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# State-of-the-Art Reactor Consequence Analyses (SOARCA) Surry Uncertainty Analysis (UA)

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- MELMACCS: Nathan Bixler, Doug Osborn (SNL)
- MACCS, consequence analysis and emergency response: Nathan Bixler, Joe Jones, Doug Osborn (SNL)
- UA methodology: Cedric Sallaberry, Dusty Brooks, Aubrey Eckert-Gallup, Jon Helton, Matthew Denman (SNL); Tina Ghosh, Trey Hathaway (NRC)

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- MACCS consequence analysis results
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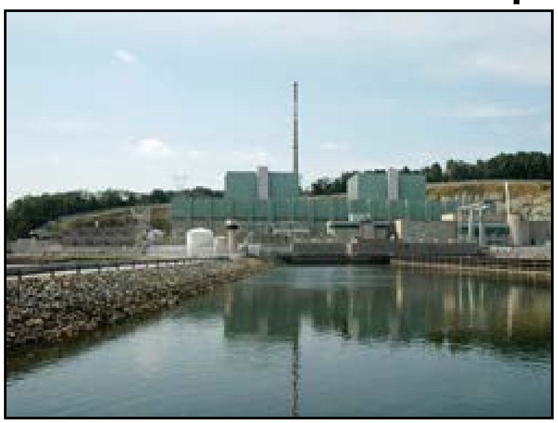
# Background on SOARCA

- SOARCA was initiated to develop a body of knowledge on the <u>realistic</u> outcomes of severe reactor accidents; two pilot plants



**Peach Bottom**

**Surry**

- SECY-12-0092, “State-of-the-Art Reactor Consequence Analyses – Recommendation for Limited Additional Analysis”
  - Staff recommended “UA for a severe accident scenario at Surry”

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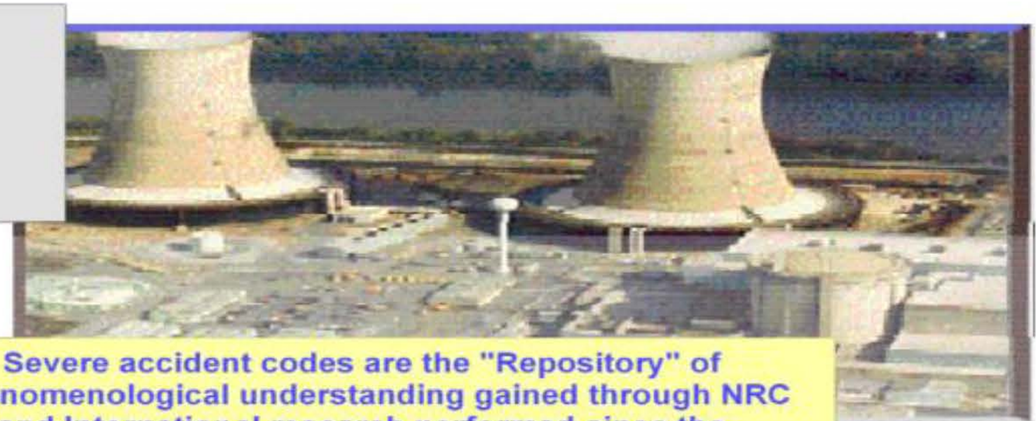
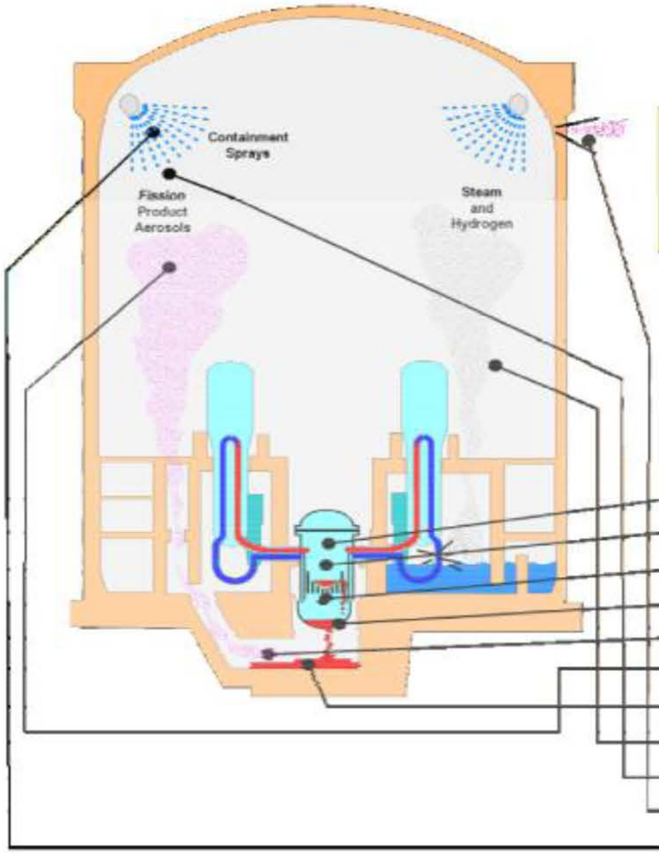
# MELCOR – Severe Reactor Accident System Code

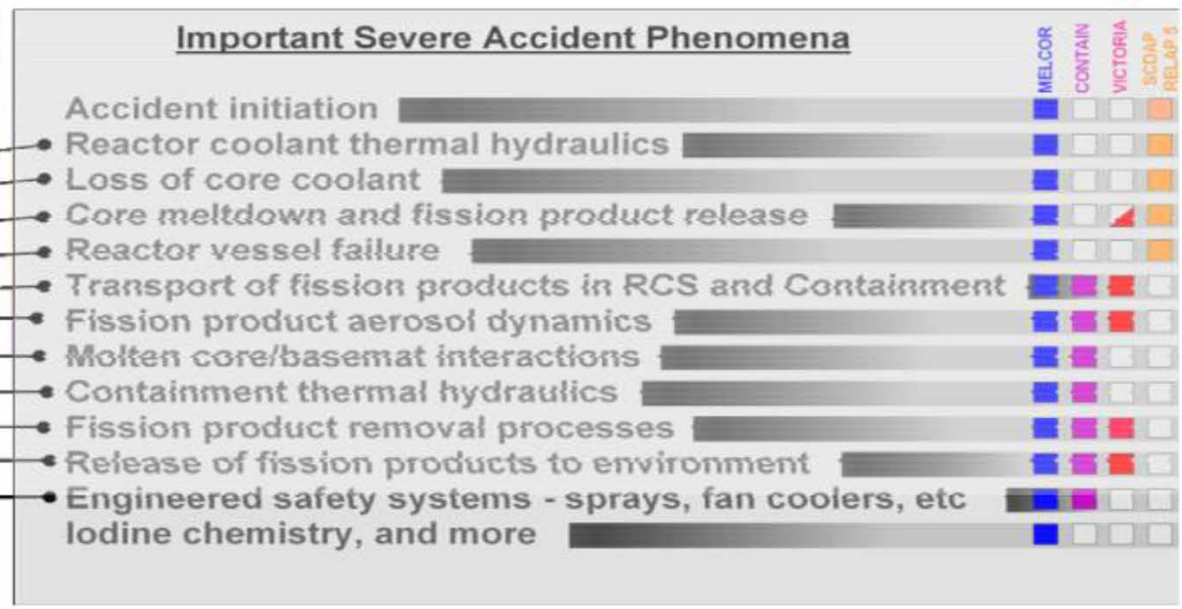
## Modeling and Analysis of Severe Accidents in Nuclear Power Plants



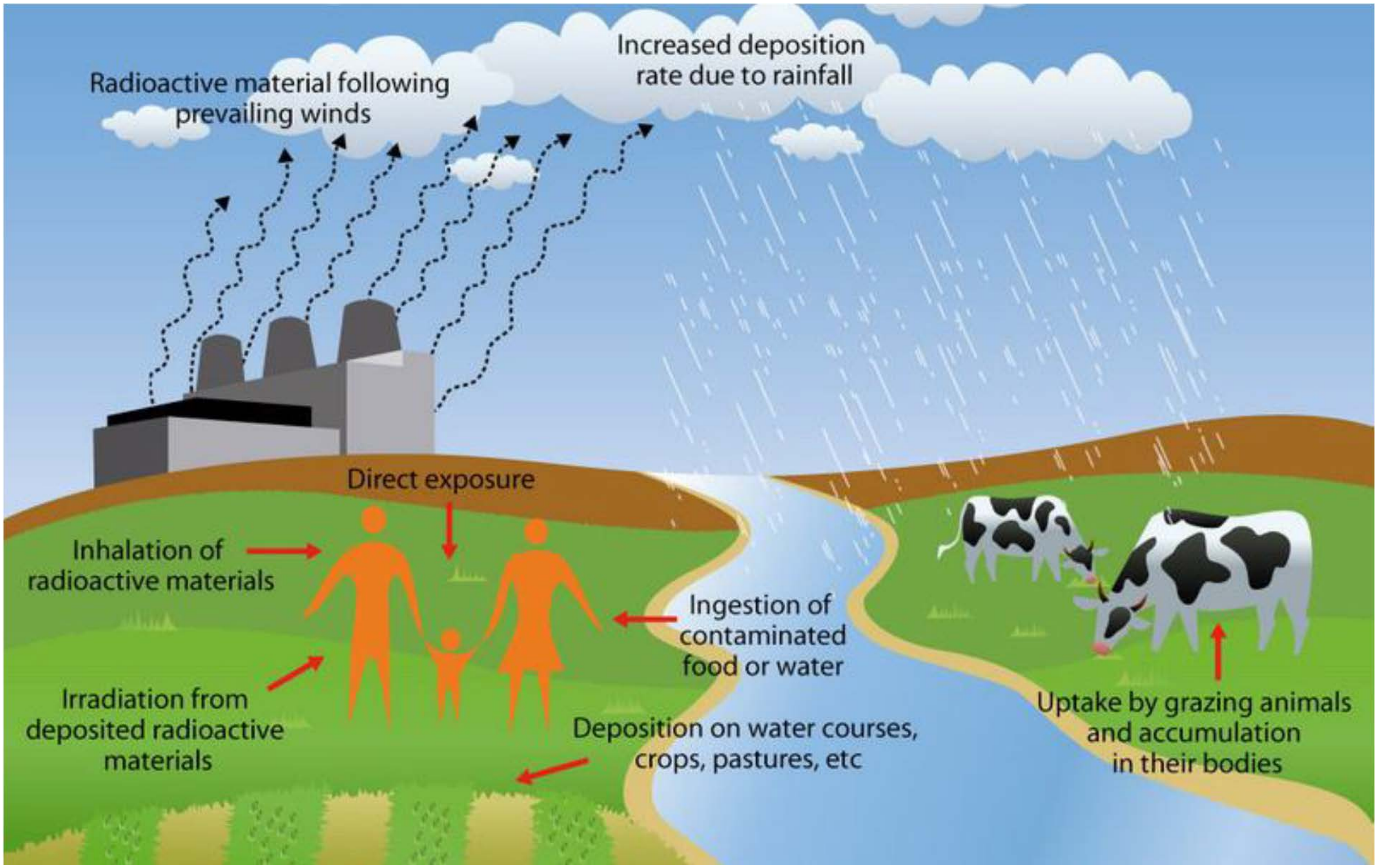



**Severe accident codes are the "Repository" of phenomenological understanding gained through NRC and International research performed since the TMI-2 accident in 1979**

***Integrated** models required for self consistent analysis*



# MACCS – MELCOR Accident Consequence Code System



# Objectives of the Uncertainty Analysis

- Develop insight into overall sensitivity of results and conclusions to uncertainty in model inputs.
- Identify the most influential input parameters contributing to variations in accident progression, source term, and offsite consequence results.
- “Complement and support” the NRC’s Site Level 3 PRA project and post-Fukushima activities including Tier 3 items. (Staff Requirements Memorandum SECY-12-0092)

# Overview

- Analysis of uncertainty in the Surry SOARCA unmitigated short term station blackout (STSBO)
- Focus on epistemic (state-of-knowledge) uncertainty in input parameter values, and limited aleatory uncertainty
  - Aleatory (random) uncertainty due to weather always handled
  - Time-at-cycle (burn-up) and stochastic nature of safety valve failure investigated (aleatory aspects of some input parameters)
- Investigated uncertainty in selected key MELCOR and MACCS inputs
- Uncertainty in these parameters was propagated in a two-step Monte Carlo simulation:
  - A set of source terms generated using MELCOR model
  - A distribution of consequence results generated using MACCS model

# Overview (continued)

- 1003 successful MELCOR Monte Carlo "realizations" completed to 48 hours were each coupled with a successful MACCS realization
- Results reported with regard to figures of merit investigated:
  - MELCOR: Cesium and Iodine release to the environment by 48 hours, in-vessel hydrogen production, and timing of initial fission product release to the environment
  - MACCS: Individual early and latent cancer fatality (LCF) risk
- Results analyzed with statistical regression based methods, scatter plots, and phenomenological investigation of selected individual realizations
  - An individual realization is a single run (or "realization") selected from the set generated in the Monte Carlo simulation

# MELCOR Uncertain Parameters

*Sequence*

- Primary SV stochastic FTC
- Primary SV stochastic FTO
- Primary SV FTC due to passing water
- Secondary SV stochastic FTC
- SV open area fraction
- Primary SV FTC due to overheating
- Reactor coolant pump seal leakage (RCPSL)
- Normalized temperature of hottest SG tube
- SG tube thickness (mm)

*In-Vessel Accident Progression*

- Zircaloy melt breakout temperature**
- Molten clad drainage rate**
- Radial molten debris relocation time constant (RDMTC)**
- Radial solid debris relocation time constant (RDSTC)**
- Time in the fuel cycle of the accident (CYCLE)
- Decay Heat (DEV_DECAY_HEAT)
- Melting temperature of the eutectic formed between $UO_2$ and $ZrO_2$

** indicates parameter was uncertain in the Peach Bottom UA

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# MELCOR Uncertain Parameters (continued)

*Ex-vessel Accident Progression*

- Hydrogen ignition criteria ($H_2$ LFL)
- SGTR location (for decontamination factor per ARTIST)

*Containment Behavior*

- Containment design leakage rate (DLEAK)
- Containment fragility curve (CFC)
- Containment convection heat transfer coefficient

*Chemical Forms of Iodine and Cesium*

- CHEMFORM iodine**
- CHEMFORM cesium**

*Aerosol Transport and Deposition*

- Dynamic Shape Factor (PARTSHAPE)

** indicates parameter was uncertain in the Peach Bottom UA

# Cesium Release Fraction to Environment

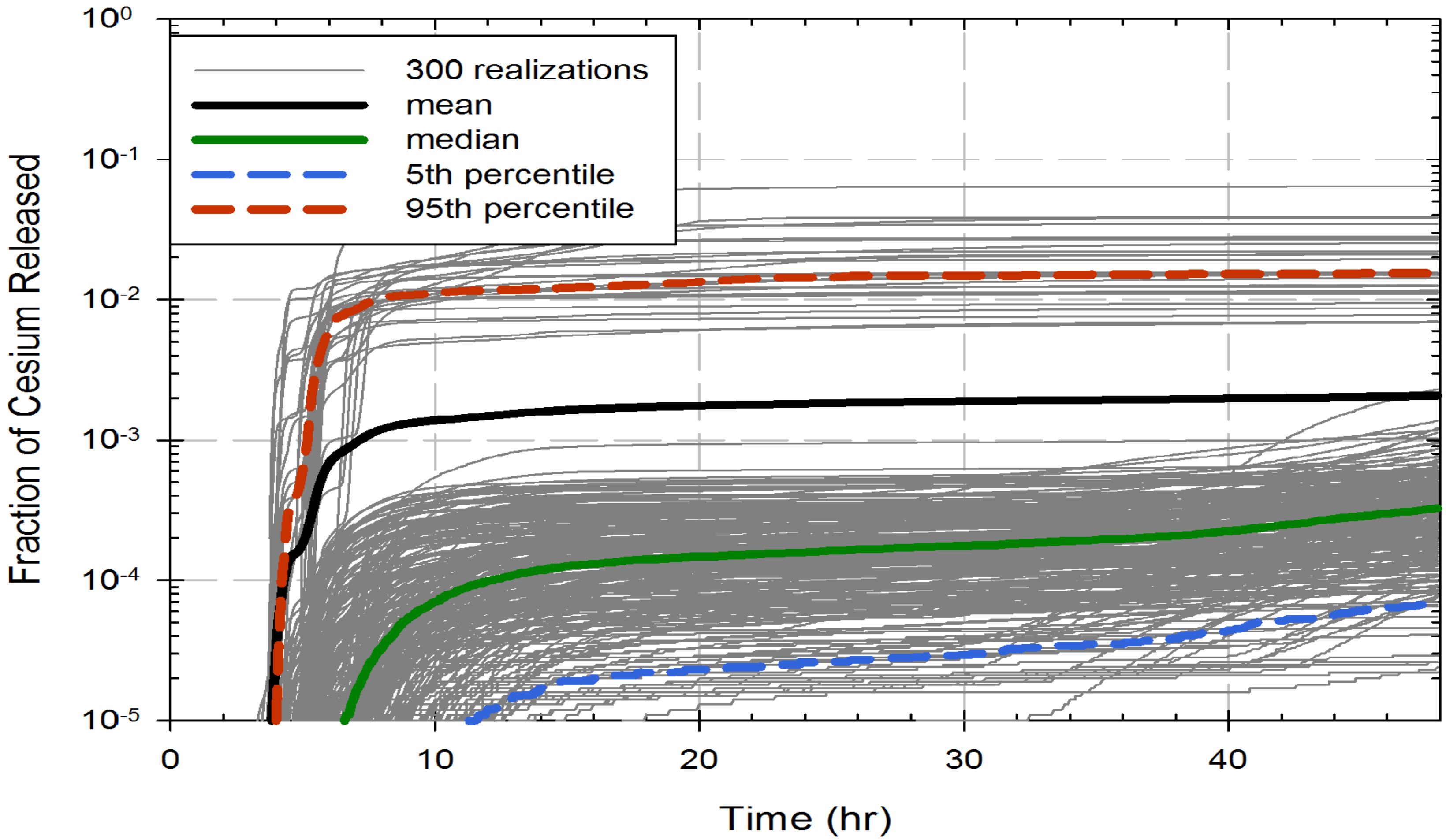


**Figure 6-13 Cesium release fractions over 48 hours with mean, median, 5$^{th}$ and 95$^{th}$ percentiles** (which are calculated at each point in time)

# Cesium Regression Analysis for non-SGTR Realizations

- Design leakage was identified by each regression technique as the largest contributor to uncertainty.
- The next two parameters, time at cycle and shape factor, explain the majority of the remaining uncertainty that is explained by the regression models. There is some uncertainty that is not explained by the regression models.

| | Rank Regression | | Quadratic | | Recursive Partitioning | | MARS | | Main Contr.* | Conjoint Contr. * |
|---|---|---|---|---|---|---|---|---|---|---|
| Final $R^2$ | 0.67 | | 0.79 | | 0.83 | | 0.68 | | | |
| Input | $R^2$ contr. | SRRC | $S_i$ | $T_i$ | $S_i$ | $T_i$ | $S_i$ | $T_i$ | | |
| *DLEAK* | 0.35 | 0.58 | 0.29 | 0.34 | 0.25 | 0.48 | 0.35 | 0.35 | 0.258 | 0.077 |
| *CYCLE* | 0.15 | 0.42 | 0.19 | 0.29 | 0.12 | 0.30 | 0.20 | 0.20 | 0.135 | 0.073 |
| *PARTSHAPE* | 0.05 | 0.23 | 0.12 | 0.16 | 0.09 | 0.33 | 0.18 | 0.21 | 0.085 | 0.081 |
| *CFC* | 0.04 | -0.20 | 0.07 | 0.12 | 0.03 | 0.20 | 0.11 | 0.12 | 0.050 | 0.060 |
| *DEV_DEC_HEAT* | 0.02 | -0.15 | 0.04 | 0.07 | 0.05 | 0.23 | 0.05 | 0.06 | 0.031 | 0.061 |
| *CHEMFORMCS* | 0.03 | -0.16 | 0.03 | 0.06 | 0.00 | 0.05 | 0.04 | 0.04 | 0.020 | 0.022 |
| *SVOAFRAC* | 0.01 | -0.12 | 0.00 | 0.05 | 0.01 | 0.10 | 0.01 | 0.04 | 0.006 | 0.044 |
| *SC1132* | 0.01 | 0.07 | 0.00 | 0.02 | 0.00 | 0.02 | 0.01 | 0.03 | 0.004 | 0.015 |
| *TUBTHICK* | 0.00 | 0.03 | 0.01 | 0.00 | 0.00 | 0.02 | --- | --- | 0.003 | 0.006 |
| *CONDENS* | 0.00 | -0.06 | 0.00 | 0.02 | 0.00 | 0.02 | 0.01 | 0.01 | 0.003 | 0.011 |
| *SGTRLOC* | 0.01 | 0.07 | 0.00 | 0.01 | --- | --- | 0.00 | 0.01 | 0.002 | 0.003 |
| *RDSTC* | 0.00 | 0.06 | --- | --- | 0.00 | 0.02 | 0.00 | 0.01 | 0.001 | 0.005 |
| *SC1131* | 0.00 | -0.04 | 0.00 | 0.00 | 0.00 | 0.02 | --- | --- | 0.001 | 0.004 |
| *RCPSL* | 0.00 | 0.08 | --- | --- | 0.00 | 0.01 | 0.00 | 0.01 | 0.001 | 0.003 |
| *SRVFAILT* | --- | --- | --- | --- | --- | --- | 0.00 | 0.01 | 0.000 | 0.001 |
| *SV_STATUS* | --- | --- | 0.00 | 0.06 | --- | --- | 0.00 | 0.00 | 0.000 | 0.016 |
| *SG_B_SV_cycl* | --- | --- | 0.00 | 0.01 | 0.00 | 0.01 | --- | --- | 0.000 | 0.008 |
| *TUBETEMP* | --- | --- | 0.00 | 0.01 | 0.00 | 0.01 | --- | --- | 0.000 | 0.006 |
| *CHEMFORMI2* | --- | --- | --- | --- | --- | --- | 0.00 | 0.00 | 0.000 | 0.000 |

* highlighted if main contribution larger than 0.02 or conjoint contribution larger than 0.1

**Table 6-4 Regression analysis of cesium release fraction in non-SGTR realizations.**

# Cesium Regression Analysis for SGTR Realizations

- Safety valve open area fraction (SVOAFRAC) is a partial indicator for the open fraction of both the primary and secondary SV system at 48 hours.
  – The number of safety valve cycles is also thought to be important, though not shown in regression results
- Sampling thickness of hottest SG tube (TUBTHICK) effectively also samples stress multiplier on the creep equation.

| | Rank Regression | | Quadratic | | Recursive Partitioning | | MARS | | Main Contr.* | Con-joint Contr.* |
|---|---|---|---|---|---|---|---|---|---|---|
| Final $R^2$ | 0.54 | | 1.00 | | 0.81 | | 0.54 | | | |
| Input | $R^2$ contr. | SRRC | $S_i$ | $T_i$ | $S_i$ | $T_i$ | $S_i$ | $T_i$ | | |
| *SVOAFRAC* | 0.13 | 0.58 | 0.30 | 0.75 | 0.39 | 0.71 | --- | --- | 0.188 | 0.234 |
| *TUBTHICK* | 0.21 | -0.27 | 0.00 | 0.02 | 0.07 | 0.14 | 0.36 | 0.36 | 0.115 | 0.023 |
| *SV_STATUS* | --- | --- | 0.04 | 0.12 | --- | --- | 0.33 | 0.33 | 0.072 | 0.026 |
| *CYCLE* | 0.08 | 0.34 | 0.00 | 0.02 | 0.06 | 0.12 | 0.22 | 0.22 | 0.062 | 0.024 |
| *PARTSHAPE* | 0.12 | 0.36 | 0.00 | 0.00 | 0.05 | 0.09 | 0.09 | 0.09 | 0.052 | 0.011 |
| *CHEMFORMCS* | --- | --- | --- | --- | 0.06 | 0.27 | --- | --- | 0.015 | 0.058 |
| *DLEAK* | --- | --- | 0.04 | 0.59 | --- | --- | --- | --- | 0.014 | 0.184 |
| *SC1141* | --- | --- | 0.00 | 0.00 | 0.01 | 0.06 | --- | --- | 0.004 | 0.013 |
| *SV_WTR_CYC* | --- | --- | 0.01 | 0.09 | --- | --- | 0.00 | 0.00 | 0.003 | 0.028 |
| *SGTRLOC* | --- | --- | 0.01 | 0.03 | --- | --- | --- | --- | 0.003 | 0.009 |
| *H2LFL* | --- | --- | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.002 | 0.001 |
| *SC1131* | --- | --- | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.002 | 0.002 |
| *RDSTC* | --- | --- | 0.00 | 0.00 | --- | --- | --- | --- | 0.001 | 0.000 |
| *SRVFAILT* | --- | --- | 0.00 | 0.01 | --- | --- | 0.00 | 0.00 | 0.000 | 0.004 |
| *CONDENS* | --- | --- | 0.00 | 0.00 | --- | --- | 0.00 | 0.00 | 0.000 | 0.002 |
| *RDMTC* | --- | --- | --- | --- | 0.00 | 0.02 | 0.00 | 0.00 | 0.000 | 0.006 |
| *RCPSL* | --- | --- | --- | --- | 0.00 | 0.00 | 0.00 | 0.01 | 0.000 | 0.001 |
| *SC1132* | --- | --- | --- | --- | --- | --- | 0.00 | 0.01 | 0.000 | 0.001 |
| *SV_NBCYC* | --- | --- | --- | --- | --- | --- | 0.00 | 0.00 | 0.000 | 0.001 |
| *DEV_DEC_HEAT* | --- | --- | --- | --- | --- | --- | 0.00 | 0.00 | 0.000 | 0.000 |
| *TUBETEMP* | --- | --- | --- | --- | --- | --- | 0.00 | 0.00 | 0.000 | 0.000 |

**Table 6-9 Regression analysis of cesium release fraction for SGTRs.**

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# MACCS Uncertain Parameter Groups

*Deposition*

- Wet Deposition (CWASH1)
- Dry Deposition Velocities (VDEPOS, m/s)

*Dispersion*

- Crosswind Dispersion Linear Coefficient (CYSIGA)
- Vertical Dispersion Linear Coefficient (CZSIGA)

*Shielding factors*

- Groundshine Shielding Factors (GSHFAC)
- Inhalation Protection Factors (PROTIN)

*Latent Health Effects*

- Dose and dose rate effectiveness factor (DDREFA)
- Lifetime Cancer Fatality Risk Factors (CFRISK)
- Long Term Inhalation Dose Coefficients

*Early Health Effects*

- Early Health Effects $LD_{50}$ Parameter (EFFACA)
- Early Health Effects Exponential Parameter (EFFACB)
- Early Health Effects Threshold Dose (EFFTHR)

*All of these parameters were uncertain in the SOARCA Peach Bottom UA too*

# MACCS Uncertain Parameter Groups (continued)

*Emergency Response*

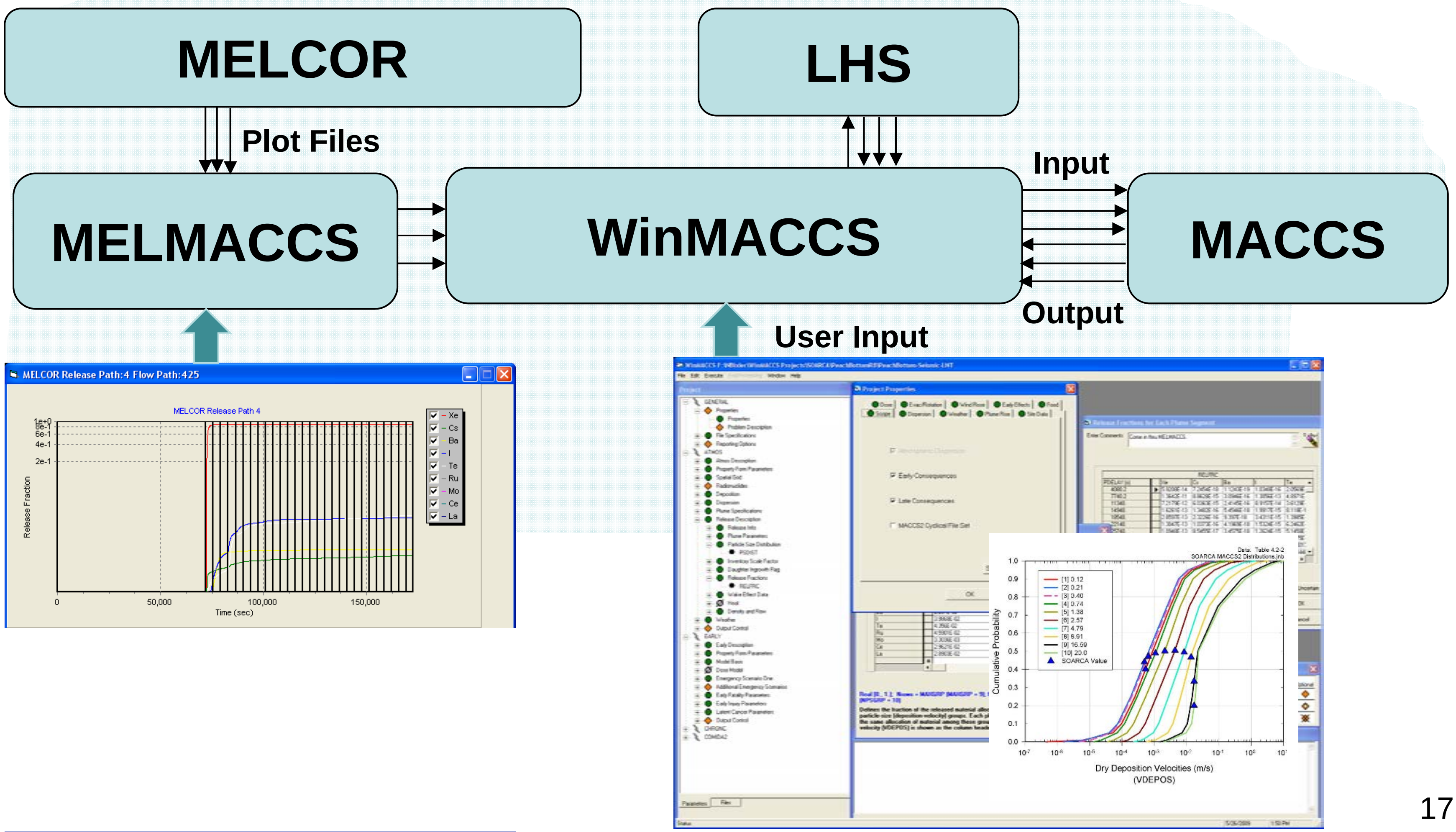
- Evacuation Delay (DLTEVA)
- Evacuation Speed (ESPEED)
- Hotspot Relocation Time (TIMHOT)
- Normal Relocation Time (TIMNRM)
- Hotspot Relocation Dose (DOSHOT)
- Normal Relocation Dose (DOSNRM)

*Aleatory Uncertainty*

- Weather trials

*All of these parameters were uncertain in the SOARCA Peach Bottom UA too*

# WinMACCS Calculation Framework as Used in SOARCA Uncertainty Analysis



# Consequence Regression Analyses, LNT (10 mile, All Rlzs)

- The most important parameter is tube thickness.
- Second most important is the SV open area fraction.
- The third most important input parameter is the time at cycle.
- Fourth is groundshine shielding factor for normal activity during the emergency phase, GSHFAC.2, which is fully correlated with the groundshine shielding factor for the long-term phase.

| | Rank Regression | | Quadratic | | Recursive Partitioning | | MARS | | Main Contr.* | Conjoint Contr. * |
|---|---|---|---|---|---|---|---|---|---|---|
| Final $R^2$ | 0.54 | | 0.60 | | 0.86 | | 0.74 | | | |
| Input | $R^2$ contr. | SRRC | $S_i$ | $T_i$ | $S_i$ | $T_i$ | $S_i$ | $T_i$ | | |
| TUBTHICK | 0.04 | -0.20 | 0.33 | 0.53 | 0.30 | 0.86 | 0.35 | 0.80 | 0.189 | 0.309 |
| SVOAFRAC | 0.03 | -0.18 | 0.23 | 0.40 | 0.09 | 0.55 | 0.11 | 0.45 | 0.082 | 0.250 |
| CYCLE | 0.18 | 0.44 | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.02 | 0.050 | 0.005 |
| GSHFAC.2 | 0.13 | 0.35 | 0.02 | 0.05 | 0.00 | 0.00 | 0.01 | 0.03 | 0.038 | 0.011 |
| DLEAK | 0.08 | 0.26 | 0.01 | 0.04 | 0.01 | 0.01 | 0.00 | 0.01 | 0.022 | 0.010 |
| CFRISK.8 | 0.02 | 0.15 | 0.02 | 0.05 | 0.00 | 0.06 | 0.02 | 0.08 | 0.011 | 0.037 |
| SV_STATUS | --- | --- | 0.04 | 0.04 | --- | --- | --- | --- | 0.006 | 0.000 |
| DDREFA.8 | 0.01 | -0.12 | 0.00 | 0.02 | 0.00 | 0.05 | 0.00 | 0.03 | 0.004 | 0.025 |
| CYSIGA.1 | 0.02 | -0.13 | --- | --- | --- | --- | --- | --- | 0.004 | 0.000 |
| TUBETEMP | --- | --- | 0.02 | 0.02 | 0.00 | 0.00 | 0.01 | 0.03 | 0.004 | 0.006 |
| DEV_DEC_HEAT | 0.01 | -0.09 | 0.00 | 0.03 | 0.00 | 0.03 | 0.01 | 0.02 | 0.004 | 0.015 |
| VDEPOS.1 | 0.01 | 0.09 | 0.01 | 0.01 | 0.00 | 0.04 | --- | --- | 0.003 | 0.011 |
| CFRISK.7 | 0.01 | 0.09 | --- | --- | --- | --- | --- | --- | 0.002 | 0.000 |
| CFC | 0.01 | -0.09 | --- | --- | --- | --- | 0.00 | 0.01 | 0.002 | 0.001 |
| CFRISK.6 | 0.01 | 0.07 | --- | --- | --- | --- | 0.00 | 0.02 | 0.002 | 0.003 |
| PROTIN.2 | --- | --- | --- | --- | 0.01 | 0.09 | --- | --- | 0.001 | 0.023 |
| CHEMFORMCS | 0.01 | -0.06 | --- | --- | --- | --- | --- | --- | 0.001 | 0.000 |
| SGTRLOC | 0.00 | 0.06 | 0.00 | 0.01 | --- | --- | --- | --- | 0.001 | 0.002 |
| CFRISK.2 | --- | --- | 0.00 | 0.03 | --- | --- | --- | --- | 0.001 | 0.005 |
| LA.140_ICH.9 | --- | --- | 0.00 | 0.04 | 0.00 | 0.03 | 0.00 | 0.01 | 0.000 | 0.018 |
| PARTSHAPE | --- | --- | 0.00 | 0.01 | 0.00 | 0.01 | --- | --- | 0.000 | 0.004 |
| CHEMFORMI2 | --- | --- | --- | --- | 0.00 | 0.02 | 0.00 | 0.01 | 0.000 | 0.009 |

** highlighted if main contribution larger than 0.02 or conjoint contribution larger than 0.1*

**Table 6-24 Mean, individual, LCF risk (based on LNT) regression results within a 10-mile circular area for all realizations.**

- The top two parameters largely control whether an SGTR occurs, which has a dominant effect on consequences. Both parameters have large conjoint contributions which imply that there is some synergistic influence on LCF risk from TUBTHICK and SVOAFRAC in conjunction with each other or other parameters.

# Overall Conclusions and Insights

- Surry UA corroborates SOARCA study conclusions
  - Public health consequences from severe nuclear accident scenarios that were modeled are smaller than previously calculated, and very small in absolute terms
  - Delayed releases calculated provide time for emergency response actions such as evacuating or sheltering
  - Long-term phase dominates health effect risks because emergency response is faster than progression to release
  - “Essentially zero” early fatality risk projected

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# Overall Conclusions and Insights (continued)

- SGTRs occurred in about 10% of the realizations and produce source terms that are one to two orders of magnitude greater
- Due to updated containment model, source terms are smaller than in the original SOARCA study
- Lower source terms lead to lower LCF risks
- Source term uncertainty contributes more than consequence parameter uncertainty when dose response is not varied
- Uncertainties in dose response may be much more significant than any other uncertainty
- The most significant parameters are those that influence the likelihood of SGTR (SV open fraction and SG hottest tube thickness)
- The other most significant parameters are
  - Time at cycle, which affects decay heat levels and isotopic inventory
  - Parameters that affect groundshine doses, especially in the long term

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# Next Steps

- Revise SOARCA Surry Uncertainty Analysis with updates following the Advisory Committee Reactor Safeguards subcommittee review meetings on the SOARCA Surry Uncertainty Analysis and SOARCA Sequoyah Analysis in February 2016 and May 2016 respectively.

- Develop summary NUREG report on insights from the SOARCA Peach Bottom, Surry, and Sequoyah Uncertainty Analyses.