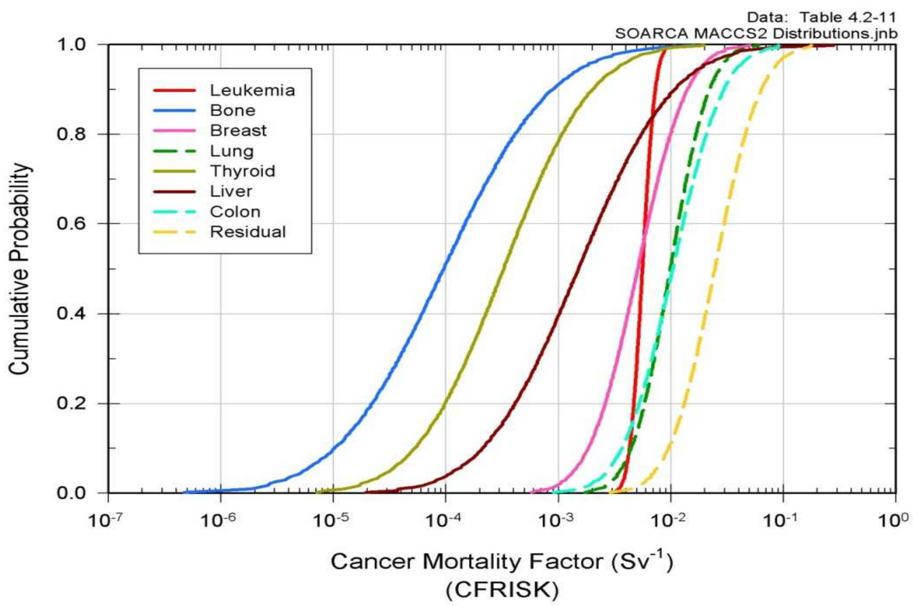
- Linear, crosswind dispersion coefficients (CYSIGA)
- Linear, vertical dispersion coefficients (CZSIGA)
- Parameter Correlation

Uncertainty Analysis Parameter
Latent Health Effects

Latent health effects:

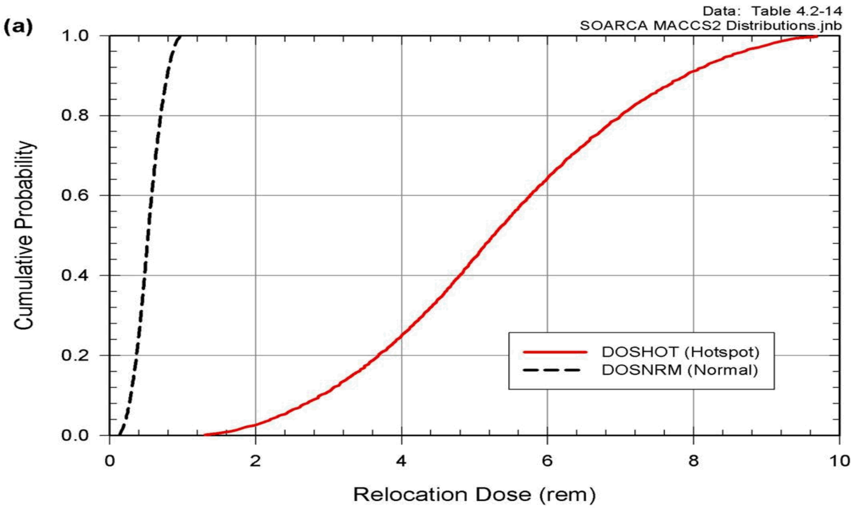
- Groundshine (GSHFAC)
- Dose and dose rate effectiveness factor (DDREFA)
- Mortality risk coefficient (CFRISK)
- Inhalation dose coefficients

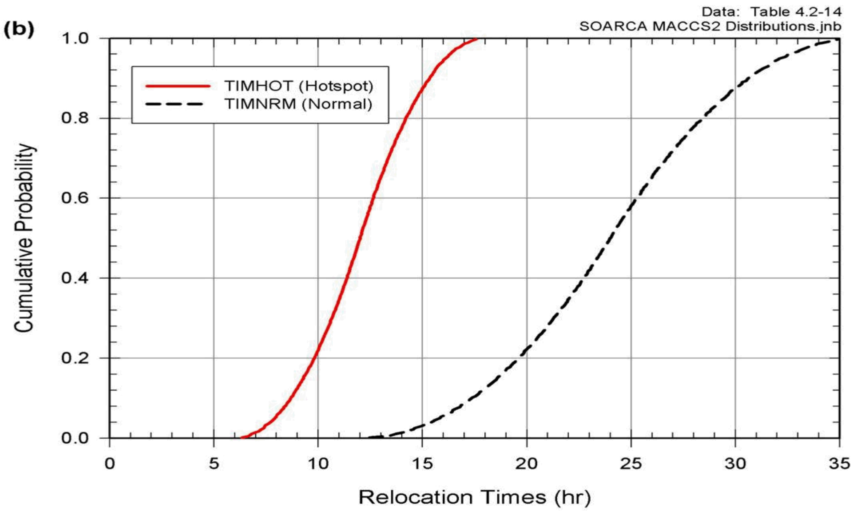




Uncertainty Analysis Parameter

Relocation



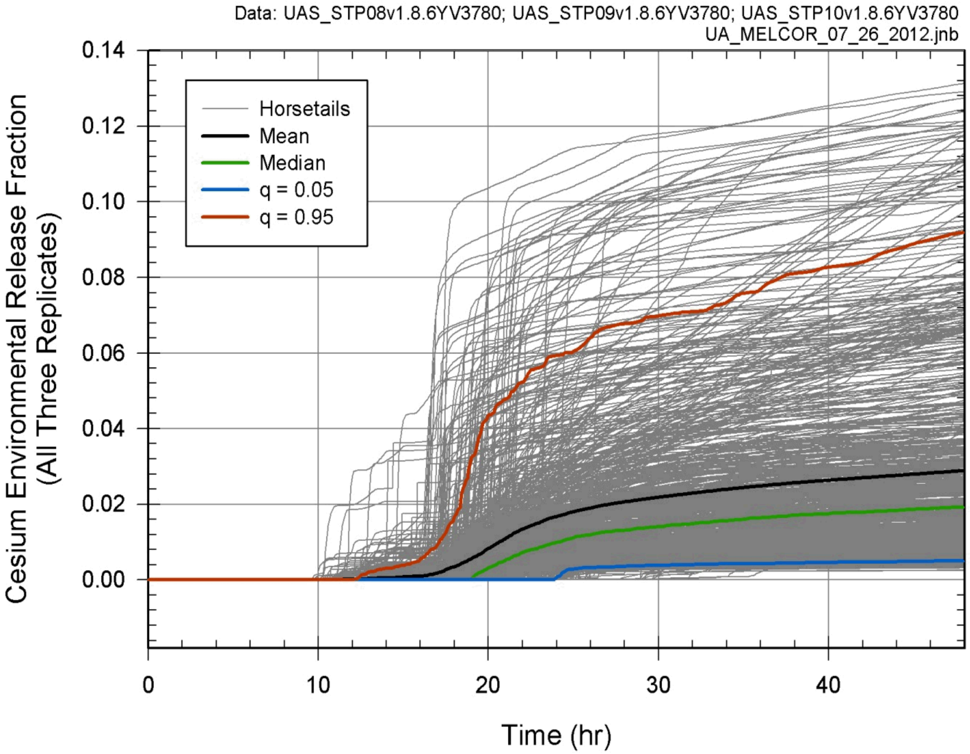


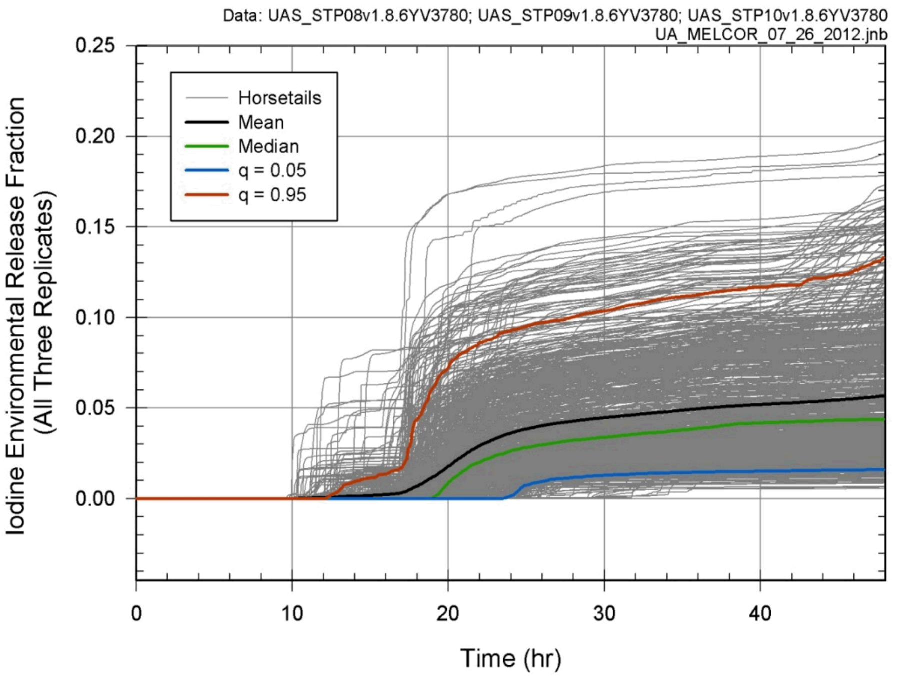
Relocation Parameters:

- Hotspot relocation (DOSHOT, TIMHOT)
- Normal relocation (DOSNRM, TIMNRM)

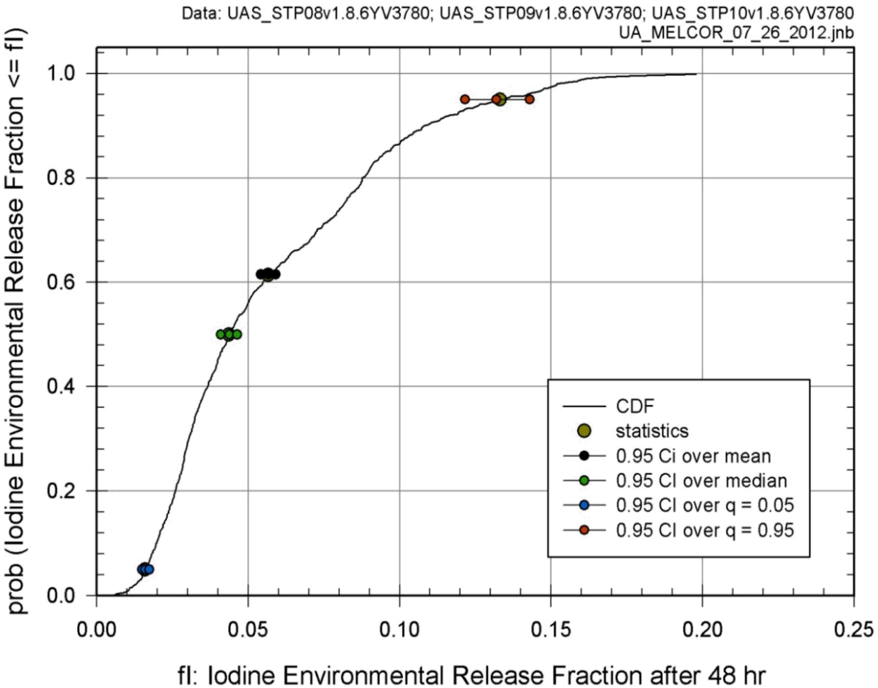
Source Term Analysis

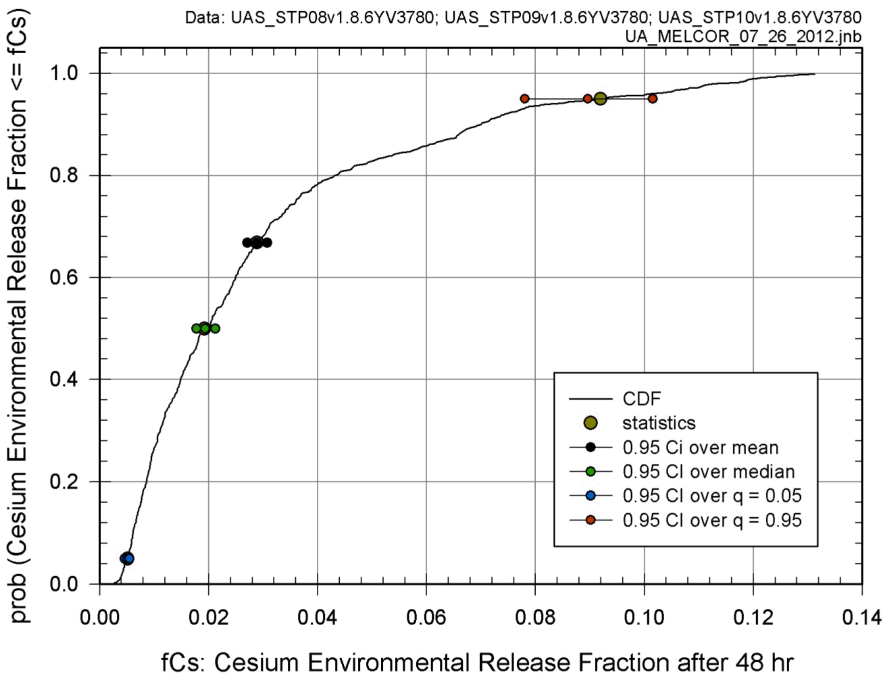
Cesium and Iodine Realizations





Cesium and Iodine CDFs





NUREG/CR-7110 Volume 1 Scenario	Core Damage Frequency (Events/yr)	Integral Release Fractions by Chemical Group									Atmospheric Release Timing	
		Xe	Cs	Ba	I	Te	Ru	Mo	Ce	La	Start (hr)	End (hr)
PB LTSBO	$3x10^{-6}$	0.978	**0.005**	0.006	**0.020**	0.022	0.0	0.001	0.000	0.0	20.0	48
PB STSBO w/ BS	$3x10^{-7}$	0.979	**0.004**	0.007	**0.013**	0.015	0.0	0.001	0.000	0.0	16.9	48
PB STSBO w/o BS	$3x10^{-7}$	0.947	**0.017**	0.095	**0.115**	0.104	0.0	0.002	0.007	0.0	8.1	48
SST1	$1x10^{-5}$	1.000	**0.670**	0.070	**0.450**	0.640	0.050	0.050	0.009	0.009	1.5	3.5

Iodine Regression Analysis

- Uncertainty in lambda in safety relief valve stochastic failure to reclose (SRVLAM)
- Chemical form of iodine and cesium (CHEMFORM)
  - Different combinations of chemical form in the uncertainty analysis vary in the amount of elemental (gaseous) iodine initialized in the core
  - Gaseous iodine in the calculations is scrubbed very effectively when introduced to the wetwell pool (99.8%)
  - For gaseous iodine to release to the environment, it must bypass the wetwell pool
    - MSL rupture interrupts the sweeping of gaseous iodine to the wetwell introducing it to the drywell instead where it is readily available to escape containment through the drywell head flange or a drywell liner melt-through
    - Still in other calculations, not all of the iodine releases from the core or core debris before lower head failure and so too introduces to the drywell where it is available for release to the environment

Iodine Regression Analysis
(continued)

- SRV open area fraction after thermal seizure (SRVOAFRAC)
  - The conjoint influence for SRVOAFRAC reflects the importance of this parameter with respect to whether a MSL rupture occurs
  - MSL ruptures consistently resulted in larger releases but SRVOAFRAC alone does not determine whether or not a MSL rupture occurs
- Flow area resulting from drywell liner failure (FL904A)
  - The dependence of FL904A reflects the larger fission product releases associated with contaminated water surging up from the wetwell given larger values of this parameter

Example of Iodine Regression

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

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

Iodine Regression Analysis

SRV Stochastic Failures

- SRVLAM and SRVOAFRAC combined influences separate the realizations into three groups, each representing a distinct mode of venting the RPV during much of the core degradation
  - SRV stochastic failure (~$^1/_2$ of the realizations)
  - SRV thermal failure without MSL creep rupture (~$^1/_3$ of the realizations)
  - SRV thermal failure with MSL creep rupture (~$^1/_6$ of the realizations)
- The importance of these parameters is large as their values strongly influence the releases of iodine and other fission products to the environment
  - The most influential parameters are FL904A and SRVLAM
  - SRV failures result in less core oxidation and less late revaporization of fission products off reactor vessel internals
  - Since most of the iodine released to the environment can be traced to material revaporized late off of reactor internals, earlier SRV failures result in smaller releases to the environment
  - In the worst case, a long period of SRV valve cycling promotes a MSL creep rupture characteristically leading to large releases to the environment.

Iodine Regression Analysis

SRV Thermal Failure without MSL failure

- CHEMFORM is the most important parameter
- The second is the condition of the railroad doors, closed or blown open by an overpressure in the reactor building
  - When the railroad doors blow open, a buoyant draft establishes in the reactor building where air enters low through the doors and exits high out opened blowout panels or failed roofing in the refueling bay
  - The draft efficiently carries aerosols released from containment out into the environment
- FL904A is third, and all other parameters are negligible

Iodine Regression Analysis

SRV Thermal Failure with MSL Failure

- CHEMFORM is the most important parameter
  - Stems from more or less elemental (gaseous) iodine being initialized in the core dependent upon the sampled value of this variable
  - MSL failure allows some of the iodine to enter the drywell instead of being vented to the wetwell through the stuck-open SRV where it would be efficiently scrubbed in the wetwell pool
- The second is the condition of the railroad doors
- Third is zircaloy melt breakout temperature (SC1131-2)
  - Larger breakout temperatures lead to greater oxidation
  - Greater oxidation leads to greater heat generation and earlier MSL rupture
  - Earlier MSL rupture allows more gaseous iodine to enter the drywell instead of being vented to the wetwell (through the stuck-open SRV) where it would be efficiently scrubbed in the wetwell pool

Timing of Iodine Release to the Environment

- Battery duration (BATTDUR) is the most influential parameter
  - BATTDUR has an obvious influence on release timing in that RCIC functions to keep the reactor cool as long as DC power is available
    - It isn't until DC power is lost that the operators lose control of RCIC and its water delivery increases overfilling the vessel and flooding the steam lines
    - The drive turbine on the RCIC pump is assumed to fail when the steam lines flood
- SRVOAFRAC is the second most influential parameter; SRVLAM is third, and all the remaining uncertain parameters seem to have negligible influence
  - The number of cycles to SRV failure (1/SRVLAM) and the open fraction of an SRV after thermal seizure (SRVOFRAC) are important to release timing because they are important to whether or not a MSL rupture occurs
    - When a MSL rupture occurs, containment over pressurizes and leaks past the drywell head flange
    - This results in an early release

Cesium Regression Analysis

- The most important parameter is SRVLAM
  - Affects the slow revaporization of material off of reactor internals
    - Longer times to SRV failure leading to more revaporization
  - The revaporization comes after reactor lower head failure and after drywell liner melt-through
    - Cesium migrates from the reactor vessel condensing to aerosol and exits the drywell through the breach in the liner

- The next most important parameter is SRVOAFRAC
  - As in the case with iodine, the importance reflects whether MSL failure occurs
  - MSL failure consistently resulted in larger releases of cesium but SRVOAFRAC alone does not determine whether or not a MSL rupture occurs
  - MSL failures result in higher releases because, for a period of time before lower head failure, the reactor vents to the drywell rather than to the wetwell

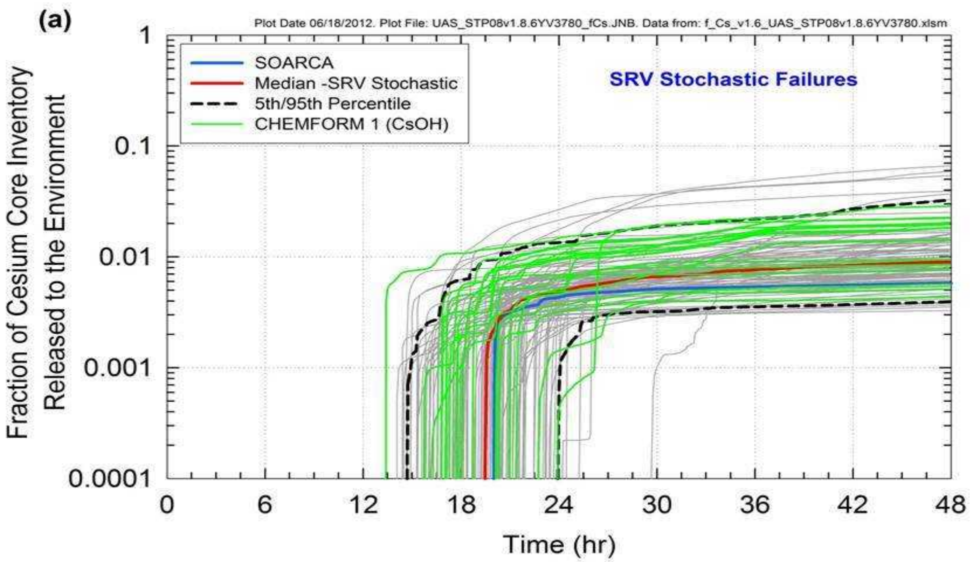
Cesium Regression Analysis
(continued – 1)

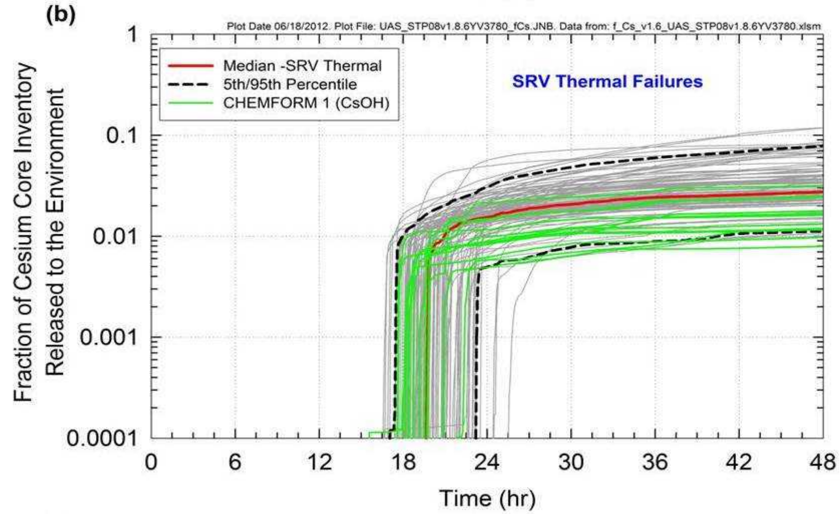
- The third most important parameter is FL904A,
  - Reflects the fission product releases associated with contaminated water surging up from the wetwell for larger values
    - The water pools on the drywell floor, in contact with the core debris relocated from the reactor, and eventually boils away, releasing its content of radionuclides including cesium.
  - Larger values from a larger drywell breaches from liner melt-through support the surging of water up from the wetwell
- Followed by the fuel failure criterion on the transformation of intact fuel into particulate debris (FFC)
  - Affects how long fuel remains standing
    - The longer fuel remains standing the longer oxidation of fuel cladding persists
    - Persistent oxidation drives continued revaporization of cesium deposits off of reactor internals late (i.e., after reactor lower head failure)
    - The revaporized cesium migrates from the reactor to the drywell condensing to aerosol and escapes containment through the drywell liner melt-through

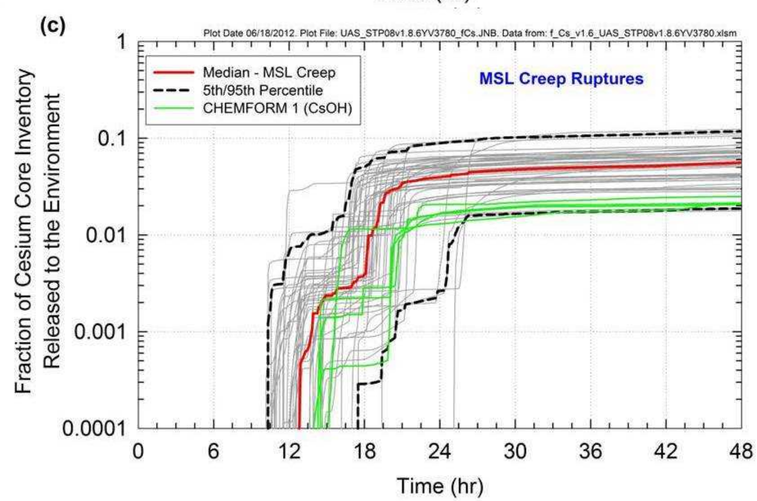
Cesium Regression Analysis
(continued – 2)

- The fifth most important parameter is the condition of the railroad doors
  - Important to cesium release in the same way as it is important to iodine release in that open doors promote the development of a buoyant draft in the reactor building
- Lastly, three parameters (CHEMFORM, SC1131_2, and RRIDFRAC) seem to explain a very small amount of variance
  - Less than 1% for each parameter
  - This makes sense physically as chemisorption, the phenomenon behind the influence of CHEMFORM, is only strong at the relatively higher core degradation temperatures consistent with SRV thermal with or without MSL creep rupture.
  - The regression analyses confirms that CHEMFORM is the most important parameter when only MSL creep rupture cases are considered

Effect of CsOH on Fraction of Cesium Chemisorbed in MSL Creep Rupture Cases

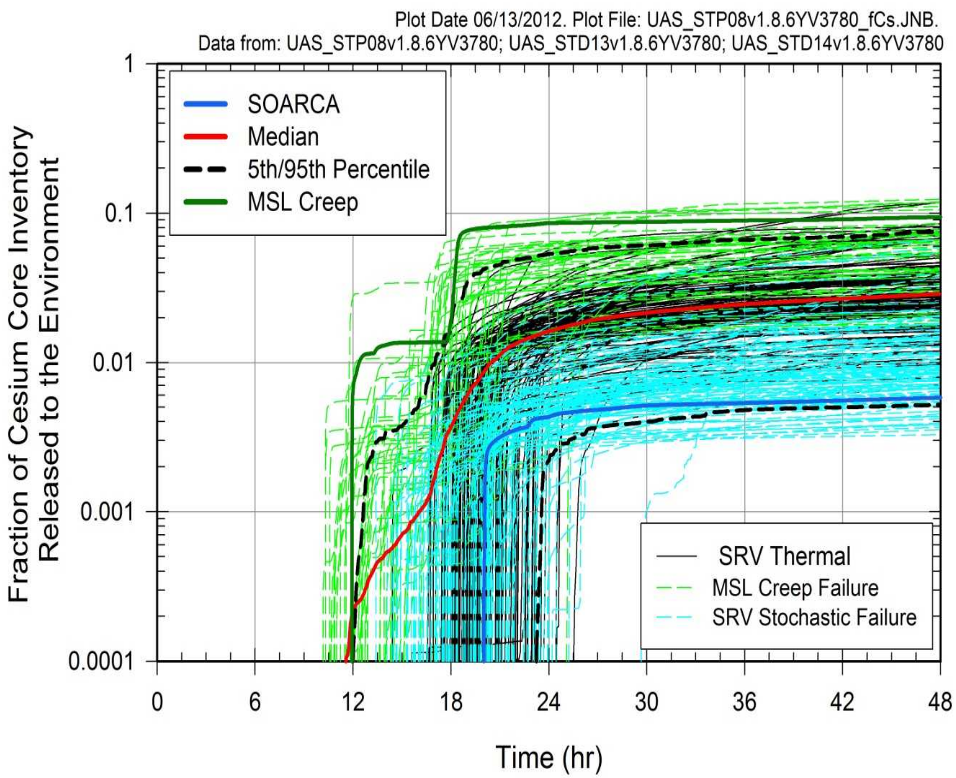


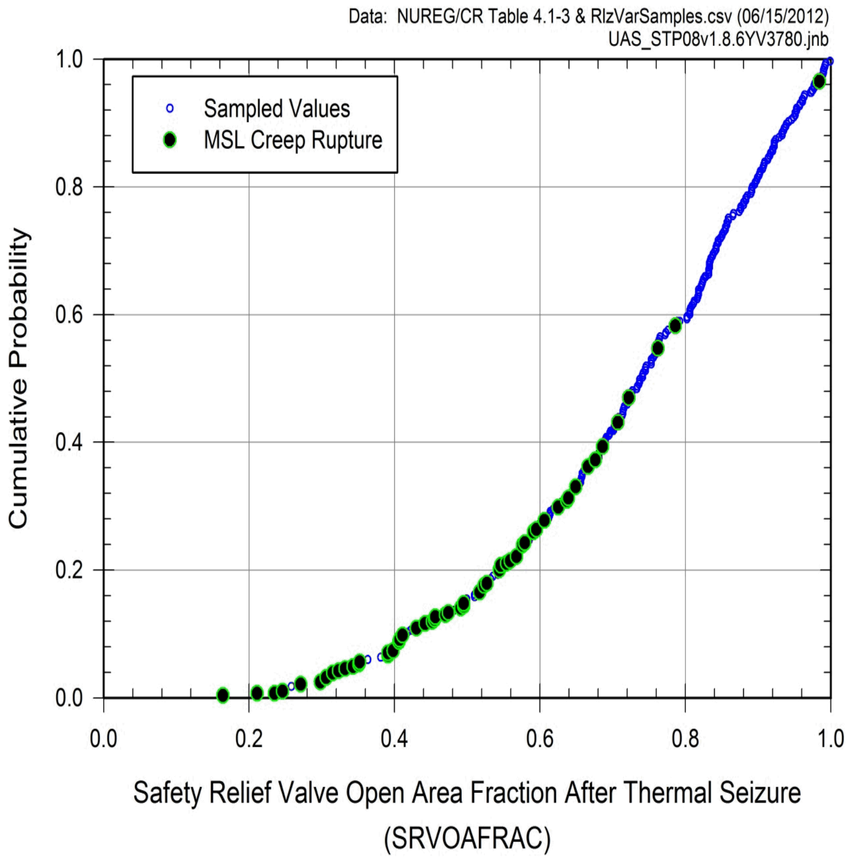




- Discrete distribution [0.125,0.125,0.125,0.125,0.5]
- Chemisorption on the steam dryers and upper RPV
- Limits the mass available for release
- Occurs in higher temperature MSL creep rupture cases
- This effect not seen in best estimate calculation (no CsOH in best estimate) or lower temperature accident progression

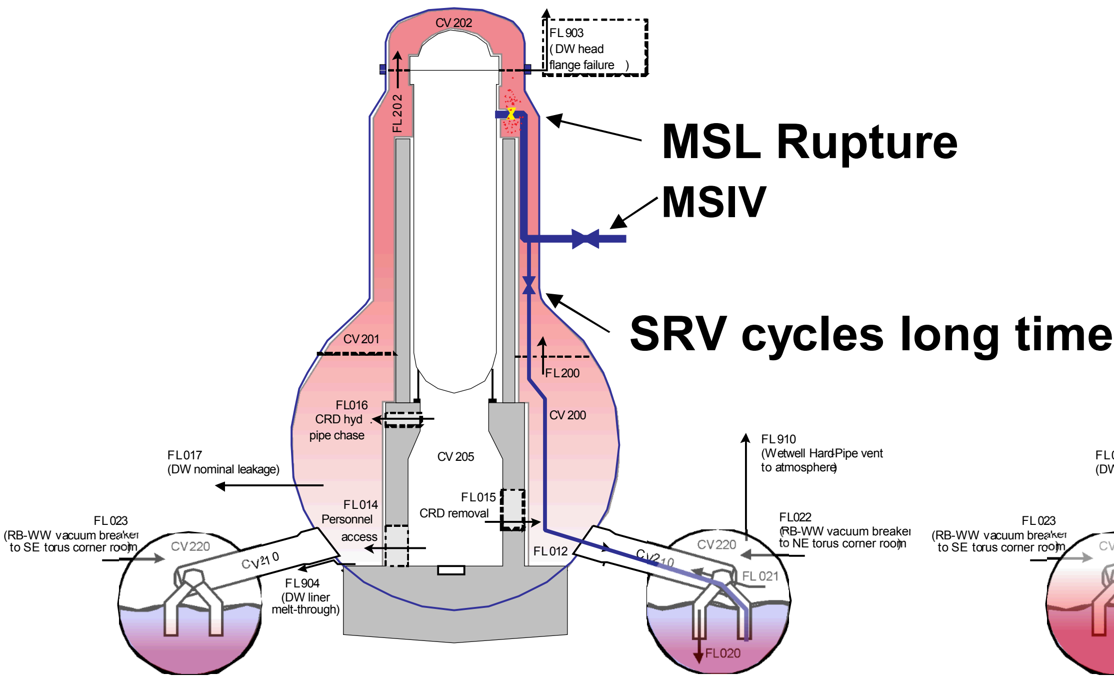
Influence of SRV thermal failure on Cesium release

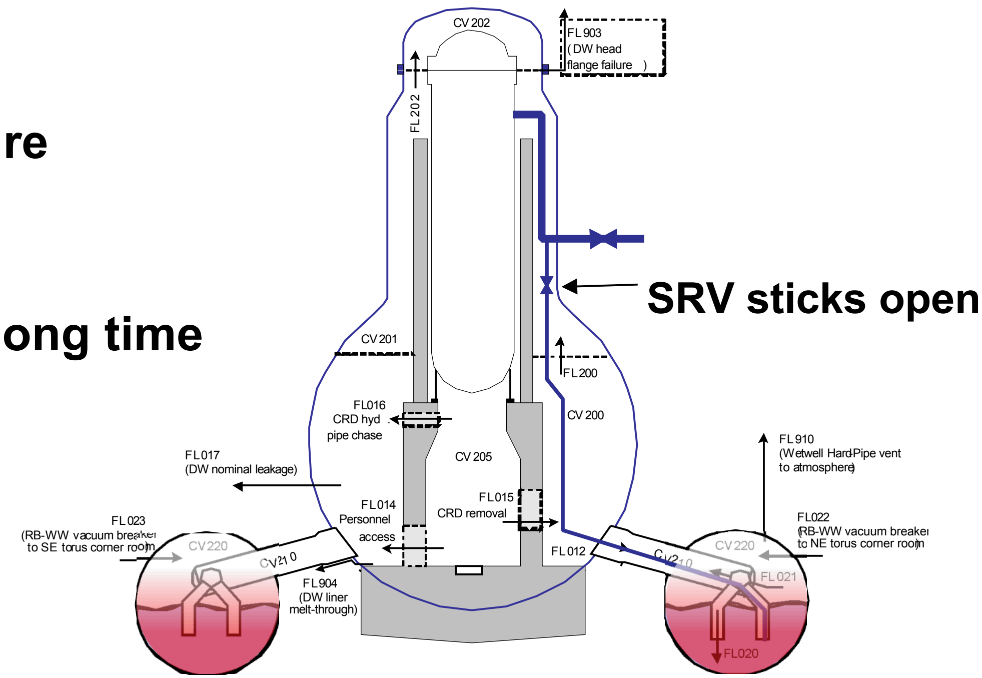




- Potential for MSL creep failure controlled by SRVOAFRAC
- SRVOAFRAC is a log uniform [0.05,1] distribution
- Timing of SRV failure is important (Stochastic vs. Thermal)
- SRV will fail thermally first in all cases for MSL creep failure

SRV failure vs. MSL failure





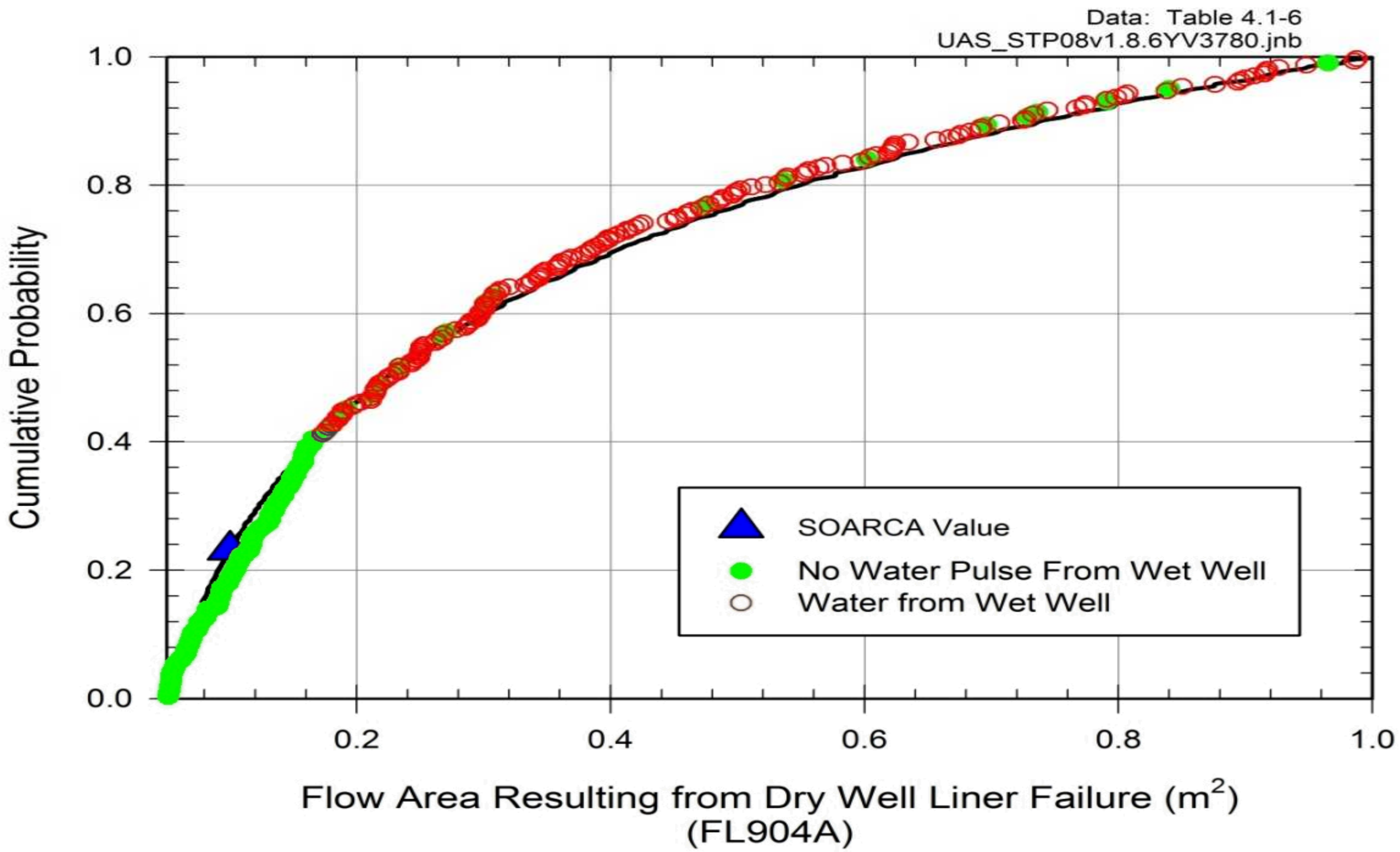
Main steam line failure vents fission products to drywell

Release to environment via drywell head flange or drywell liner melt through

SRV failure vents fission products into wetwell

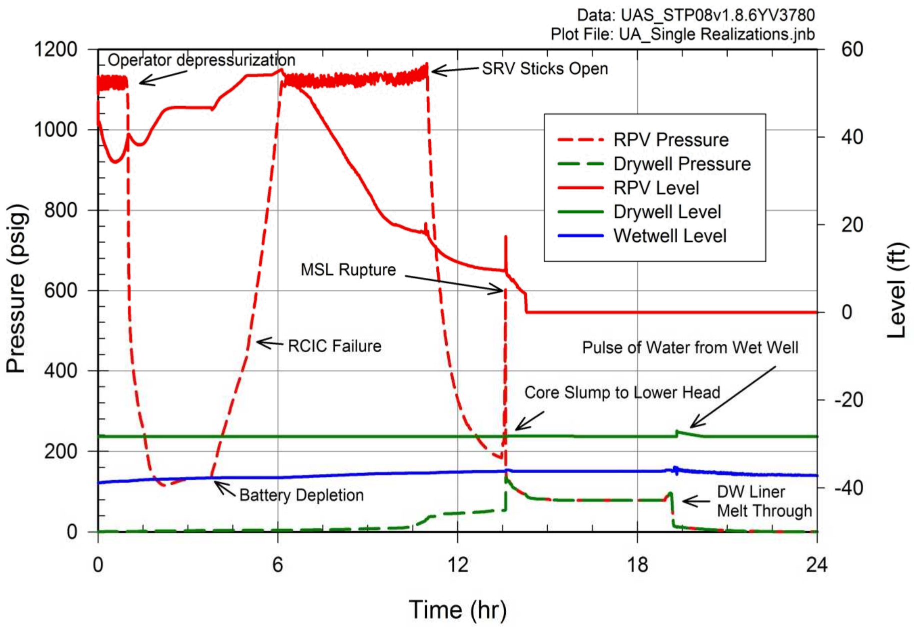
Wetwell scrubbing minimizes release to the environment

Drywell Liner Open Area

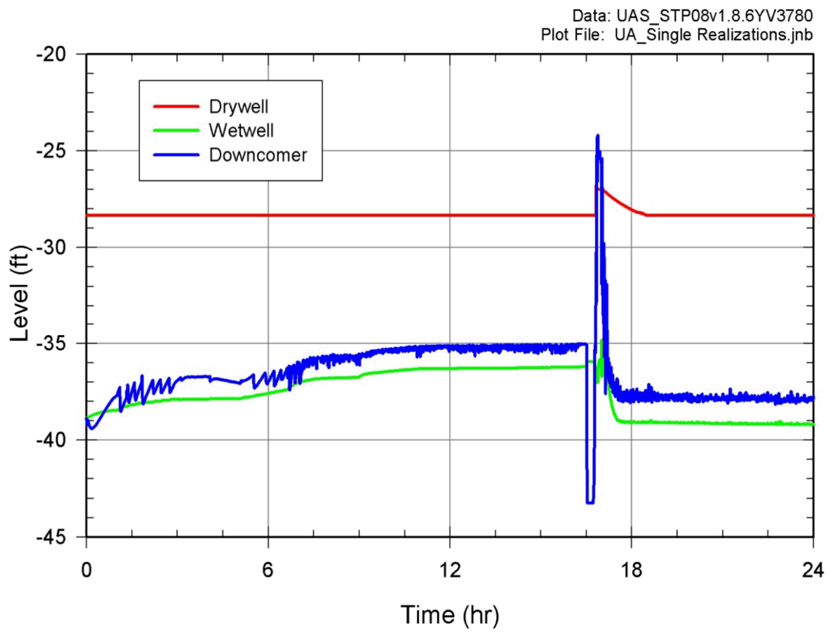


- Log Uniform distribution selected from [0.05,1]
- Vacuum breakers overwhelmed by pressure vented from dry well
- Mass of RN relocated in water flashed into dry well
- Mass is deposited on surfaces in dry well and can be slowly released to environment
- Timing of opening area is important
- This effect not seen in best estimate calculation

Example of wetwell water surge

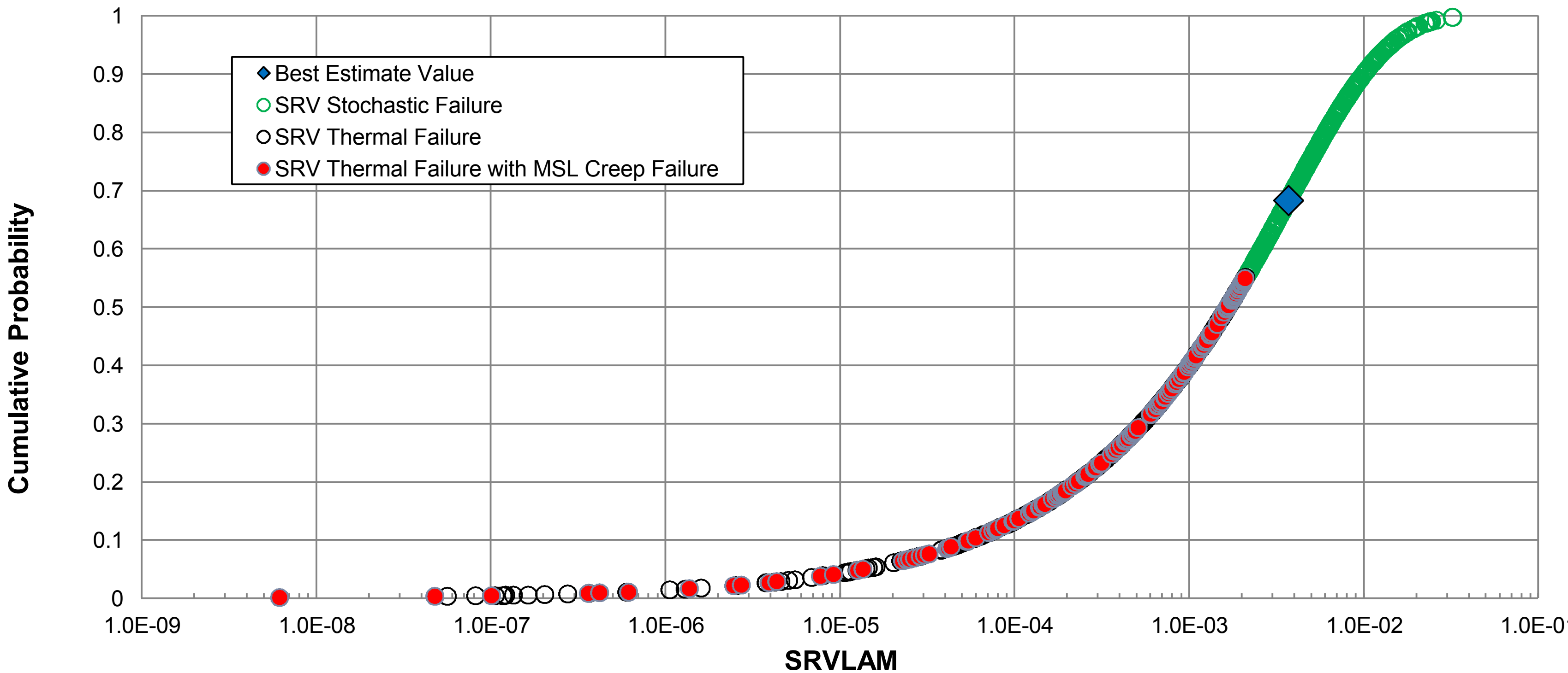


Reactor and containment pressure and water level for Replicate 1, Realization 62
a MSL creep rupture



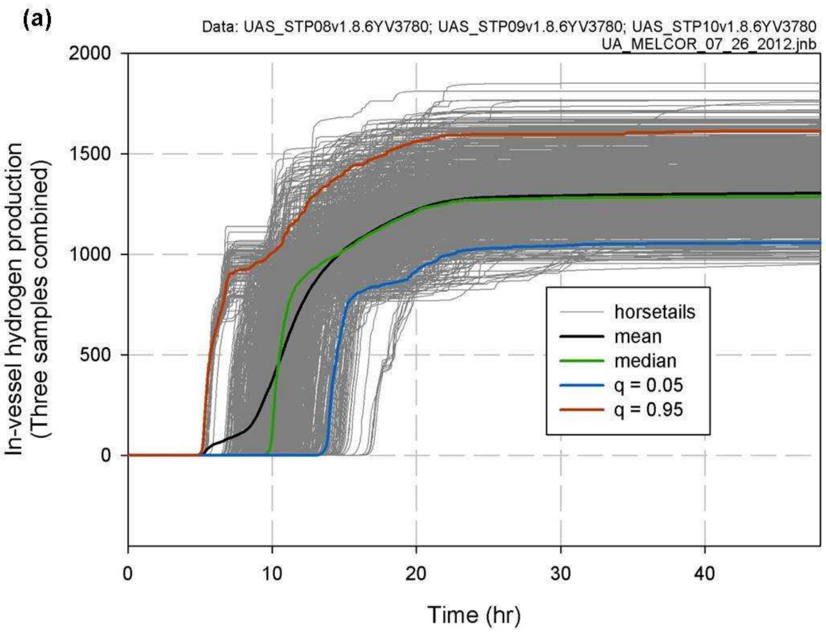
Water level in containment for Replicate 1, Realization 170
a SRV Stochastic failure

Influence of Number of SRV Cycles before Failure to Re-Close

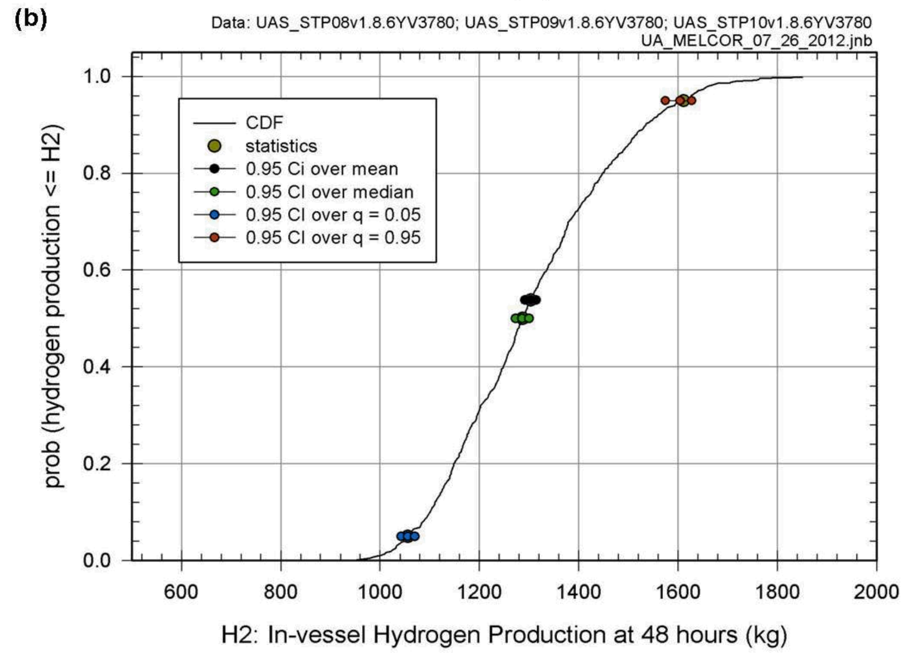


- Beta distribution was fit for the mean value from the Peach Bottom IPE (the SOARCA value) using the methodology in NUREG/CR-7037
- SRVLAM mean value = 1.68×10^{-3} per demand (596 cycles)
- SRVLAM best estimate value = 3.70×10^{-3} per demand (270 cycles)
- Timing of SRV failure is important
- Lower SRVLAM results in longer SRV cycling and thus, the SRV will fail thermally
- Potential for MSL creep failure controlled by SRVOAFRAC

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

Hydrogen Production Regression Analysis

- SRVLAM is the most important parameter
  - If the SRV sticks open early, before the onset of core damage, no core degradation takes place at high pressure and relatively little hydrogen is produced
  - If the SRV sticks open late, after the onset of core damage, substantial core degradation takes place at high pressure and a large amount of hydrogen is produced
- SC1131_2 is the second most influential uncertainty, followed by SC1141_2 and all the other parameters have negligible influence
  - SC1131_2 & SC1141_2 are important to hydrogen production, in that they determine how long un-oxidized molten zirconium is reacted
  - The longer the zirconium is held the longer oxidation takes place and the more hydrogen produced
- Principally important to hydrogen generation is how much core degradation occurs at high pressure
  - More core degradation at high pressure relates to more hydrogen generation from oxidation
  - The most important parameter affecting the amount of core damage occurring at high pressure is SRVLAM

Phenomenological Insights

MELCOR Analyses

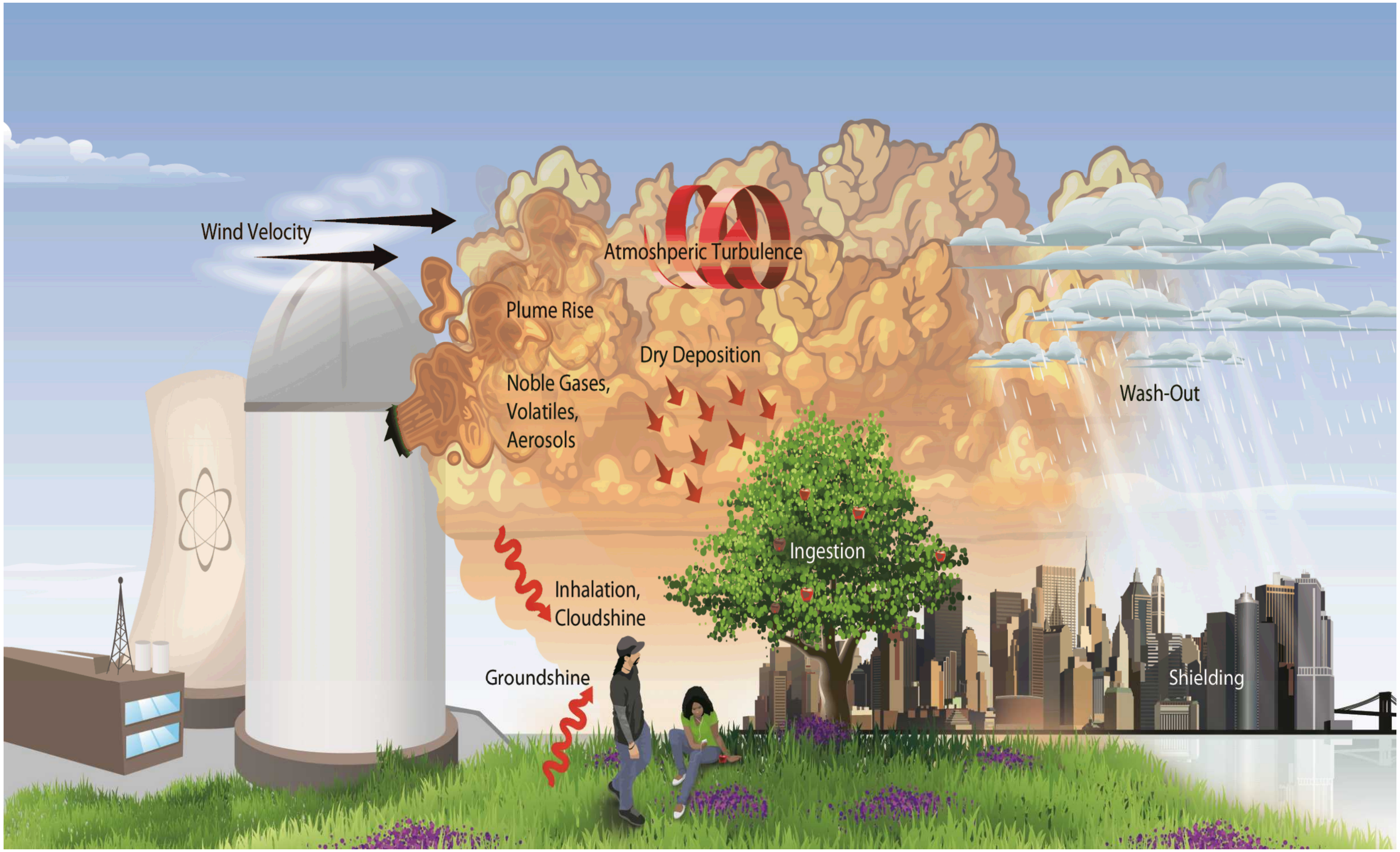
- Confirmation of phenomenology seen in the SOARCA best estimate:
  - Whether the stuck-open SRV occurs before or after the onset of core damage
  - Strong dependence between number of SRV cycles before failure to re-close and probability of thermal SRV and/or MSL creep rupture
  - Dependence between area fraction of SRV open when failed thermally and occurrences of MSL creep rupture
  - Chimney effect when rail road doors are failed open
- Nothing invalidates the SOARCA best estimate
- Additional new insights

Phenomenological Insights

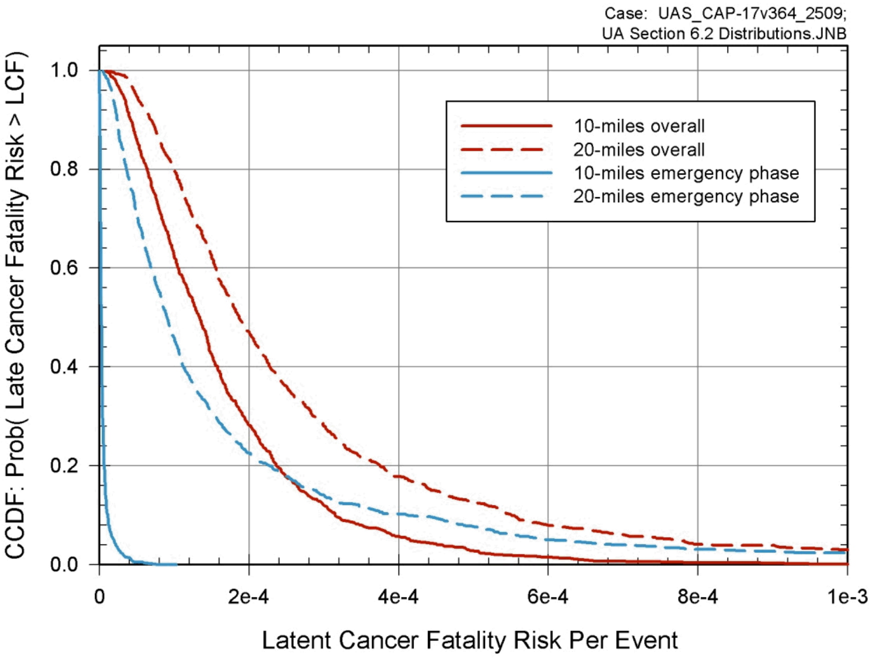
Additional Findings

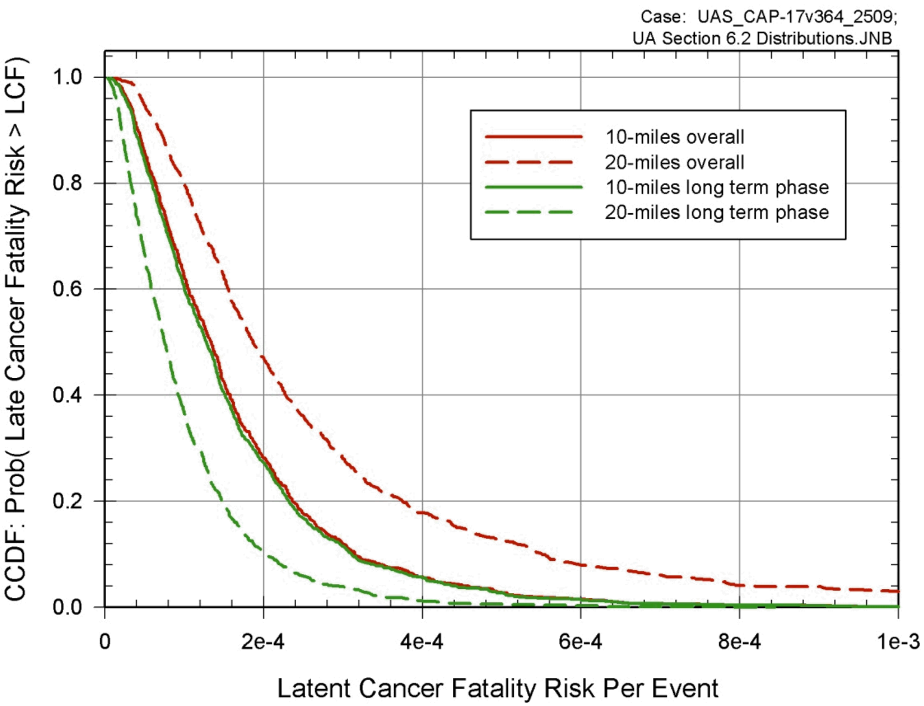
- The amount of cesium chemisorbed when cesium is in the form of CsOH into the stainless steel of reactor pressure vessel (RPV) internals decreases the overall release of core inventory to the environment
- When core debris relocates from the RPV to the reactor cavity all at once will decrease or over an extended period of time will increase the release of core material to the environment due to the potential for aerosol re-vaporization
- The degree of oxidation, primarily fuel-cladding oxidation, occurring in-vessel (identified by the amount of in-vessel hydrogen production) increases the release of core material to the environment
- A surge of water from the wetwell up onto the drywell floor occurring at drywell liner melt-through will increase the release of core material to the environment
- An overpressure rupture of the wetwell above the waterline can decrease the release of core material to the environment
- When the reactor building railroad doors are blown open by a hydrogen deflagration an increase in the overall release of core material to the environment occurs

Environmental Consequence Analysis



CCDF of LCF Risk





LCF Risk Regression Analysis

338 MACCS2 and 21 MELCOR input variables

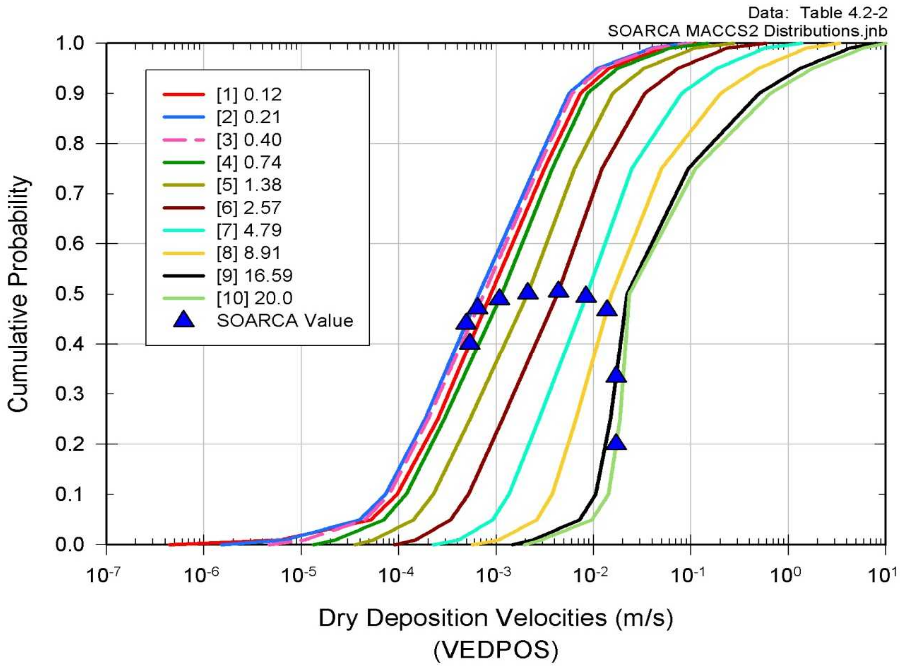
- MACCS2 dry deposition velocity (VDEPOS)
- The MELCOR SRV stochastic failure probability (SRVLAM)
  - The MELCOR fuel failure criterion (FCC)
  - The MELCOR drywell liner melt-through open area flow path (FL904A)
  - The MELCOR DC station battery duration (BATTDUR)
- The MACCS2 risk factor for cancer fatalities for the residual organ (CFRISK – Residual)
  - The MACCS2 dose and dose-rate effectiveness factor for the residual organ (DDREFA–Residual)
  - The residual organ is represented by the pancreas and is used to define all latent cancers not specifically accounted for in the MACCS2 model
  - The pancreas is chosen to be a representative soft tissue

Example of Regression Tables

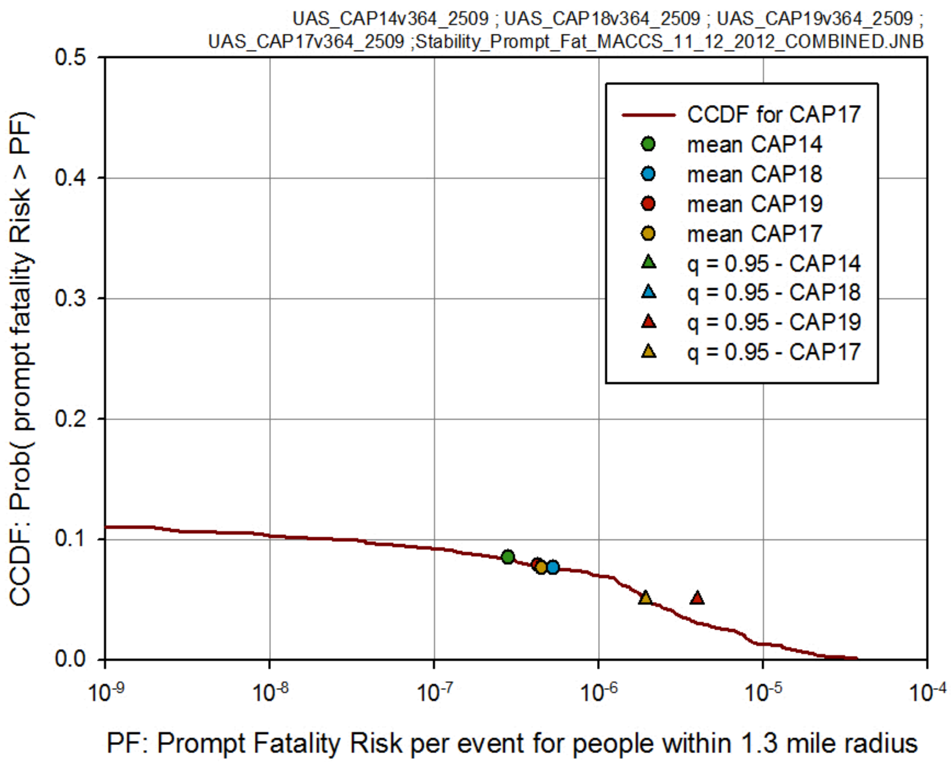
LCF Risk 0-10 miles	Rank Regression			Quadratic			Recursive Partitioning			MARS		
Final R^2	**0.73**			**0.76**			**0.85**			**0.72**		
Input	**R^2 inc.**	**R^2 cont.**	**SRRC**	**S_i**	**T_i**	**p-val**	**S_i**	**T_i**	**p-val**	**S_i**	**T_i**	**p-val**
VDEPOS	0.31	0.31	0.56	0.15	0.28	0	0.22	0.53	0	0.33	0.37	0
SRVLAM	0.43	0.12	-0.35	0.07	0.21	0	0.16	0.35	0	0.12	0.12	0.02
Fuel failure criterion	0.44	0.01	0.15	0.01	0.03	0.55	---	---	---	0.07	0.13	0
FL904A	0.45	0.01	0.12	---	---	---	---	---	---	0	0	1
BATTDUR	---	---	---	---	---	---	0	0.01	0.55	0	0	1
CFRISK Residual	0.54	0.09	0.31	0.16	0.27	0	0.15	0.48	0	0.18	0.25	0
DDREFA Residual	0.57	0.03	-0.18	0.03	0.19	0	0.01	0.05	0.05	0.05	0.16	0
GSHFAC Normal	0.63	0.06	0.24	0.05	0.22	0	---	---	---	0.04	0.09	0.01

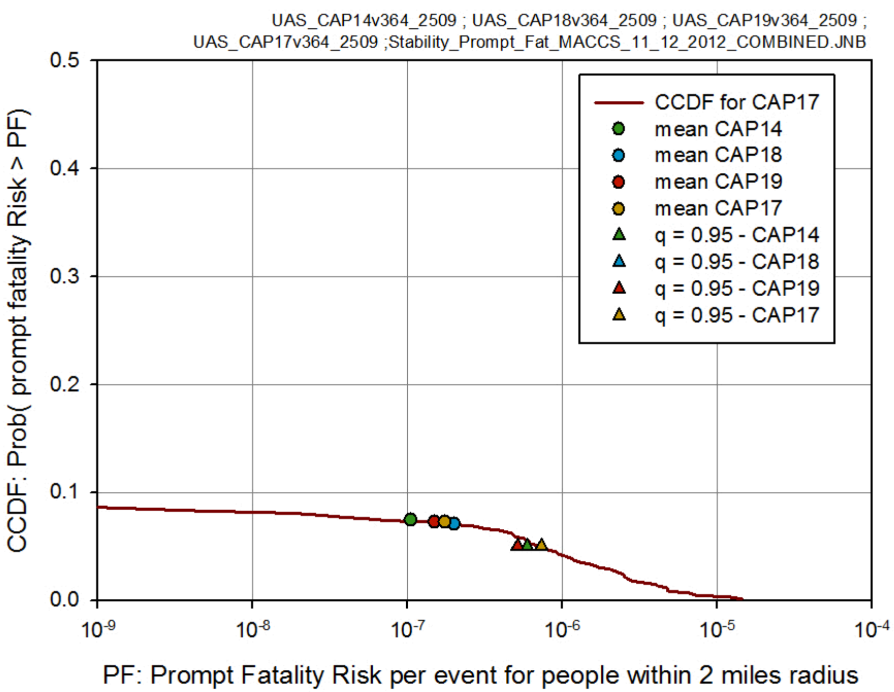
Dry Deposition Velocity

- Currently, MACCS2 uses a fixed deposition velocity that is independent of wind speed and other conditions
- A potential improvement is to allow deposition velocity to vary with wind speed and even variations in surface roughness



CCDF of Prompt Fatality Risk





Prompt Fatality Risk Regression

Less than 2 miles

(112 MACCS2 and 21 MELCOR input variables)

- The MACCS2 wet deposition model (CWASH1)
- The MELCOR SRV stochastic failure probability (SRVLAM)
  - The MELCOR SRV open area fraction (SRVOAFRAC)
  - The MELCOR DC station battery duration (BATTDUR)
- The MACCS2 early health effects threshold for red bone marrow (EFFTHR-Red Marrow)
  - The MACCS2 early health effects beta (shape) factor for red bone marrow (EFFACB-Red Marrow)
- The MACCS2 linear, crosswind dispersion coefficient (CYSIGA)
- The MACCS2 amount of shielding between an individual and the source of groundshine during normal activities for the non-evacuated residents (GSHFRAC-Normal)
- The MACCS2 evacuation delay for Cohort 5 (DELTVA-Cohort 5)

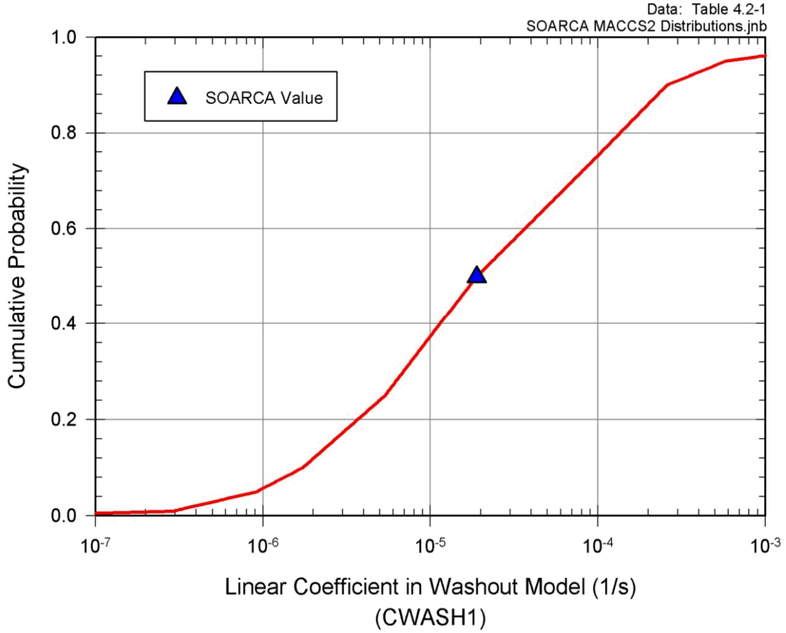
Prompt Fatality Risk Regression

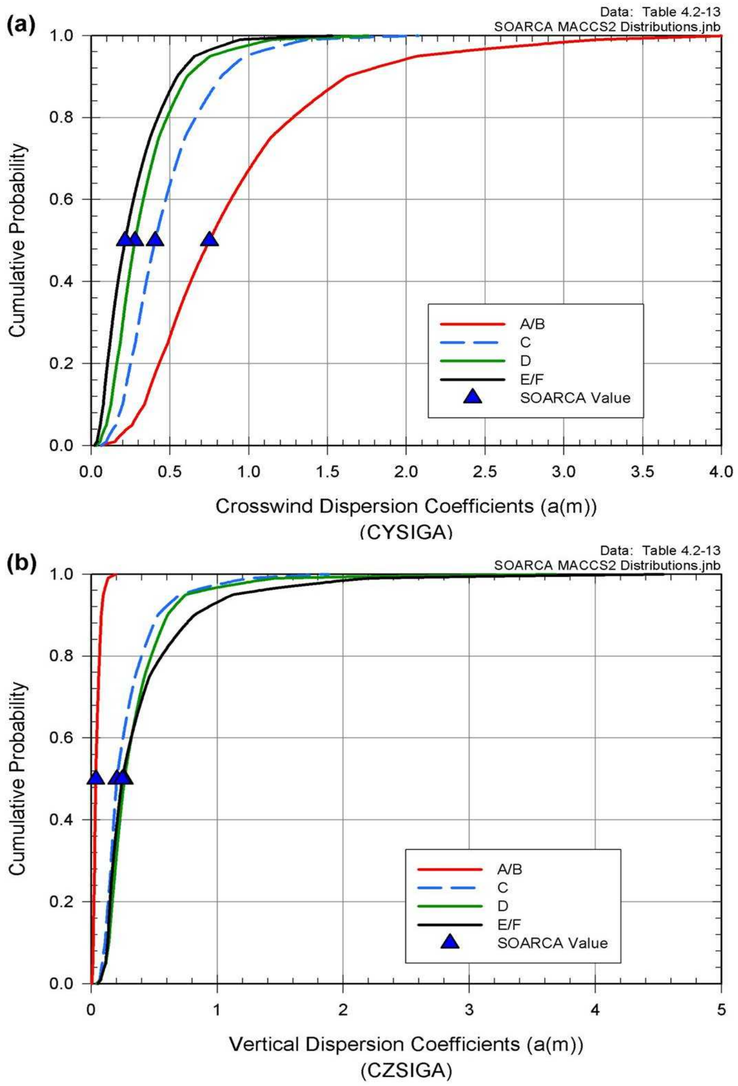
Greater than 2 miles but less than 5 miles

(112 MACCS2 and 21 MELCOR input variables)

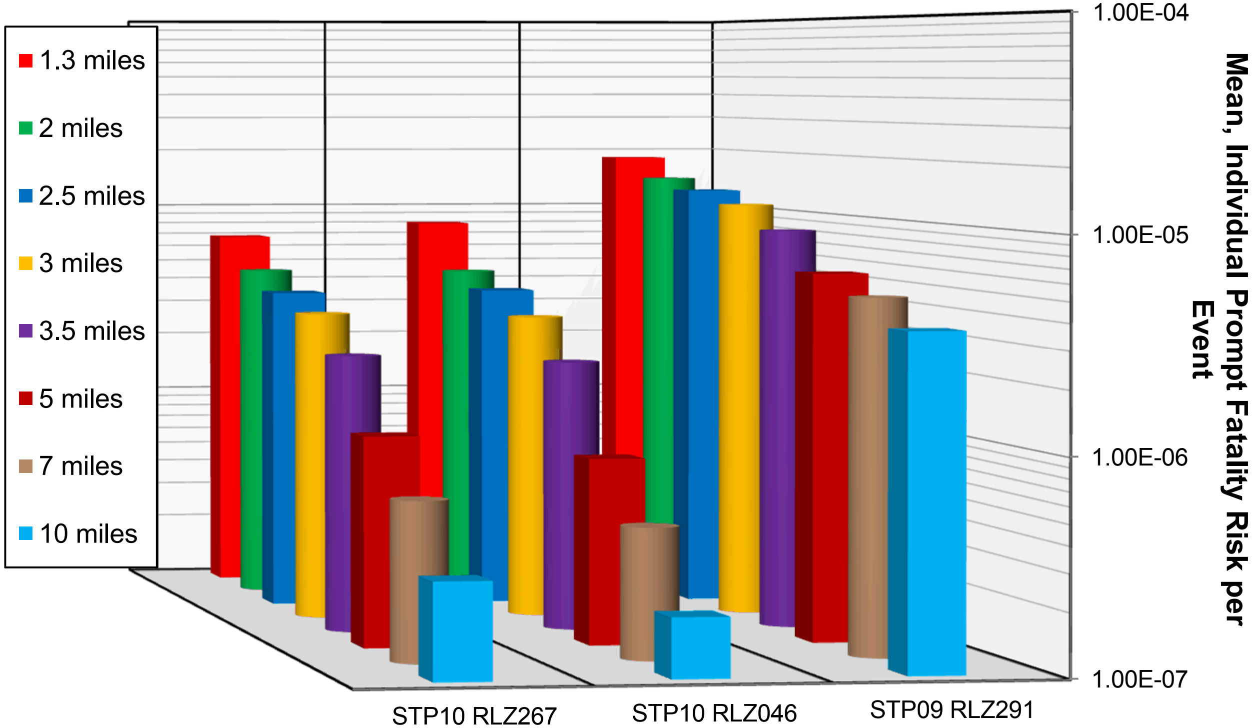
- The MACCS2 crosswind dispersion coefficient (CYSIGA),
- The MACCS2 early health effects threshold for red bone marrow (EFFTHR-Red Marrow),
  - The MACCS2 early health effects beta (shape) factor for red bone marrow (EFFACB-Red Marrow)
- The MELCOR SRV stochastic failure probability (SRVLAM)
  - The MELCOR SRV open area fraction (SRVOAFRAC)
  - The MELCOR DC station battery duration (BATTDUR)
  - The MELCOR railroad inner door open fraction (RRIDFRAC)
- The MACCS2 inhalation protection factor during sheltering activities for non-evacuated residents (PROTIN-Sheltering)

Wet Deposition Model & Dispersion Coefficients





Single Realizations



PF Risk	STP09 RLZ291	STP10 RLZ046	STP10 RLZ267
10 miles	3.7×10^{-6}	1.9×10^{-7}	2.9×10^{-7}
13 miles	1.4×10^{-4}	0.0	0.0
16 miles	1.3×10^{-4}	0.0	0.0
20 miles	1.1×10^{-4}	0.0	0.0
25 miles	8.4×10^{-5}	0.0	0.0
30 miles	5.4×10^{-5}	0.0	0.0
40 miles	0.0	0.0	0.0

- Only one realization resulted in prompt fatality risks beyond the EPZ
- This realization has multiple ‘extreme’ MACCS2 input parameters

STP09 RLZ291

- EFFTHR for red bone marrow is near the 1st percentile of the distribution
  - 83 RAD (Best estimate = median = 232 RAD)
- EFFACB for red bone marrow is near the 10th percentile of the distribution
- CSFACT for sheltering is near the 80th percentile of the distribution
- CYSIGA is near the 5th percentile of the distribution
- CZSIGA is near the 5th percentile of the distribution
- Source term is near the 95th percentile of the distribution

Scenario	Integral Release Fractions by Chemical Group									Atmospheric Release Timing	
	Xe	Cs	Ba	I	Te	Ru	Mo	Ce	La	Start (hr)	End (hr)
SOARCA Best Estimate	0.978	0.005	0.006	0.020	0.022	0	0.001	0	0	20	48
SOARCA UA Base Case	0.981	0.005	0.010	0.025	0.019	0	0	0	0	19.9	48
Replicate 2 RLZ291	0.792	0.085	0.134	0.160	0.132	0	0.019	0.012	0	11.5	48

Distance (miles)	Mean Peak Lifetime Committed Dose (rem)	Mean Peak Dose to the Red Bone Marrow (rads)
1.3	5,800	530
2	4,700	430
2.5	3,900	370
3	3,400	320
3.5	3,000	290
5	2,500	240
7	1,900	190
10	1,500	150
13	1,100	110
16	880	90
20	660	68
25	490	50
30	360	37

Sensitivity Analyses

Manual Control of the SRV Sensitivity

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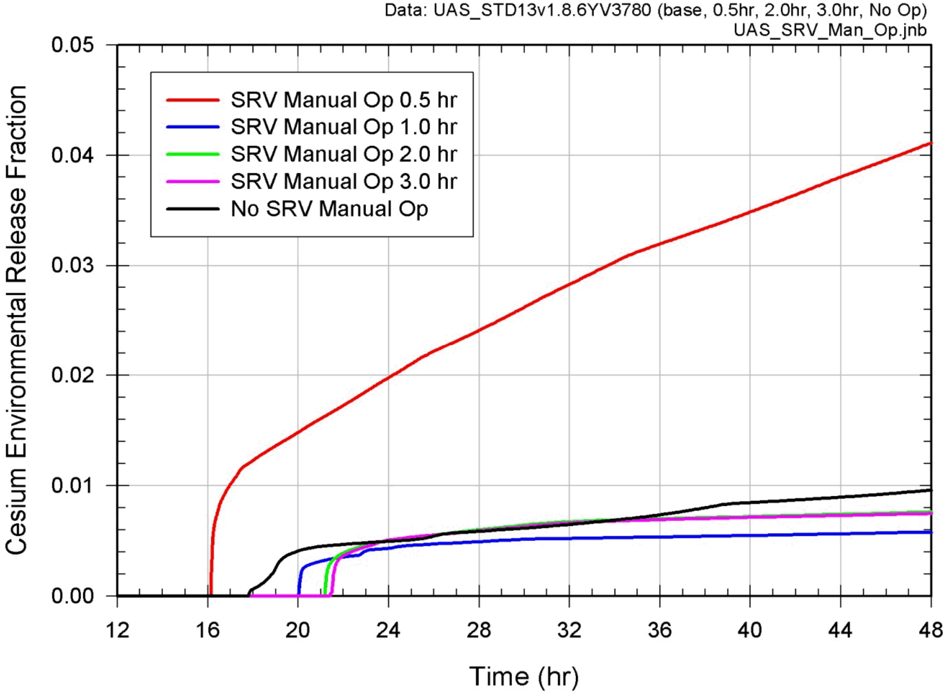
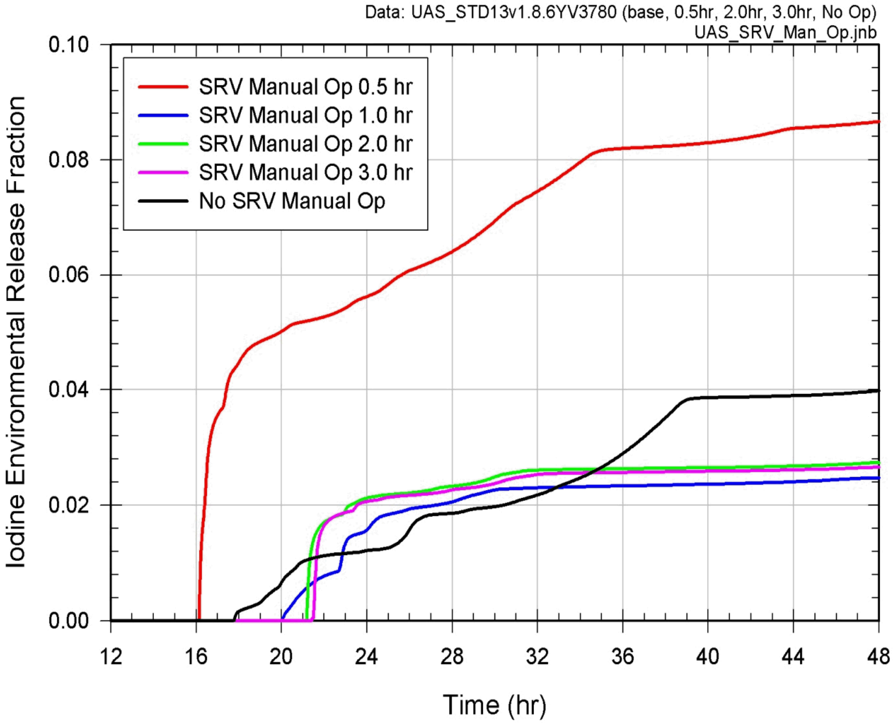


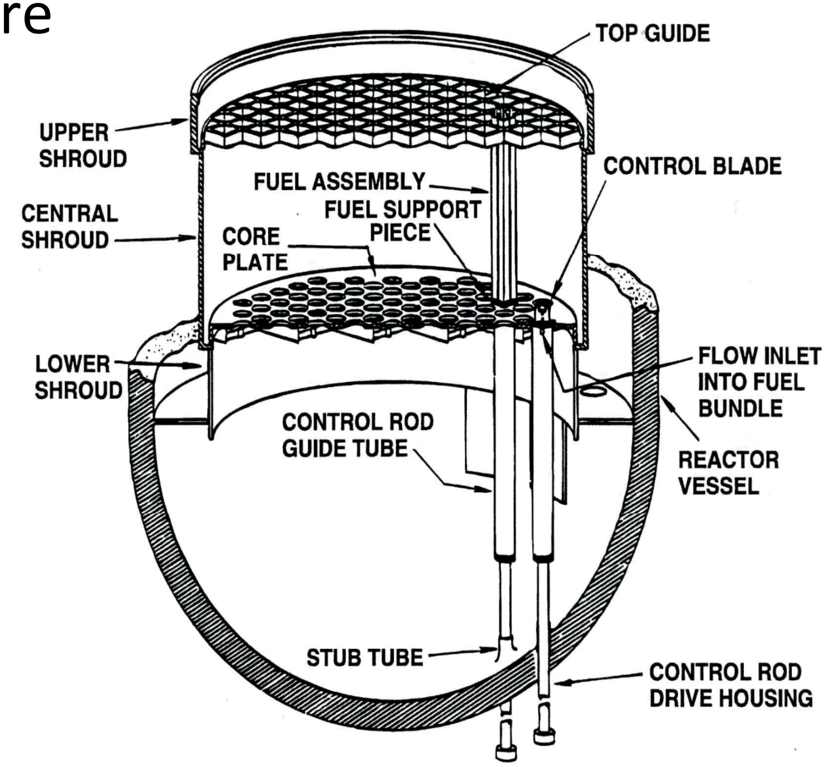
Opening at 0.5 hours of the SRVs:

- Depressurizes the reactor below 75 psig
- Trips the RCIC system
- Terminates the RCIC injection into the feedwater lines
- Less core makeup water being delivered to the reactor



Lower Head Penetration Sensitivity

- Past work only considered ‘gross creep failure’ of the RPV lower head
- Sensitivity considers penetration failure
  - 2 to 38 instrument tubes
  - Average of 13.5 tubes
- Sampled additional variables
  - Heat transfer coefficient between penetrations and core debris
  - Failure temperature



Lower Head Penetration Results

- Penetration failures generally occurred 3 hours before the gross lower head failure
- Relatively insensitive to variations in the sampled input parameters
- Relocation of core debris to the reactor cavity through penetrations generally began within 6 minutes of the first penetration failure once appreciable molten material resided near the penetration
- The penetrations did not ablate significantly
- Fractional releases of cesium to the environment showed the statistics:
  - Min: 0.006
  - Mean: 0.04
  - Max: 0.07
- Base Case cesium release = 0.005
  - Did not consider the possibility of penetration failures
  - Suggests a marked increase in release if penetration failures are considered

Lower Head Penetration Summary

- Sensitivity study suggests that it may be important to consider lower head penetration failures when modeling severe accidents in a BWR
- Influence on relative cesium release to the environment is potentially large
- In considering the results of the study, it may be important that the penetration modeling available in MELCOR lacks provisions for calculating the plugging of an open penetration by freezing melt
- If this phenomenon were accounted for, penetration failures might be immaterial in that the associated openings readily reclose promoting an eventual gross failure of the lower head
- Such plugging was observed to have occurred in the Three Mile Island accident where metallic debris was found refrozen inside instrument tubes outside of the reactor pressure vessel

Dose Truncation Regression Analysis

USBGR – 0.62 rem/yr

- The MACCS2 inhalation protection factor for normal activity (PROTIN–Normal)
- The MACCS2 lung lifetime risk factor for cancer death (CFRISK-Lung)
- The MELCOR SRV stochastic failure probability (SRVLAM)
  - The MELCOR SRV open area fraction (SRVOAFRAC)
  - The MELCOR DC station battery duration (BATTDUR)
- The most important input parameters using the USBGR dose truncation model are those associated with doses received in the first year and not ones associated with the long-term phase risk beyond the first year

Dose Truncation Regression Analysis

HPS – 5 rem/yr not to exceed 10 rem lifetime

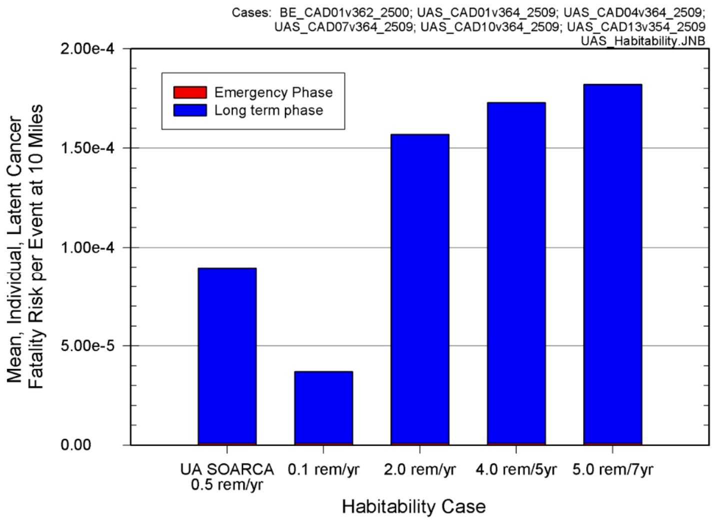
- The MACCS2 lung lifetime risk factor for cancer death (CFRISK-Lung)
- The MACCS2 inhalation protection factor for normal activity (PROTIN–Normal)
- The MELCOR SRV stochastic failure probability (SRVLAM)
  - The MELCOR SRV open area fraction (SRVOAFRAC)
  - The MELCOR DC station battery duration (BATTDUR)
  - The MELCOR fuel failure criterion (FCC)
- The most important input parameters using the HPS dose truncation model are those associated with doses received in the first year and not ones associated with the long-term phase risk beyond the first year

Habitability Sensitivity

- LNT, USBGR, & HPS dose-response models
- State of Pennsylvania
  - 0.5 rem/yr
- EPA PAG Guidance
  - 2 rem 1st year and 0.5 rem 2nd through 7th year (5 rem/7yrs)
- NUREG-1150 (1989 EPA draft document)
  - 2 rem 1st year and 0.5 rem 2nd through 5th year (4 rem/5yrs)
- ICRP 103 & 111 guidance
  - Lower bound of 0.1 rem/yr
  - Upper bound of 2 rem/yr

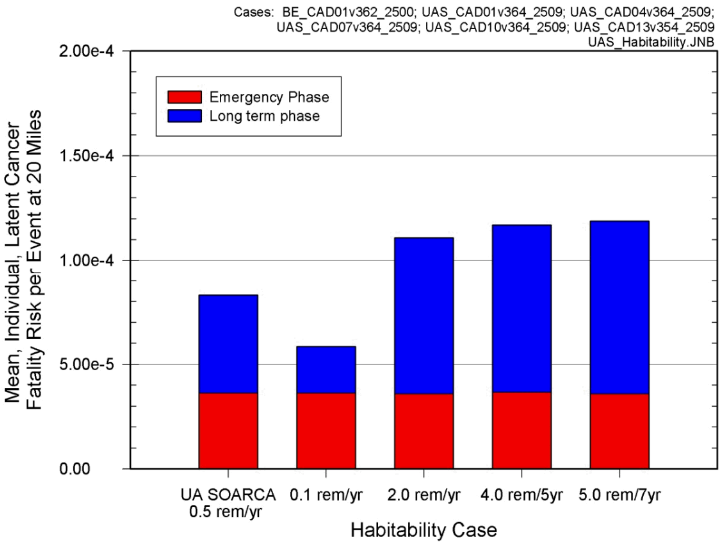
Habitability Insights - LNT

- The majority of the LCF risk contribution within the EPZ results from the long-term phase for all of the habitability choices investigated
- The higher the habitability dose limit, the higher the LCF risk as a result of long-term dose within the EPZ
- The majority of the LCF risk outside the EPZ for the 0.1 rem/yr habitability criterion is from the emergency phase
- While the emergency phase LCF risk for the 0.1 rem/yr habitability criterion is the same as the risk for all the habitability criteria, the low threshold reduces long-term LCF risk
- All other habitability criteria have the majority of their respective LCF risk from the long-term phase outside the EPZ



Within EPZ

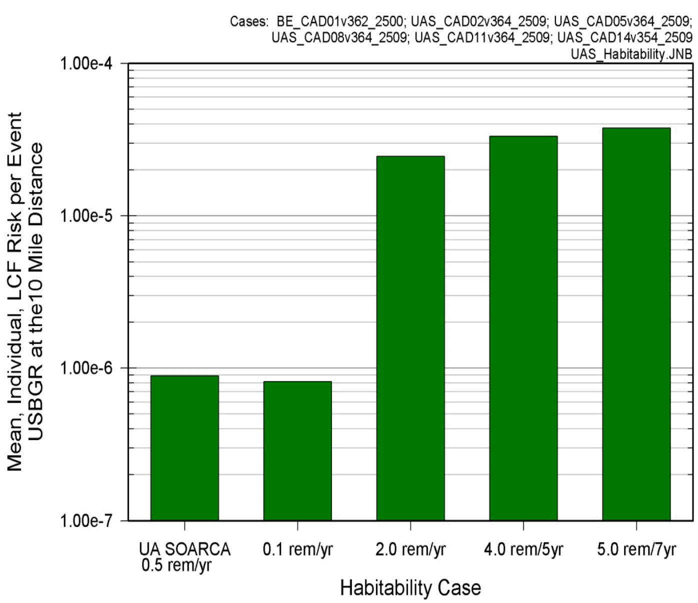
20-mile circular area



Habitability Insights - USBGR

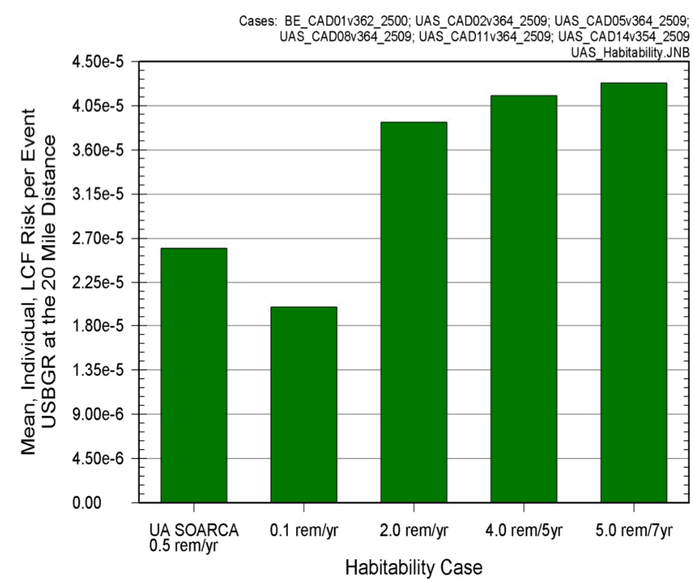
- Within the EPZ, when the dose rate for the habitability criterion is below the dose truncation level (0.62 rem/yr), LCF risks are two orders of magnitude lower than when the dose rate for the habitability criterion is above the dose truncation level

- The habitability sensitivities have little effect on the overall LCF risk when the USBGR dose-response model is applied beyond the EPZ. The risks are similar to those presented in the SOARCA study



Within EPZ

20-mile circular area



Aleatory Weather Sensitivity

- The overall difference between the SOARCA weather sampling technique (984 sampled weather trials) and sampling all 8,760 hourly data points is small
- The SOARCA weather sampling technique always produces greater LCF risk results for all dose-response models
- The increase in computational time is eight fold
  - Not necessarily long for the LNT dose-response remodel (i.e., ~1 hour to ~8 hours for a single MACCS2 realization)
  - Increase in computation time for the USBGR and HPS dose response models makes uncertainty analysis applications less feasible (i.e., ~1 day to ~8 days for a single MACCS2 realization)

Distance	Difference		
	LNT	USBGR	HPS
10	0.8%	0.8%	0.9%
20	2.4%	5.0%	11.0%
30	1.7%	5.2%	11.6%
40	1.1%	5.7%	11.6%
50	1.3%	5.5%	11.7%

Aleatory Weather Sensitivity *(continued – 1)*

- In SOARCA, the aleatory uncertainties due to weather were characterized in terms of mean values. However, a CCDF of aleatory uncertainties can be obtained using a single MACCS2 analysis for each source term
  - Three source terms were selected, which provided insights into the overall distribution of LCF risk for the sensitivity simulations
- A set of sensitivity analyses to evaluate the aleatory weather uncertainty using the SOARCA weather sampling technique was evaluated for the LNT, USBGR, and HPS dose-response models

Aleatory Weather Sensitivity *(continued – 2)*

- For LNT, the individual LCF risk per event for aleatory weather uncertainty is bounded for all analyses by the epistemic uncertainty for the mean, individual LCF risk per event results of the MACCS2 uncertainty analysis
  - The epistemic uncertainties within the MACCS2 uncertainty analysis have a greater effect on the overall uncertainty than the aleatory weather uncertainty
- For the USBGR and HPS dose-response models, the epistemic uncertainties for the mean, individual LCF risk results of the MACCS2 uncertainty analysis have a greater effect on the overall uncertainty than the aleatory weather uncertainty for the higher source term releases. The following trends are observed and are specific to the three source terms analyzed:
  - The dose-truncation model has a larger contribution of the LCF risk from the emergency phase and earlier years of the long-term phase
  - The emergency phase risk for the smaller source term release has a larger effect on the overall LCF risk
  - The three source terms used in these analyses are bounded at the upper end of the CCDF individual LCF risk distribution for aleatory weather uncertainty by the epistemic uncertainties for the mean, individual LCF risk results of the MACCS2 uncertainty analysis, but are not bounded at the lower end of the distribution for individual LCF risk
- This sensitivity analysis also indicates that a higher dose-truncation threshold is more sensitive to aleatory weather uncertainty

Aleatory Weather Sensitivity
(continued – 3)

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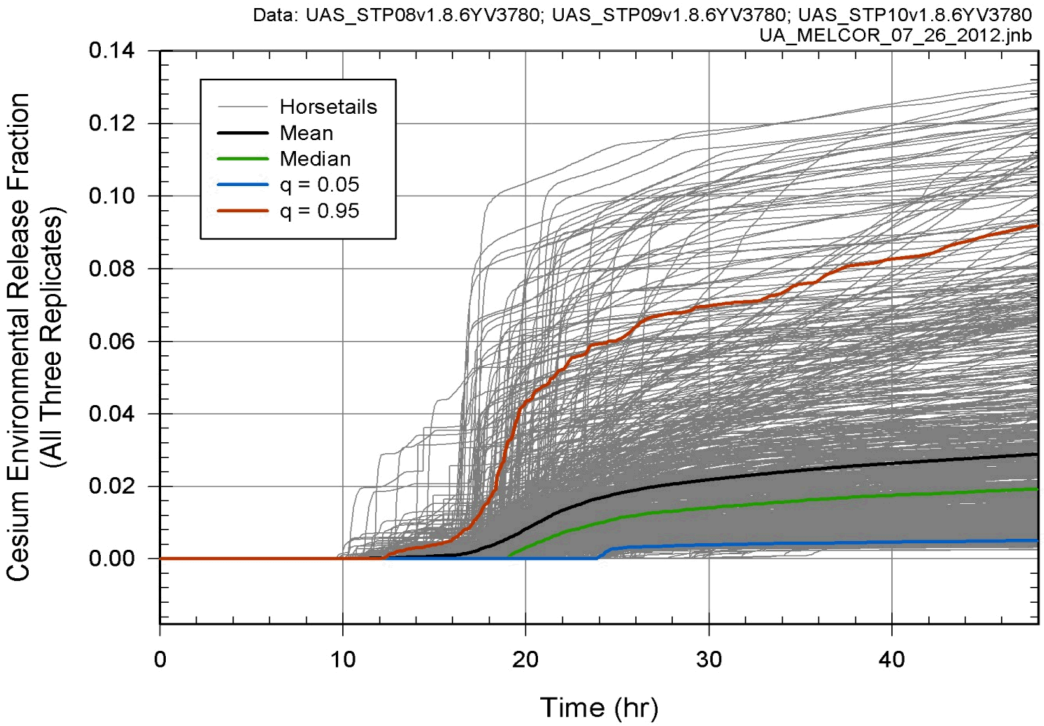
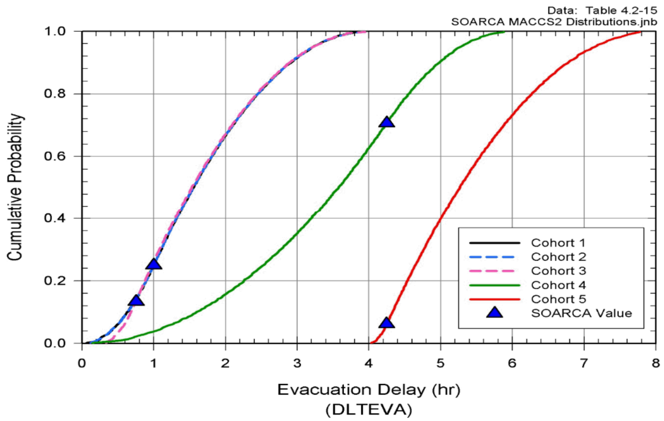
Individual LCF risk per event ratio of the 5th and 95th percentile for the MACCS2 aleatory uncertainty analyses and the MACCS2 uncertainty analysis for specified circular areas

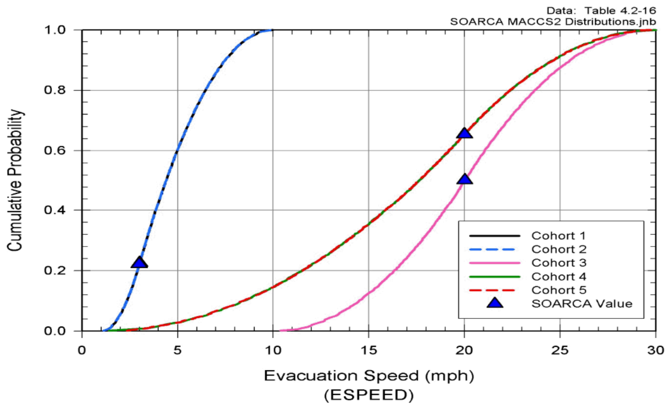
Radius of Circular Area (miles)	SOARCA UA Base Case	Replicate 1 Realization 62	Replicate 1 Realization 170	MACCS2 Uncertainty Analysis
LNT – 10	4.9	3.4	4.3	13
LNT – 20	8.3	5.5	6.5	15
LNT – 30	11	4.5	6.8	15
LNT – 40	9.4	5.4	7.4	15
LNT – 50	9.6	5.8	9.0	14
USBGR – 10	11	10	12	45
USBGR – 20	190	12	26	58
USBGR – 30	400	11	43	70
USBGR – 40	420	11	53	73
USBGR – 50	480	12	58	72
HPS – 10	110	34	80	80
HPS – 20	10,000	150	2,800	780
HPS – 30	11,000	170	3,600	1,400
HPS – 40	12,000	180	3,900	1,900
HPS – 50	12,000	190	3,400	2,100

Emergency Protection Parameters

- Only one instance was an EP parameter considered important for any regression analysis or sensitivity study
  - Prompt Fatality Risk Regression for less than 2 miles
    - Evacuation delay for Cohort 5 (DELTVA-Cohort 5)







Conclusions

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Peach Bottom UA corroborates SOARCA study conclusions:

- Public health consequences from severe nuclear accident scenarios modeled are smaller than 1982 SNL Siting Study (NUREG/CR-2239)
- The delay in releases calculated provide more time for emergency response actions such as evacuating or sheltering
- Long-term phase dominates health effect risk within EPZ because the emergency response is faster than the onset of environmental release
- More than half the time (55%), the long-term phase is the larger contributor (>50%) to the overall health risk beyond the EPZ
  - Long-term health effect risk is largely controlled by the habitability criterion

Conclusions
(continued – 1)

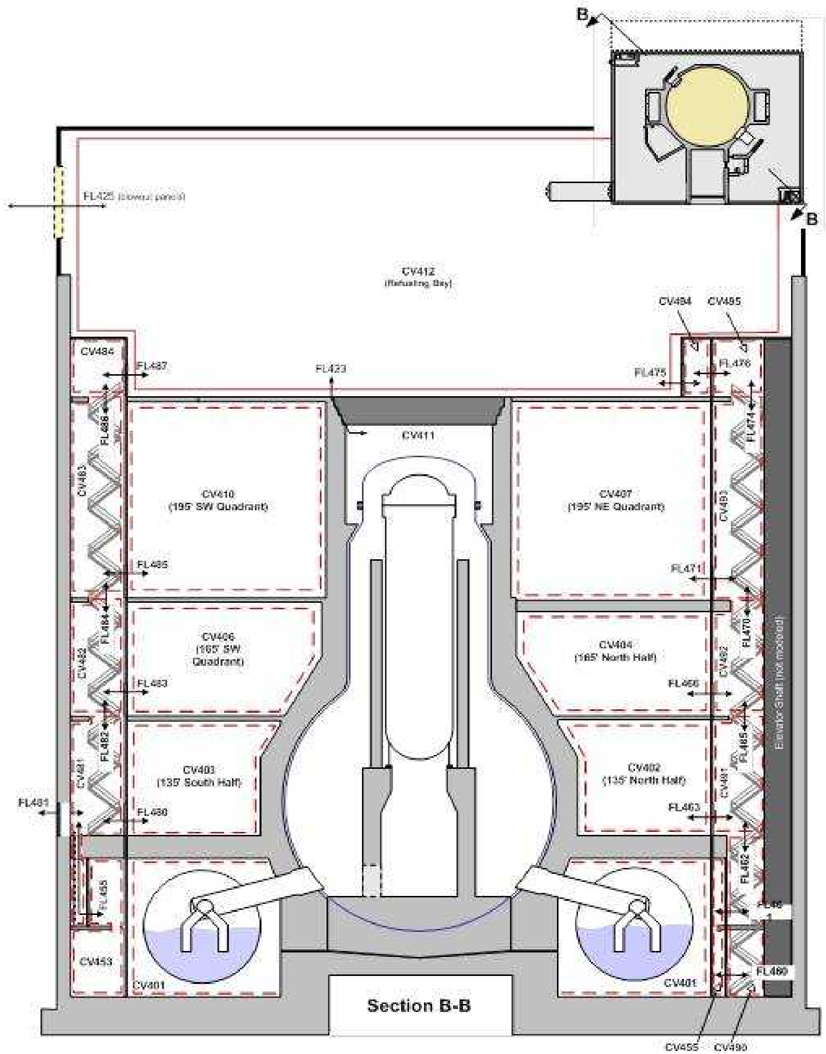
- "Essentially zero' absolute early fatality risk projected:
  - Mean absolute early fatality risk is 1.4×10^{-12} pry within 1 mile of EAB
  - NRC QHO for prompt fatalities is 5.0×10^{-7} pry
- A major determinant of source term magnitude is whether the sticking open of the SRV occurs before the onset of core damage
  - Compounding this effect is whether or not main steam line creep rupture occurs
    - Leads to higher consequences
- Health-effect risks vary sublinearly with source term because people are not allowed to return to their homes until dose is below habitability criterion

Conclusions
(continued – 2)

- Analysis confirms known importance of some phenomena, and reveals some new phenomenological insights
  - Dry deposition velocity
  - Late phase revaporization with RPV

- The use of multiple techniques, most of which include nonlinear interactions between input variables, to post-process Monte Carlo and LHS results provides better explanatory power of which input parameters are most important to uncertainty in results

Questions



CV412
(Refueling Bay)
CV411
CV410
(195' SW Quadrant)
CV407
(195' NE Quadrant)
CV406
(165' SW
Quadrant)
CV404
(165' North Half)
CV403
(135' South Half)
CV402
(135' North Half)
CV401
CV494
CV495
CV484
CV453
CV455
CV490
Section B-B