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RECENT PLANT STUDIES USING VICTORIA 2.0

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ABSTRACT

VICTORIA 2.0 is a mechanistic computer code designed to analyze fission product behavior within the reactor coolant system (RCS) during a severe nuclear reactor accident. It provides detailed predictions of the release of radioactive and nonradioactive materials from the reactor core and transport and deposition of these materials within the RCS and secondary circuits. These predictions account for the chemical and aerosol processes that affect radionuclide behavior.

VICTORIA 2.0 was released in early 1999; a new version, VICTORIA 2.1, is now under development. The largest improvements in VICTORIA 2.1 are connected with the thermochemical database, which is being revised and expanded following the recommendations of a peer review.

Three risk-significant severe accident sequences have recently been investigated using the VICTORIA 2.0 code. The focus here is on how various chemistry options affect the predictions. Additionally, the VICTORIA predictions are compared with ones made using the MELCOR code. The three sequences are a station blackout in a GE BWR and steam generator tube rupture (SGTR) and pump-seal LOCA sequences in a 3-loop Westinghouse PWR. These sequences cover a range of system pressures, from fully depressurized to full system pressure. The chief results of this study are the fission product fractions that are retained in the core, RCS, secondary, and containment and the fractions that are released into the environment.

1. INTRODUCTION

The primary purpose for the analyses that are presented here is to test the effects of the detailed chemistry modeling used in VICTORIA 2.0 (Bixler, 1998) on fission product releases for several risk-significant severe accident sequences. A secondary objective is to compare VICTORIA and MELCOR 1.8.4 (Gauntt et al., 1997) predictions. To perform the required analyses, MELCOR was first run to calculate the thermal-hydraulic data needed as input for VICTORIA. The MELCOR analyses also treated fission product release from fuel and transport through the reactor coolant system (RCS) and into the containment or the environment.

Three chemistry options were tested with VICTORIA. The first two options assume thermochemical equilibrium to exist between all chemical species and phase behavior to be ideal. The first option is the original VICTORIA model (Heames et al., 1990, 1992), in which only one condensed phase is treated. The second option is the one recommended by the VICTORIA peer review committee (Mubayi et al., 1997), in which three condensed phases are modeled. The three phases are (1) a metallic phase, including hydrides and borides; (2) an oxidic phase, including hydroxides; and (3) an iodide phase. The third chemistry option that was tested used the frozen-chemistry model (Bixler, 1998). In this third option, the only chemistry that is modeled at temperatures below 2000 K is change of phase and all condensed-phase species are treated as being pure. This third option undoubtedly the least realistic,

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but was used because it comes closest to mimicking the treatment of chemistry that is used in MELCOR. MELCOR treats each fission product class (elements grouped to be chemically similar) as pure and nonreactive. Even this third option does not adequately represent MELCOR's treatment of chemistry because VICTORIA includes a much larger set of chemical species than does MELCOR. It would have been difficult to force VICTORIA to treat only the smaller set of chemical species (classes) that are treated by MELCOR and this was not attempted.

Of the three chemistry options explored with VICTORIA, the first option generally predicts the lowest volatilities and the third option generally predicts the highest volatilities. This is because the vapor pressures in equilibrium with a single condensed phase are always less than or equal to those in equilibrium with three condensed phases. Likewise, the vapor pressures in equilibrium with three condensed phases are always less than or equal to those in equilibrium with a number of pure condensed phases. In the latter case, the vapor pressures take the maximum values that are attainable. Therefore, the expected trend is that fission product deposition in the RCS should be greatest using the first option and least using the third option; conversely, fission product release to the containment or environment should be greatest using the third option and least using the first option.

For all three accident sequences, the thermal hydraulic calculations were conducted using MELCOR. The MELCOR results were used to drive VICTORIA, which requires thermal-hydraulic data as input. MELCOR also treated fission product behavior. The CORSOR-M model was selected to predict fission product release from the fuel and the default temperature of 2800 K was used to control conversion of fuel to rubble. Additional details of the sequences and of the nodalizations are described in the following sections.

VICTORIA takes a more mechanistic approach to fission product release modeling than does MELCOR. VICTORIA treats fission product release from fuel as a sequence of the following steps: (1) diffusion of fission product elements to fuel grain surfaces; (2) volatilization from grain surfaces into grain pores; and (3) advection and diffusion of fission product vapors through fuel pores, the fuel/cladding gap, and cladding breaches into the coolant channel. Chemical equilibrium is enforced within the fuel, so fission products can condense and interact on fuel and cladding surfaces. By contrast, MELCOR treats all of the steps listed above in terms of a rate that only depends on fuel temperature for each fission product class, which are groups of the fission product elements.

Since VICTORIA does not explicitly model fuel relocation, a simple procedure was used to map fuel temperatures when MELCOR predicted that no fuel remained in a node. The procedure was to assign the fuel temperature in a VICTORIA node to be the rubble temperature at the same location or at the closest location below the current node, that contained rubble, according to the MELCOR prediction.

In the VICTORIA analyses, physical properties, such as flow areas, hydraulic diameters, and surface areas, were chosen to be consistent with the values used in MELCOR. Twelve aerosol mass bins were used to represent the aerosol size distribution, which ranged from 10^{-22} to 10^{-11} kg. The spacing of the mass bins (or nodes) was logarithmically uniform. The bins correspond to aerosol diameters ranging from 0.003 to 13 microns. The cladding failure temperature was chosen to be 1173 K to match the MELCOR predictions. The melting point for the cladding was chosen to be 2140 K. Other values were chosen to be the standard ones recommended for most VICTORIA calculations (Bixler, 1998).

2. GRAND GULF STATION BLACKOUT SEQUENCE

Table 1 summarizes the timing of the major events for the station blackout sequence that was investigated, using the initiating event, the station blackout, as the reference time. Reactor scram was taken to occur immediately after loss of AC power and one safety relief valve (SRV) cycled open shortly afterward to relieve the pressure in the RCS. A vacuum breaker on the tailpipe connected to the SRV was assumed to stick open when the SRV first opened. This provided a pathway by which fission products could be injected directly into the drywell atmosphere rather than into the suppression pool.

Table 1. Timing of Major Events in Station Blackout Sequence at Grand Gulf Predicted by MELCOR

Event in Accident Sequence	Time (s)
Station Blackout, Loss of All AC Power	0
Reactor Scram	0
SRV First Opens, Tailpipe Vacuum Breaker Sticks Open	100
Fission Product Release Begins	2,000
Core Support Plate Fails at Centerline	2,500
Operator Manually Opens SRV to Depressurize Reactor	2,700
Drywell and Containment Walls Fail at First Hydrogen Burn	5,000
Rupture of Lower Head, Termination of Analysis	13,700

Fission product releases began in both the MELCOR and VICTORIA calculations at about 2,000 s after the initiating event. MELCOR calculated failure of the core support plate at the centerline of the reactor at 2,500 s, but the lower head did not fail until much later. At about 2,700 s, the accident progressed to the point where operating procedures call for manual depressurization of the RCS. Manual depressurization was assumed to succeed and to be through the line with the stuck-open vacuum breaker. Leakage between the drywell and wetwell was modeled throughout the calculation. In addition, at 5,000 s MELCOR calculated that a hydrogen burn occurred

in the containment. This burn was assumed to result in a detonation that failed the wall separating the drywell from the wetwell and the outer containment wall. This opened a direct path, bypassing the suppression pool, between the stuck open vacuum breaker on the tailpipe and the environment. Thus, fission products could flow directly from the RCS, through the tailpipe, through the drywell and wetwell, and into the environment, bypassing the suppression pool.

The VICTORIA nodalization that was used to model the core region of Grand Gulf contains 24 fuel nodes and is shown schematically in Fig. 1. It was designed to match the MELCOR nodalization to facilitate mapping of fuel and gas temperatures. The MELCOR calculation used a single hydrodynamic volume to model the entire fueled region, but treated fuel and gas temperatures on the finer nodalization shown in Fig. 1. It also included a second hydrodynamic control volume to model the core bypass, which was not modeled with VICTORIA.

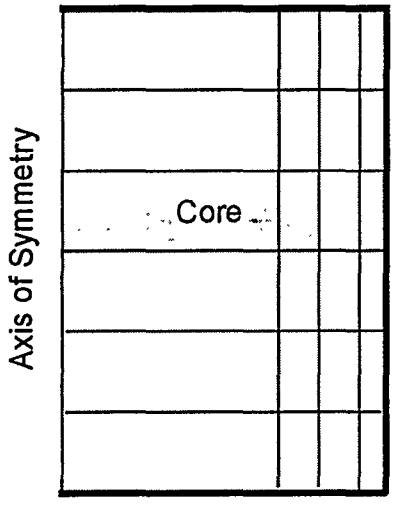

Figure 1. Schematic of the VICTORIA nodalization of the core region of Grand Gulf.

Figure 2 contains a schematic of the VICTORIA nodalization of the upper plenum of the Grand Gulf plant. Two nodes were used, one to represent the steam separators and one to represent the steam dryers. MELCOR also treated the downcomer, but this was not modeled with VICTORIA. In addition to the nodalization of the reactor vessel and RCS described above, the MELCOR analysis included two nodes to represent the containment: one each for the drywell and the wetwell.

Because VICTORIA does not contain all of the models needed to treat fission product behavior in the containment, MELCOR was used to perform all of the containment analyses. Thus, the VICTORIA calculations were done using the following three steps: (1) MELCOR was used to calculate the thermal-hydraulic data, which was used as input for VICTORIA; (2) VICTORIA was run to analyze fission product behavior in the core and RCS; and (3) MELCOR was run to calculate fission product behavior in the containment using the source term predicted by VICTORIA. Step (1) only had to be performed once. Steps (2) and (3) were performed for each of the three chemistry options described above. The original MELCOR calculation that was used to generate the thermal-hydraulic data was also used to generate fission product results to compare with the VICTORIA predictions.

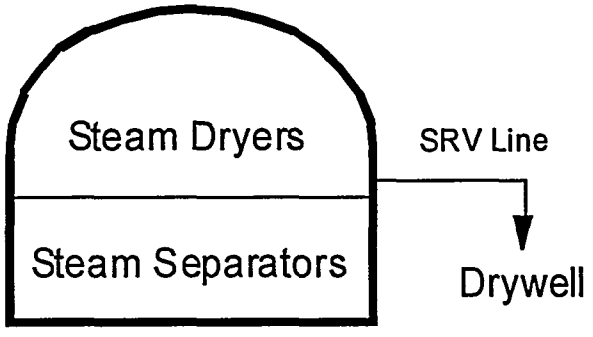

Figure 2. Schematic of VICTORIA nodalization of the upper plenum of Grand Gulf.

Figure 3 shows the final (i.e., at the time of lower head failure) distribution of the fission products. Generally, VICTORIA predicts little fission product retention in the RCS for this station blackout sequence. This is because there is only a short residence time in the reactor vessel during which fission products can deposit. Using the single-condensed-phase option in VICTORIA, predicted fractions deposited in the drywell and wetwell are roughly equal for most of the fission products. This is because about 1/3 of the releases into the drywell occurs late in the transient. Therefore, large fractions of the fission products are not swept out of the drywell and into the wetwell by the end of the transient. Fractions released to the environment are about 13% for iodine, 12% for cesium, and 5% for tellurium. Nearly 30% of the noble gases are released to the environment.

Most of the observations given for the single-condensed-phase results also apply to the predictions shown in Fig. 4, which are for the three-condensed-phase option. Predicted release fractions to the environment are nearly identical for these two cases. Somewhat less deposition in the RCS is indicated in Fig. 4 than in Fig. 3, especially for iodine. Less deposition in the RCS, however, is compensated by slightly more deposition in the containment, resulting in only about 0.3% more release of iodine to the environment when using the three-condensed-phase option than using the single-condensed-phase option. Behavior of the other fission products is also almost the same for the two cases.

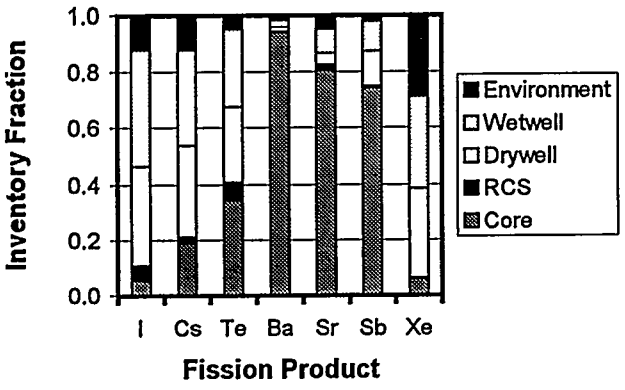

Figure 3. Fraction of inventory retained by region for a station blackout sequence at Grand Gulf using VICTORIA with the single-condensed-phase-chemistry option.

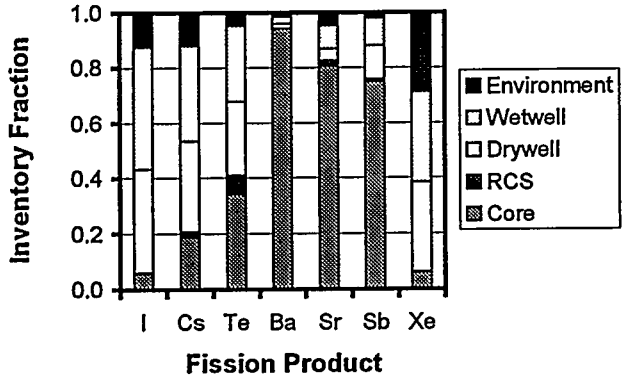

Figure 4. Fraction of inventory retained by region for a station blackout sequence at Grand Gulf using VICTORIA with the three-condensed-phase-chemistry option.

The observed trends for iodine are as expected. Iodine, chiefly in the form of cesium iodide, is calculated to be more volatile using the three-condensed-phase option than it is using the single-condensed-phase option. This accounts for less deposition of iodine in the RCS and slightly greater release of iodine to the environment in the three-condensed-phase case. Nonetheless, the overall differences between the single- and the three-condensed-phase-chemistry cases are small enough to be negligible in terms of offsite dose calculations.

Figure 5 shows the VICTORIA predictions using the frozen-chemistry option. In terms of iodine behavior, the predictions are more similar to those using the single-condensed-phase-chemistry option shown in Fig. 3 than to those using the three-condensed-phase option shown in Fig. 4. This observation is unanticipated and requires some explanation. The predicted dominant form of iodine in the RCS is condensed-phase CsI using the single-condensed-phase-chemistry option. Using the three-condensed-phase option, CsI is more volatile and the dominant forms of iodine are cesium iodide and its dimer, Cs_2I_2, both in the vapor phase. Formation of the dimer enhances the fraction of iodine in the vapor form because two vapor species compete for the available iodine. Using the frozen-chemistry option, the reaction to form the dimer is inhibited. Consequently, the CsI vapor is supersaturated and most of it condenses to form CsI aerosol. Thus, for iodine, the frozen-chemistry option leads to results that are similar to those for the single-condensed-phase option.

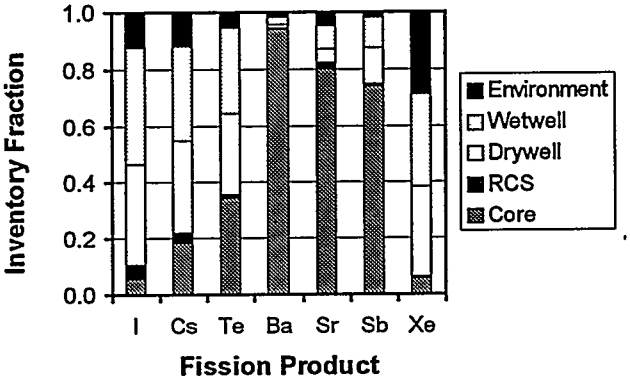

Figure 5. Fraction of inventory retained by region for a station blackout sequence at Grand Gulf using VICTORIA with the frozen-chemistry option.

The dominant form of cesium for the single- and three-condensed-phase cases is condensed-phase cesium molybdate, Cs_2MoO_4; using the frozen-chemistry option, it is condensed-phase CsOH, which forms at the high temperatures of the core region and is not allowed to react with other elements as it passes through the RCS into the drywell. Although CsOH is much more volatile than Cs_2MoO_4, chemisorption of CsOH vapor onto structural surfaces is a significant deposition mechanism. (Chemisorption of Cs_2MoO_4 vapor might occur but is not treated in VICTORIA. In any case, since Cs_2MoO_4 exhibits an extremely low vapor pressure, it is unlikely that chemisorption is a significant deposition mechanism). For this reason, the frozen-chemistry option leads to slightly more retention of cesium in the RCS than the other two options. Nonetheless, predicted releases of cesium to the environment are within 0.1% for all three chemistry options. Furthermore, the predicted release fraction for each of the fission products is within 0.5% for the three chemistry options that were studied.

The MELCOR predictions shown in Fig. 6 are dramatically different from the VICTORIA predictions shown in the three previous figures. The biggest differences are due to

the predictions of fission product releases from fuel. These are only 23%, 25%, and 18% for iodine, cesium, and tellurium, respectively. Even most of the xenon is predicted to remain in the core (about 76% of the inventory). The authors do not understand why the MELCOR release predictions are so low in this case. There could be an undiscovered problem or inconsistency in the input parameters that affect fission product release. In any case, this issue bears further investigation.

The MELCOR-predicted retentions in the RCS are slightly higher than those predicted by VICTORIA; predicted deposition in the drywell and wetwell are both significantly less than for the calculations using VICTORIA. The higher predicted retentions in the RCS may result from the fact that not all of the heat structures and flow paths were modeled with VICTORIA, as explained above. MELCOR-predicted releases of iodine, cesium, and tellurium to the environment are in the range of 3% to 5% of the core inventory, about a factor of three less than the releases predicted by VICTORIA. Releases of the noble gases (xenon group) to the environment were predicted to be about a factor of two less than the values predicted by VICTORIA.

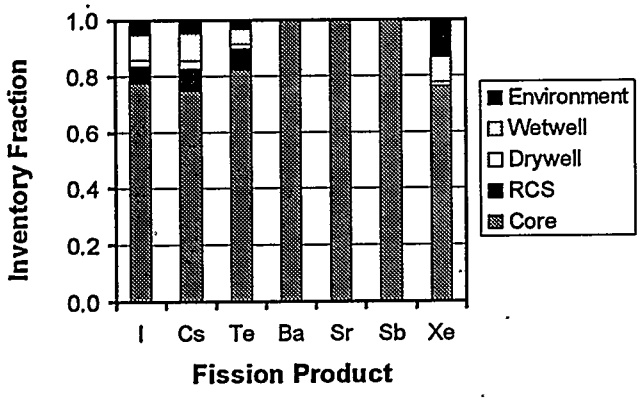

Figure 6. Fraction of inventory retained by region for a station blackout sequence at Grand Gulf using MELCOR.

3. SURRY SGTR SEQUENCE

Table 2 summarizes the timing of the major events for a SGTR sequence at Surry, using the initiating event, a double-ended guillotine rupture of a single, steam generator tube, as the reference time. High-pressure injection terminates when the water supply is depleted at about 49,000 s. After this the accumulators periodically inject water. At about 115,000 s, core uncovery begins. Fission product releases start at 123,000 s. The accident is terminated shortly after the lower core support plate fails when the lower head ruptures. Failure of the lower head would have led to a DCH event followed by air ingress; however, these events were not simulated in the current analyses, which were mainly concerned with fission product bypass of the containment through the ruptured steam generator tube.

Table 2. Timing of Major Events in SGTR Sequence at Surry Predicted by MELCOR

Event in Accident Sequence	Time (s)
Double-Ended Guillotine Break of One Steam Generator Tube	0
Reactor Scram	0
High Pressure Injection Terminates	49,000
Core Uncovery Begins	115,000
Fission Product Release Begins	123,000
Core Support Plate Fails at Centerline	167,500
Lower Head Fails, End of Calculation	168,000

The VICTORIA nodalization of the core region consists of 20 fuel nodes, which are shown schematically in Fig. 7. This nodalization was designed to be similar to the one used by MELCOR in order to facilitate the mapping of fuel temperatures. However, the VICTORIA nodalization used five equally spaced axial levels; whereas, the MELCOR nodalization used ten equally spaced levels. Moreover, the VICTORIA nodalization used four radial rings; whereas, the MELCOR nodalization used five radial rings. While some averaging had to be done to transfer thermal data from the MELCOR nodalization to the VICTORIA nodalization, the VICTORIA nodalization was designed so that this was straightforward. This nodalization is somewhat different than the one used in the Grand Gulf calculation shown in the preceding section, chiefly to capture the effects of natural convection, which are more important in high-pressure sequences than in low-pressure sequences. The differences in the two nodalizations should not have significantly affected the comparisons given here.

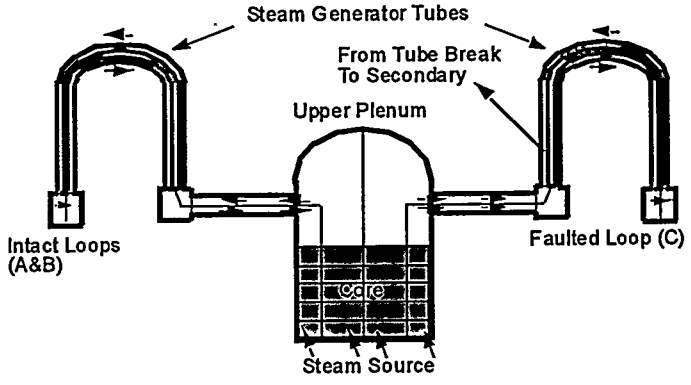

Figure 7. Schematic of VICTORIA nodalization of the Surry core and RCS.

The RCS is also shown schematically in Fig. 7. The RCS, as the term is used here, includes the upper plenum and all three primary circuits, two of which (A & B) are represented as a single circuit. The VICTORIA nodalization does not include the cold leg of the primary circuits because MELCOR predicted that the loop seals remain full of water during the transient. Some other components that were simulated with MELCOR were also omitted in the VICTORIA nodalization, such as the surge line, pressurizer, and the refueling water storage tank. MELCOR predicted that little or no fission product deposition occurred in these components during the transient, so it was justified to omit them in the VICTORIA nodalization.

Figure 8 contains a schematic of the VICTORIA nodalization of the faulted secondary circuit of the Surry plant. Four nodes were used. One represented the steam separators, one the steam dryers, and two the long steam line that leads from the steam generator outside of the containment building.

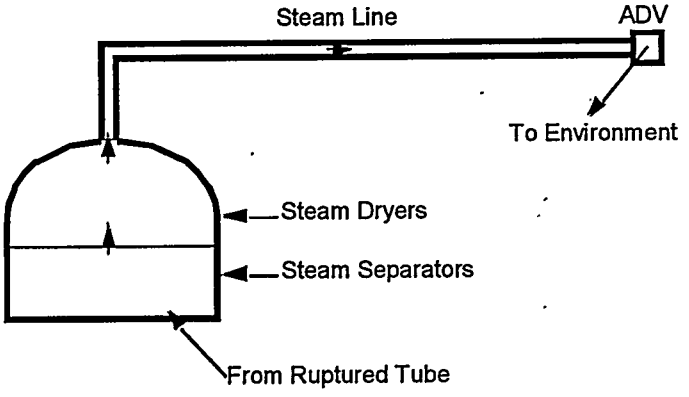

Figure 8. Schematic of the VICTORIA nodalization of the faulted secondary circuit of a Surry unit.

In this sequence, the atmospheric dump valve (ADV) on the faulted secondary circuit was assumed to fail in the open position the first time that it opened. The broken steam generator tube and stuck-open ADV provided a direct transport path for fission products to go from the reactor core to the environment.

Figure 9 shows the final distribution of fission products predicted by VICTORIA using the single-condensed-phase-chemistry option. This option results in significant retention in the core, i.e., in the fuel rods or rubble, even for cesium and tellurium. Because of the relatively low predicted volatilities using this chemistry option, most of the fission products that were released from the core were deposited within the RCS. Furthermore, most of the fission products that were released from the RCS were deposited in the secondary. Less than 5% of the iodine, cesium, and tellurium inventories were ultimately released into the environment. The exception of course is for the noble gases, which were almost totally released into the environment. Unexpectedly, this chemistry option, which is the farthest from the modeling approach used in MELCOR, results in predictions that are the most similar to those obtained from MELCOR, as demonstrated below.

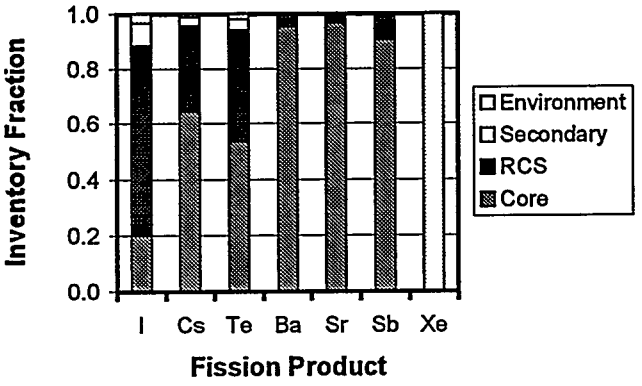

Figure 9. Fraction of inventory retained by region for a SGTR sequence at Surry using VICTORIA with the single-condensed-phase-chemistry option.

Figure 10 shows the final distribution of fission products predicted by VICTORIA using the three-condensed-phase-chemistry option. Releases from fuel were significantly greater than those predicted using the single-condensed-phase option. Of the fission product elements, iodine was the most affected by the choice of the chemistry modeling option. Whereas less than 5% of the iodine was released into the environment using the single-condensed-phase option, nearly 60% was predicted to be released into the environment using the three-condensed-phase option. Differences in the predicted release fractions of the other fission products are noticeable but not significant in terms of consequence.

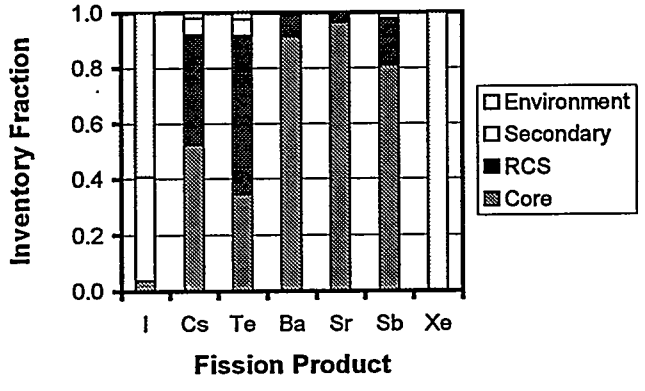

Figure 10. Fraction of inventory retained by region for a SGTR sequence at Surry using VICTORIA with the three-condensed-phase-chemistry option.

Unfortunately, convincing evidence to support a choice between the one- and three-condensed-phase-chemistry options does not exist at present. Previous comparisons with experimental data, such as the Phebus FPT-1 test (Bixler et al., 1999), have generally favored the three-condensed-phase option, but not overwhelmingly so. Moreover, differences in predictions for the two chemistry options have generally been much smaller than the ones shown above. The specific conditions in this plant sequence appear to be near the boundary at which CsI changes phase. Depending on the modeling option, most of the CsI either condenses or remains a vapor. Further comparisons with experimental data may shed light on the question of which chemistry option is more realistic.

Figs. 10 and 11 show that predictions using the frozen-chemistry and three-condensed-phase-chemistry options differ significantly. Generally, predicted fission product retention in the fuel is much less using the frozen-chemistry option than it was using the three-condensed-phase-chemistry option. As expected, volatilities were predicted to be higher for most elements using the frozen-chemistry option than using the three-condensed-phase-chemistry option. Consequently, retention in the RCS and the faulted secondary circuit was less and releases to the environment were higher using the frozen-chemistry option than they were using the three-condensed-phase-chemistry option.

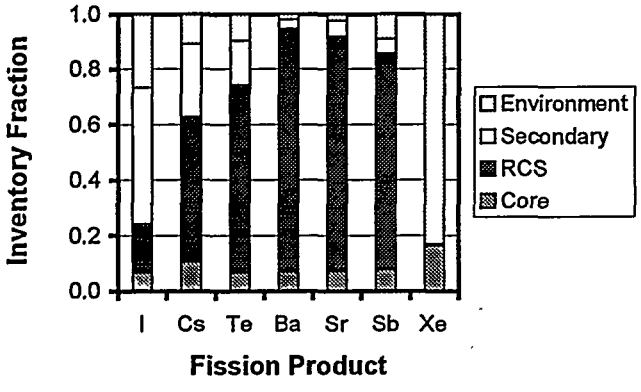

Figure 11. Fraction of inventory retained by region for a SGTR sequence at Surry using VICTORIA with the frozen-chemistry option.

However, there is one exception to this general rule, which is for iodine. Retention of iodine in the RCS and faulted secondary circuit is actually higher using the frozen-chemistry option than using the three-condensed-phase-chemistry option. The reason is that CsI is the dominant iodine-bearing species throughout the transient using the frozen-chemistry option. Formation of CdI_2 and Cs_2I_2, which contribute significantly to the iodine release predicted by the three-condensed-phase model, are inhibited and do not contribute significantly to the overall release of iodine into the environment when the frozen-chemistry option is used. Even so, more than 25% of the core inventory of iodine was released into the environment by the end of the transient. Approximate predicted releases of the other fission product elements into the environment were as follows: 10% of the cesium and tellurium, 2% of the barium and strontium, 8% of the antimony, and nearly 85% of the noble gases.

The frozen-chemistry option, as it was employed in this study, is significantly less realistic than the other two chemistry options. The frozen-chemistry option should normally be used below a temperature threshold of 800 or 1000 K rather than 2000 K, as it was here. The choices here were made to best mimic with a VICTORIA model the treatment of chemistry that is normally used in MELCOR. It was believed that predictions using this option would most closely compare with MELCOR predictions. This belief turned out not to be true.

Figure 12 shows the final locations of the fission products, as fractions of the core inventory predicted by MELCOR. As mentioned above, the final distribution of fission products predicted by MELCOR most closely resembles the VICTORIA predictions using the single-condensed-phase option (cf., Figs. 9 and 12), even though this option is least like the chemistry model employed in MELCOR. On the other hand, the predictions using the frozen-chemistry option in VICTORIA least resemble the MELCOR predictions (cf., Figs. 11 and 12). With the exception of the xenon group (the noble gases), MELCOR predicts that less than 2% of any of the fission products are released into the environment. MELCOR predicts that about 85% of the noble gases (xenon group) are released into the environment, which is relatively similar to the VICTORIA prediction for Xe.

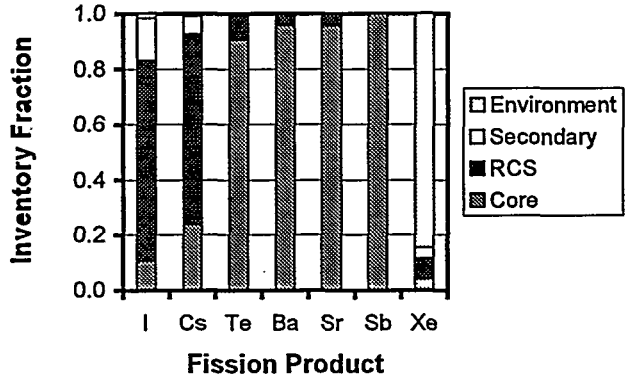

Figure 12. Fraction of inventory retained by region for a SGTR sequence at Surry using MELCOR.

According to MELCOR, most of the fission products that are released from the core are retained within the RCS, as shown in Figure 12. Likewise, most of the fission products that are released into the faulted secondary are retained there.

Although MELCOR treats most of the cesium released from core as being CsOH, which is highly volatile, most of this is predicted to be retained by chemisorption within the RCS. While cesium hydroxide chemisorption was modeled using both codes, the predicted chemisorption was much greater using MELCOR (about 85% of the core inventory) than it was using VICTORIA (about 12% of the core inventory). This discrepancy is not currently understood and is worthy of further investigation.

4. SURRY PUMP SEAL LOCA SEQUENCE

Table 3 summarizes the timing of the major events for a pump seal LOCA sequence in one of the Surry units, using the initiating event, a station blackout, as the reference time. Because all AC power was assumed lost, high-pressure injection was not operative during this sequence. However, the accumulators were assumed to function and, thus, injected water when the system pressure periodically fell below the set point.

Table 3 shows that predicted fission product release began at 12,500 s in this sequence. The accumulators first injected water into the system at 32,000 s. Finally, the accident was terminated shortly after the lower core support plate failed when the lower head ruptured at 51,000 s. In this high-pressure sequence, failure of the lower head would have led to a DCH event followed by air ingress. However, these events were not simulated because the focus of this investigation was on fission product release into the containment prior to lower head failure.

Table 3. Timing of Major Events in Pump Seal LOCA Sequence at Surry Predicted by MELCOR

Event in Accident Sequence	Time (s)
Station Blackout and Failure of Pump Seal	0
Reactor Scram	0
Fission Product Release Begins	12,500
Accumulator Injection Begins	32,000
Core Support Plate Fails at Centerline	50,800
Lower Head Fails, End of Calculation	51,000

The VICTORIA and MELCOR nodalizations were the same as in the SGTR analyses already described. The VICTORIA nodalization is shown schematically in Fig. 7. Since the releases were into the containment, it was not necessary to treat fission product transport within any of the secondary circuits. Releases into the environment were not evaluated for this sequence.

Figure 13 shows the final distribution of fission products predicted by VICTORIA using the single-condensed-phase-chemistry option. This option resulted in significant retention in the core, i.e., in the fuel rods or rubble, even for cesium and tellurium. Because of the relatively low predicted volatilities using this chemistry option, a significant fraction of the fission products that are released from the core are deposited within the RCS. Nonetheless, about 55% of the iodine, 15% of the cesium, and 40% of the tellurium inventories are ultimately released into the containment. The noble gases (as exemplified by xenon) are almost totally released into the containment. Again, this chemistry option, which is the farthest from the modeling approach used in MELCOR, results in predictions that are the most similar to those obtained from MELCOR, as demonstrated below.

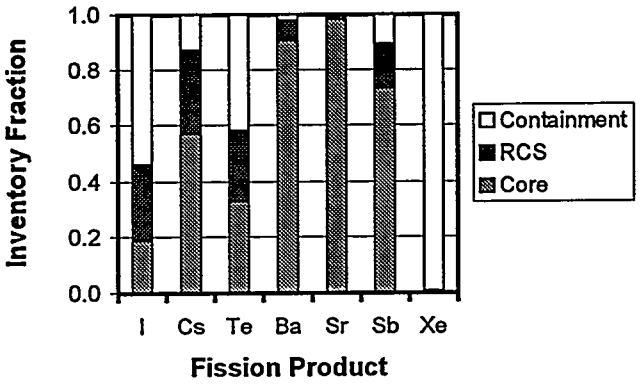

Figure 13. Fraction of inventory retained by region for a pump seal LOCA sequence at Surry using VICTORIA with the single-condensed-phase-chemistry option.

Figure 14 shows the final distribution of fission products predicted by VICTORIA using the three-condensed-phase-chemistry option. Releases from fuel are noticeably greater than those predicted using the single-condensed-phase-chemistry option. The most significant difference between the predictions using the three- and the single-condensed-phase options is in the behavior of iodine. Whereas about 55% of the iodine released into the containment using the single-condensed-phase option, about 95% released into the containment using the three-condensed-phase option. Differences in the predicted release fractions of the other fission products are noticeable but would be relatively insignificant in terms of consequence.

Comparing Figs. 14 and 15 shows that predicted fission product behavior using the frozen-chemistry option departs significantly from that using either the single- or the three-condensed-phase-chemistry options. For one thing, predicted fission product retention in the fuel for this sequence is very small when the frozen-chemistry option is used. As expected, volatilities are predicted to be significantly higher for most elements using the frozen-chemistry option than using the single- or the three-condensed-phase-chemistry options. Consequently, retentions in the RCS are less and releases into the containment are higher using the frozen-chemistry option

than they are using either the single- or the three-condensed-phase-chemistry options.

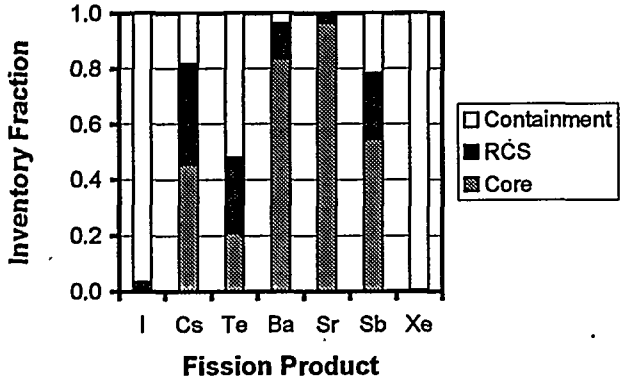

Figure 14. Fraction of inventory retained by region for a pump seal LOCA sequence at Surry using VICTORIA with the three-condensed-phase-chemistry option.

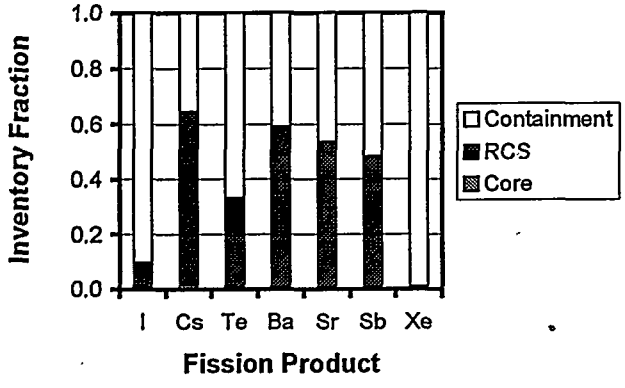

Figure 15. Fraction of inventory retained by region for a pump seal LOCA sequence at Surry using VICTORIA with the frozen-chemistry option.

Again, there is one notable exception to this generalization, which is for iodine. Retention of iodine in the RCS is higher using the frozen-chemistry option than it is using the three-condensed-phase-chemistry option. The reason is that the cesium iodide dimer, Cs_2I_2, is predicted to dominate the iodine release for the three-condensed-phase option. On the other hand, formation of the cesium iodide dimer is inhibited using the frozen-chemistry option and does not contribute much to the overall release of iodine into the containment. Predicted releases of the fission product elements into the containment using the frozen-chemistry option are as follows: 90% of the iodine, 35% of the cesium, 65% of the tellurium, 40% of the barium, 45% of the strontium, 50% of the antimony, and nearly 100% of the noble gases.

Again, the frozen-chemistry option, as it is employed here, is not expected to provide realistic results. Rather, it is used as a way of mimicking the MELCOR treatment of chemistry with VICTORIA. As before, it does not adequately mimic the MELCOR predictions.

Figure 16 shows the final locations of the fission products predicted by MELCOR. As mentioned above, the final distribution of fission products most closely resembles the VICTORIA prediction using the single-condensed-phase option (cf., Fig. 13), although this option is least similar to the chemistry model employed in MELCOR. On the other hand, the predictions using the frozen-chemistry option in VICTORIA, which should be most similar to the model used in MELCOR, least resemble the corresponding MELCOR predictions. This is the same observation that was made for the SGTR sequence.

With the exception of the xenon group (the noble gases), MELCOR predicts that the greatest release fraction of any of the fission products is for iodine, about 55% release into the containment. MELCOR predicts that about 95% of the noble gases are released into the containment. With the exceptions of iodine and xenon, most of the fission products that are released from the core are retained within the RCS. MELCOR treats most of the cesium released from core as being CsOH, which is highly volatile. However, most of this is retained by chemisorption within the RCS. The predictions of the CsOH chemisorption model in MELCOR differ significantly from those of the similar model in VICTORIA, as described above for the SGTR sequence.

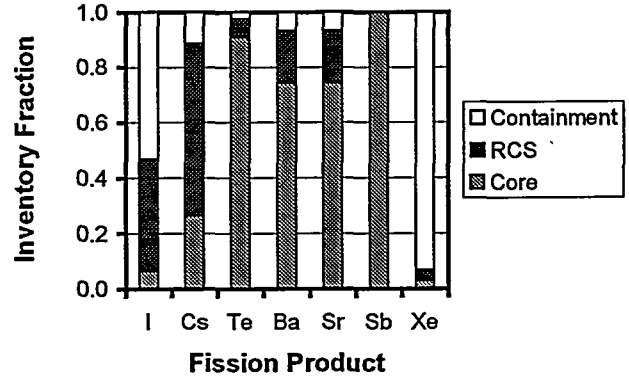

Figure 16. Fraction of inventory retained by region for a pump seal LOCA sequence at Surry using MELCOR.

5. DISCUSSION

A set of analyses were conducted to determine the effect of three chemistry modeling options in VICTORIA on predicted retention and release to the environment in a station blackout

sequence at one of the Grand Gulf units. These options are shown to have a minor effect on predicted fission product retention and release for this sequence. This is because the system is depressurized by the time most of the fission product release occurs. Higher system pressures result in longer residence times of the fission products in the RCS and more opportunity for fission products to diffuse to surfaces where they can deposit.

By far the largest source of the differences between the VICTORIA and MELCOR predictions reported for the Grand Gulf sequence are due to differences in the models of fission product release from fuel. The MELCOR model used in this study, CORSOR-M, predicted very low releases compared with VICTORIA. The CORSOR-M model in MELCOR underpredicted fission product releases from fuel for the Phebus FPT-1 test, while the VICTORIA model predicted the releases quite well (Bixler et al., 1999). Further investigation of the CORSOR models, as they are implemented in MELCOR, may be warranted. Like VICTORIA, MELCOR predicted that most of the fission products released from the fuel are retained in the RCS and the containment, although the locations where deposition occurred were somewhat different.

A set of analyses were also performed to investigate the same three chemistry options for a spontaneous steam generator tube rupture sequence (SGTR) at one of the Surry units. The initiating event was taken to be a double-ended guillotine rupture of a single, steam generator tube in the loop containing the pressurizer. A stuck-open ADV provided a direct path for fission products to bypass the containment and to reach the environment. The system pressure remained high throughout this sequence until lower head failure, which is when the calculation was terminated.

Unlike the predictions for the Grand Gulf station blackout, those using the three chemistry options differ markedly from each other for the SGTR sequence. They also differ from the MELCOR predictions. As expected, predicted releases to the environment are generally least using the single-condensed-phase-chemistry option and greatest using the frozen-chemistry option, which treats all condensed-phase species as being pure. However, this general rule does not hold for iodine, for which chemical evolution in the RCS and secondary circuit enhances the predicted integral release to the environment. Chemical evolution is inhibited using the frozen-chemistry option, which only allows change of phase.

Perhaps the most surprising result of this investigation is that the predicted releases to the environment using MELCOR were lower than any of those using VICTORIA, even using the single-condensed-phase-chemistry option. The VICTORIA chemistry option that most closely resembles the treatment in MELCOR, the frozen-chemistry option, predicts significantly higher releases to the environment than does MELCOR, especially for iodine. MELCOR predicts much more cesium chemisorption in the RCS than does VICTORIA, although the MELCOR model is based on the one in VICTORIA. Further investigation may be needed to determine why MELCOR predicts so much CsOH chemisorption.

A third plant sequence was investigated, a pump seal LOCA, also at one of the Surry units. This sequence was initiated by a station blackout. A pump seal was assumed to fail at the same time as the station blackout. The system pressure remained high throughout this sequence until lower head failure, at which point the calculations were terminated. For this sequence, fission product retention in the core and RCS and release into the containment were the focus of the investigation. Like the two other sequences studied here, three chemistry-modeling options in VICTORIA were investigated and these results were compared with the MELCOR predictions.

As expected, predicted releases into the containment using VICTORIA were generally least using the single-condensed-phase-chemistry option and greatest using the frozen-chemistry option, which treated all condensed-phase species as being pure. Again, this general rule did not hold for iodine, for which chemical evolution in the RCS enhanced the predicted integral release into the containment.

Again, MELCOR results are most similar to the VICTORIA predictions using the single-condensed-phase-chemistry option. In fact, these two sets of results are very similar for most of the fission products in this sequence, with the notable exception of tellurium. MELCOR predicted much less tellurium release from fuel than did VICTORIA. Consequently, VICTORIA predicted significantly higher releases of tellurium into the containment than did MELCOR. Differences in the release predictions for tellurium are undoubtedly related, at least in part, to the way the two codes model tellurium interactions with unoxidized cladding. Tellurium interactions with partially oxidized cladding are not fully understood. Consequently, the two codes model tellurium release from fuel differently. Thus, the differences in predictions for the two codes are not surprising.

In both of the high-pressure sequences, the SGTR and the pump seal LOCA sequences, MELCOR predicted that a large fraction of the cesium released from the core is chemisorbed onto structures within the RCS. VICTORIA also models chemisorption of CsOH, but predicted only about 1/3 as much of the cesium to be chemisorbed as did MELCOR. This discrepancy is unexpected and may require further investigation.

Further investigation may also be needed to better understand differences in the release modeling used in the two codes. The release models used in VICTORIA and MELCOR are quite different and are not expected to produce identical results. However, in some cases the differences are greater than anticipated.

The major advantage of MELCOR is that it is a fully integrated tool, capable of modeling fission product transport from fuel to the environment. On the other hand, VICTORIA only models fission product behavior in the RCS and

secondary circuits. Consequently, complete calculations must be performed as a two- or three-step process. Even with the added inconvenience, VICTORIA continues to be the NRC's state-of-the-art tool for performing best-estimate analyses.

Undoubtedly, the most significant finding from this work is the larger that expected sensitivity of predicted releases on the chemistry modeling option that is employed in VICTORIA. The differences in predicted releases to the environment for the single- and three-condensed-phase options are substantial, especially for the SGTR sequence. The single-condensed-phase model is the original one that was used in VICTORIA (Heames et al., 1990, 1992). The three-condensed-phase option was recommended by the VICTORIA peer review committee (Mubayi, et al., 1997) and is now an option in VICTORIA 2.0 (Bixler, 1998). Both have been tested against experimental data, primarily from the recent Phebus FPT-1 test (Bixler et al., 1999). While the three-condensed-phase model seems to match experimental data better, the support of the evidence has been mixed. Thus, it is not clear at present which of the two, or perhaps even a compromise, should be recommended. Fortunately, in most cases, the predictions from the two options are much more similar than they are for the SGTR sequence shown in Section 3.

The predictions using the frozen-chemistry option, as it was used in this investigation, are undoubtedly less realistic than those using the single- and three-condensed-phase-chemistry options. The motivation for exploring the frozen-chemistry option was to provide a point of comparison between the VICTORIA and MELCOR approaches to chemistry modeling. However, the VICTORIA predictions using the frozen-chemistry option and the MELCOR predictions were far apart. Apparently, the data used in MELCOR result in lower volatilities than the ones predicted by VICTORIA when each condensed species is treated as a pure phase.

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