SOARCA Surry Power Station Uncertainty Analysis: Parameter Methodology and Insights

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Abstract: The State-of-the-Art Reactor Consequence Analyses (SOARCA) project for the Peach Bottom Atomic Power Station (the pilot boiling-water reactor) and Surry Power Station (the pilot pressurized-water reactor) represents the most complex deterministic MELCOR analyses performed to date. Uncertainty analyses focusing on input parameter uncertainty are now under way for one scenario at each pilot plant. Analyzing the uncertainty in parameters requires technical justification for the selection of each parameter to include in the analyses and defensible rationale for the associated distributions. This paper describes the methodology employed in the selection of parameters and corresponding distributions for the Surry uncertainty analysis, and insights from applying the methodology to the MELCOR parameters.

Keywords: Uncertainty Analysis, MELCOR, SOARCA, Parameter Uncertainty

1. INTRODUCTION

In 2012, the U.S. Nuclear Regulatory Commission (NRC) completed the State-of-the-Art Reactor Consequence Analyses (SOARCA) project for two pilot nuclear power plants, the Peach Bottom Atomic Power Station (Peach Bottom), which is a boiling water reactor (BWR) with a Mark I containment and the Surry Power Station (Surry), which is a pressurized water reactor (PWR) with a large dry (subatmospheric) containment. The deterministic analyses completed in the SOARCA project [1] has advanced the state of severe accident understanding, and integrated uncertainty analyses of parameter uncertainty are underway. The uncertainty analysis for the Peach Bottom unmitigated long-term station blackout is substantially complete [2] and is providing important insights regarding how uncertainties in the most influential parameters associated with severe accident progression and consequences in a BWR affect analysis results. These insights in turn are informing other NRC activities, such as the analysis of filtered vents and filtration strategies for Mark I and II containments. A second SOARCA uncertainty analysis is now under way, to develop similar insights for PWRs. The methodology described in this paper is now being applied in the analysis of uncertainty for a short-term station blackout (STSBO) scenario for the Surry Power Station.

The SOARCA Surry PWR MELCOR model represents a complex set of systems and analyses. These include thermal-hydraulic response in the reactor coolant system, reactor cavity, containment, and confinement buildings; core heatup, degradation, and relocation; core-concrete attack; hydrogen production, transport, and combustion; and, fission product release and transport behavior. Current uses of MELCOR include estimation of severe accident source terms and their sensitivities and uncertainties in a variety of applications. MELCOR uses thousands of parameters in the execution of equations and algorithms embedded in the models. The vast majority of the parameters are default inputs required for operation of the models. Many parameters are basic input, such as core inventory, materials, sizes and lengths of piping, equipment, etc. There are also many parameters for which the base values were established long ago by subject matter experts and are deemed reasonable for the application (e.g., natural circulation).

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This Surry study has identified a set of MELCOR parameters to include in the integrated uncertainty analysis. The goal is to increase the knowledge base of the severe accident community through insights into influential phenomena and parameters for accident progression and radionuclide release. The level of uncertainty in these parameters varies from high confidence, in other words small projected variation around the point estimate, to, in some cases, orders of magnitude potential variation [3]. The reasons for including parameters in the analysis include: (1) known uncertainty, (2) an expectation that in the chosen accident scenario, the parameter can contribute significantly to release timing and/or magnitude and hence potential offsite consequences, and (3) the potential to contribute to the state of knowledge in a particular area of severe accident modeling. Reasons for not including parameters include that varying the parameter would require significant MELCOR model enhancements, and too little is known about the parameter to vary it in a meaningful way. In some cases, separate sensitivity analyses are planned for potentially important parameters that are too challenging to include in the integrated uncertainty analysis.

A few of the parameters selected have little technical basis for establishing a distribution about the parameter. The team believed that including these parameters was important nonetheless to establish an understanding of the potential effects, even though the technical basis for the parameter bounds may not have been as technically sound as the more mature parameters. The bounds for these parameters were established with values judged reasonable by the team. Parameter selection, as well as their related distributions, was also informed by insights gained from the sensitivity studies conducted with the SOARCA project in NUREG/CR-7110 Vol. 2 [4]. The NUREG/CR report that will document the Surry STSBO uncertainty analysis will identify the technical basis and rationale for each of the parameter choices.

2. METHODOLOGY

Evaluating the uncertainty in severe accident analyses requires an understanding of how MELCOR models the systems and associated parameters. It is not practical or necessary to vary all of the parameters. Furthermore, varying a parameter in many cases requires a MELCOR model enhancement, where an analyst modifies the model to accept a range rather than a single value, which requires additional testing and quality assurance review.

The implementation of an effective and efficient analysis of uncertainty required a method be established to leverage the expertise of MELCOR experts to optimize the parameter selection process. A multi-faceted approach was applied in developing the parameters to be varied in the Surry analysis. This included starting with the Peach Bottom Uncertainty Analysis parameter list, brainstorming among subject matter experts (SMEs), conducting a formal parameter review from a total systems approach and conducting a comprehensive review of the MELCOR Reference Manual [5]. In addition, lessons were learned and insights gained from the Peach Bottom Uncertainty Analysis [2], and through the NRC Advisory Committee on Reactor Safety (ACRS) reviews of the Peach Bottom Uncertainty Analysis.

2.1 Establishing the Parameter List

The current analysis of uncertainty is for the unmitigated STSBO scenario for the Surry Power Station. Although the reactor systems and sequences are different, extensive investigation into parameters had been conducted for the nearly completed Peach Bottom uncertainty analysis, and the team leveraged that information by using the Peach Bottom final list of parameters as the starting point for the Surry analysis. This list was then refined in order to account for differences in plant design and operation. Most of the selected parameters have historically been considered to be important by severe accident SMEs. Although some of the selected parameters did not show importance in the Peach Bottom results, the team still believed these parameters could be important for a different reactor type and different scenario, and kept them in the analysis. For example, in the Peach Bottom analysis the overwhelming importance of a handful of parameters in determining whether the accident progressed to main-steam line rupture (which in turn was a large determinant of release magnitude), may have masked parameters that are important for other scenarios and reactor types. Hence, the team for this analysis sought to ensure that such masked parameters were identified and included in the Surry STSBO analysis. Parameters specific to BWRs only, such as the railway doors, were removed from consideration. The final set of parameters is not all-inclusive or unique, but rather represents the team's judgement of how to capture sensibly the most interesting phenomena for this MELCOR analysis. There are many alternative parameters that could represent the phenomenology of interest, and a practical subset was chosen to capture important aspects of modelling without introducing redundancies and unnecessary complications, such as the need to specify correlations extensively.

Developing the parameter list was a multi-step iterative process that, as discussed above, started with the Peach Bottom final parameter list. The Sandia team and NRC conducted a brainstorming session where additional parameters were discussed and added to the list for investigation. This brainstorming identified some of the obvious areas of interest such as natural circulation and steam generator tube ruptures in the PWR plant. The next step was more comprehensive where the team conducted a parameter review from a systems approach with a detailed review of the following elements of MELCOR modelling:

- Sequence issues
- In-vessel accident progression
- Ex-vessel accident progression
- Containment behavior
- Chemical form
- Aerosol deposition

Team experts described the phenomenology and characteristics of each system and discussed why selected parameters within these areas may be important for review and candidate parameters were identified. After the systems review, the parameter list was updated to reflect the MELCOR parameters within the related model field. At this point, identification of parameters through expert judgment had been exhausted and the parameter list was fairly complete.

The last activity in the process was a comprehensive review of the MELCOR Reference Manual [5] by senior MELCOR experts who systematically reviewed the manual by chapter to determine whether additional candidate parameters should be considered. The Reference Manual was used to allow a top down approach and focused the team review toward a phenomenologically-based review rather than a mechanistic review of each parameter in the MELCOR User's Guide [3]. Such a review of the User's Guide, which contains thousands of parameters and inputs, would not be practical. The Package Reference Manual chapters are listed below with example notes related to each.

- Burn (BUR) Package Reference Manual
    - Sample hydrogen lower flammability limit based on variability in direction of flame propagation
    - Sample the maximum steam concentration supportive of a hydrogen burn based on the variability in direction of flame propagation
- Cavity (CAV) Package Reference Manual
    - Consider addressing uncertainty in the amounts of gasses generated by molten core-concrete interaction by sampling the proportions of common sand and aggregate in the concrete.
- Condenser (CND) Package Reference Manual
    - Not applicable. The Surry units do not have isolation condensers or a passive containment cooling system.
- Core (COR) Package Reference Manual
    - Consider varying core blockage user input
- Control Volume Hydrodynamics-Flow Path (CVH/FL) Packages Reference Manual

- No related parameters identified as potentially significant for further investigation.
- Decay Heat (DCH) Package Reference Manual
    - Address variation in decay heat dependent on where the core is in its lifecycle when the accident occurs.
- Fan Cooler (FCL) Package Reference Manual
    - This is an SBO sequence, and without AC power the fan coolers would not be operating.
- Fuel Dispersal (FDI) Package Reference Manual
    - This parameter is only important if the analysis shows a high pressure ejection. After the initial set of 300 MELCOR uncertainty runs, the results will be reviewed, and if a high pressure ejection is shown to occur, the FDI package will be revisited.
- Heat Structures (HS) Package Manual
    - Condensation was identified as a potential parameter. The effect of the presence of non-condensable gas on condensation rate is a potential concern, considering the large sizes of the control volumes representing different regions of containment relative to the localized extent of condensation influences.
- Material Properties (MP) Package Manual
    - Eutectic temperatures for zircaloy oxide and uranium oxide
- Non-condensable Gas (NCG) and Water (H20) Package Reference Manual
    - No uncertainty modeling suggested here.
- Passive Autocatalytic Hydrogen Recombiner (PAR) Package Manual
    - Not applicable. There are no PARs in the Surry model.
- Radionuclide (RN) Package Reference Manual
    - Model uncertainty in particle shape factor
- Containment Sprays (SPR) Package Reference Manual
    - Not applicable. Containment sprays are not available in the SBO scenario.

After the MELCOR reference manual review, the team finalized the list of MELCOR parameters. Table 1 provides a list of all MELCOR parameters that are included in the Surry uncertainty analysis.

Table 1: Surry MELCOR Model Uncertain Parameters

MELCOR
Sequence
Primary Safety Relief Valve (SRV) stochastic failure to reclose
Primary SRV stochastic failure to reopen
Primary SRV failure to close due to water swell
Primary SRV thermal seizure criterion
Primary SRV open area fraction
Secondary SRV stochastic failure to reclose
Reactor Coolant Pump Seal Leakage (RCPSL)
Main Steamline Isolation Valve Leakage (MSIV)
Steam generator tube rupture influences/variability
In-Vessel Accident Progression
Zircaloy melt breakout temperature (SC1131(2))
Molten clad drainage rate (SC1141(2))
Fuel failure criterion (FFC)
Radial molten debris relocation time constant (RDMTC)
Radial solid debris relocation time constant (RDSTC)
Decay Heat

Material Properties: Eutectic temperatures for zircaloy oxide and uranium oxide
Ex-Vessel Accident Progression
No parameters identified
Containment Behavior
Containment Fragility Curve (CFC)
Hydrogen ignition criteria (H2 LFL)
Maximum diluent mole fraction for ignition (XMSCIG)
Secondary side decontamination factor (ARTIST)
Containment Leakage Rate
Condensation – effect of non condensable gas on condensation rate.
Chemical Forms of Iodine and Cesium
Iodine and Cesium fraction (CHEMFORM)
Aerosol Deposition and Transport)
Particle Shape Factor

Next, the team studied the transcripts from the project team's meetings with the NRC's ACRS on the Peach Bottom Uncertainty Analysis, to gain insights. (The ACRS served as an informal external expert review group for the Peach Bottom analysis.) This was an important step because some of the Surry parameters were also developed for Peach Bottom, and this helped the team understand the level of detail the ACRS considered defensible for the technical bases. A key comment from the ACRS was for the technical team to clearly identify the point of departure from a known technical basis, using professional judgment. Such judgment was often required in the development of parameters and has been identified, where applicable, in this project. Another area of interest of the ACRS was the level of detail of the technical justification for the uncertainties assigned to each parameter and the rationale for the type of distribution used to characterize the uncertainty.

2.2 Storyboard Process

To ensure sufficient detail was captured for parameter justification and rationale, a storyboard process was implemented for the Surry project. Figure 1 illustrates the form that was created to identify the parameter, responsible owner, technical justification for uncertainty, type of distribution, and rationale for the distribution type and bounds. The intent was to capture in a concise format the justification and rationale for each parameter from which the detailed technical bases could ultimately be developed. The storyboards were reviewed internally in small groups where analysts explained and defended each parameter.

Figure 1: Parameter Storyboard Used to Capture Key Information for Each Parameter Investigated.

<table>
<tr><td>Parameter Name:</td><td rowspan="2">Type of Distribution:</td></tr>
<tr><td>Responsible Technical Expert:</td></tr>
<tr><td colspan="2">Technical justification for the uncertainties:</td></tr>
<tr><td colspan="2">Rational for type of distribution:</td></tr>
<tr><td colspan="2">Were similar or related parameters considered and rejected.</td></tr>
<tr><td colspan="2">Graphic: (plot of the distribution)</td></tr>
</table>

The purpose of the reviews was to obtain information and insights from a team of experts on severe accident and MELCOR analysis that could be used to further define and defend the parameters and distributions. The team challenged the technical leads to explain the basis and defend the appropriateness of supporting data. This approach often required the analyst revise or revisit the technical basis and obtain additional supporting detail for the rationale. The project team was ultimately required to make some judgment decisions based on ability to obtain sufficient information to address specific parameters. The state of knowledge continues to be developed for some of the parameters investigated, which is evident in the MELCOR Code Manual where many parameters are identified as "order-of-magnitude parameters" [3].

When significant changes were required to a storyboard, the parameter was reviewed internally again. When a set of storyboards was ready, Sandia coordinated a joint review meeting with NRC staff SMEs to review and critique all of the parameter storyboards.

2.3 Additional Parameters

The process described above included multiple review steps, each of which provided opportunity to add parameters, or justify why further consideration of a parameter was not needed. The parameters below represent some of those that were considered but not included in the analysis.

SRV reseat pressure

SRV reseat pressure was considered, but was omitted from further investigation based on insights from the Peach Bottom project and because SRV dynamics are well represented in the Surry analysis. The Peach Bottom project identified that SRV Setpoint Drift will produce analogous results to the distributions considered for SRV stochastic failure to close (FTC) [2]. A delay in the SRV stochastic FTC or failure to open (FTO) will be representative of those scenarios within the Surry analysis that have long SRV cycle periods prior to stochastic failure. These long SRV cycle periods will produce sequence results similar to what would be expected from uncertainty in the SRV reseat pressure.

Ablation temperature

MELCOR does not treat ablation temperature in a manner amenable to sampling. This parameter was not varied within the project.

Concrete properties

The molten core-concrete interaction (MCCI) is an important phenomenon in ex-vessel accident progression where uncertainty is expected. Sandia considered the possibility of varying COR-CON parameters. The team considered the potential for varying the aggregate quantity of the concrete mix, which could affect gas generation. However, the aggregate is based on a concrete mix design for the plant, and the concrete mix is routinely inspected during construction to ensure any variation is within the specification. The team decided there was little basis to vary the mix design. This parameter was not varied within the project.

RPV drain line off the lower head

Drain lines from the reactor pressure vessel (RPV) provide pathways for investigation. Review of plant drawings found no evidence that an RPV drain line off the lower head exists at Surry. The parameter was removed from further consideration.

Metal Clad Thickness

The remaining fuel clad thickness to begin the fuel failure criterion (FFC) treatment is identified as an uncertain parameter. The treatment of wide uncertainties in the remaining lifetime for oxidized rods (via the FFC parameter) for the Surry UA is assumed to subsume the uncertainty associated with the time at which the FFC treatment begins; therefore, remaining fuel clad thickness was removed from further consideration.

Decontamination Factor
An alternative to implementing the ARTIST approach would be to turn on normal MELCOR models for aerosol capture and settling on the secondary side. For this to be a reasonable alternative, significant effort would have to be made to model all possible deposition structures on the secondary side. The experts did not believe this approach would produce a more physically realistic result. Because of this, the total secondary DF (ARTIST approach) was selected.

3. INSIGHTS

The Surry analysis of uncertainty is extremely detailed and complex. It is very important to remember that this analysis is for a specific plant and a specific scenario. The following insights were gained in the parameter development process.

- MELCOR code parameters have been developed over many years with input from the severe accident analyst user community. For some parameters, such as speciation of certain radionuclides, even if uncertainty remains there is a referenceable technical basis from experiments (such as PHEBUS) and other research projects. For other parameters, the technical basis is not easily traceable and some parameter values are identified simply as "order of magnitude." The level of technical defensibility is a factor in establishing the bounds and distributions for an analysis of uncertainty.

- Group meetings with senior severe accident SMEs tend to identify a common set of important parameters based on their expert judgment from decades' worth of analyses and experience modelling severe accident progression rather than an easily traceable basis in written documentation.

- Establishing a parameter review methodology and implementing the rigorous approach helped ensure that historical parameters of interest, plant specific parameters of interest, and system specific parameters of interest were included in the initial investigation. The level of effort required to implement this due diligence methodology was not overly burdensome, but did require team commitment and active participation throughout the review process.

4. CONCLUSION

The SOARCA Surry MELCOR model represents a complex set of systems that applies thousands of parameters in the execution of equations and algorithms embedded in the models. The vast majority of the parameters are default inputs or system design inputs (e.g., piping lengths and material types) required for basic operation of the models. There are also many parameters for which the base values were established long ago by severe accident management analysts who have an advanced understanding of MELCOR parameter sensitivities through years of modelling severe accident progression. The technical basis for many parameters is not experimental data but expert judgment and does not always have an easily traceable basis. To conduct an analysis of uncertainty on these parameters as part of the SOARCA project, a due diligence parameter investigation methodology was employed. The process established for the Surry project provided an effective method for implementation of parameter development and review.

The systematic approach to developing, reviewing, debating, and critiquing the technical justification and rationale for parameters and associated distributions is a key step and provides a firm foundation from which to conduct the analysis. The level of knowledge gained by team members through the in-depth parameter investigations to support the distribution rationales and ranges benefited the entire project team and will help advance the state of knowledge of severe accident analyses.

Finally, although the investigation and review of parameters was extensive, it must be emphasized that this set of parameters should not be considered a list of the most important for MELCOR analyses. These are the parameters of most interest to this Surry analysis of uncertainty for the STSBO scenario. There are many alternative parameters that could represent the phenomenology in a similar manner. It is very important to remember that these analyses are for specific plants and specific accident sequences.

The next steps in the Surry Uncertainty Analysis are to apply this parameter development methodology to parameters in the MACCS model, which project the offsite consequences for a given source term; and use a two-step Monte Carlo simulation to generate a distribution of source term results from MELCOR and a distribution of off-site consequences from MACCS. The study will be documented in a NUREG/CR report.

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