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FISSION-PRODUCT TRANSPORT AND RETENTION IN THE PHTS UNDER ACCIDENT CONDITIONS

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ABSTRACT

The current CANDU® safety analysis methodology for predicting the release of radionuclides into containment is based on the bounding assumption that fission products released from the fuel go directly into containment. Allowing for FP retention in the PHTS will help achieve the following objectives: (1) improved estimates of doses to safety equipment in environmental qualification (EQ) analyses, (2) improved estimates of public and operator doses from an improved assessment of less volatile radionuclide behaviour, (3) improved ability to perform best-estimate safety analyses, (4) improved post-accident management plans from a better knowledge of FP location, and (5) less restrictive exclusion area boundary (EAB) designs from better source term estimates. Two LWR fission-product behaviour codes, VICTORIA and SOPHAEROS, have been assessed for their ability to provide a CANDU PHTS FP transport and retention modelling capability. The assessment of VICTORIA and SOPHAEROS was conducted by comparing the features of the two codes with the requirements for CANDU PHTS fission-product transport software, and performing simulations representative of the Loss-of-Coolant Accident with additional Loss of Emergency Coolant Injection (LOCA/LOECI) and stagnation feeder break scenarios with both codes. Based on this assessment, SOPHAEROS is better suited for simulating fission-product transport and retention in the PHTS for CANDU safety and licensing analysis, and VICTORIA should be retained to support more detailed calculations and R&D activities.

1. INTRODUCTION

Modelling fission product (FP) behaviour in the Primary Heat Transport System (PHTS) during accident scenarios is becoming increasingly important in assessment of accident consequences. As CANDU licensing methodologies move from bounding assumptions toward "best estimate plus uncertainty", tools are required to predict the time-dependent distribution of fission products throughout the reactor and containment. Properly accounting for fission product behaviour in the PHTS will help achieve the following objectives: (1) improved estimates of doses to safety equipment in environmental qualification (EQ) analyses, (2) improved estimates of public and operator doses from an improved assessment of less volatile radionuclide behaviour, (3) improved ability to perform best-estimate safety analyses, (4) improved post-accident management plans from a better knowledge of FP location, and (5) less restrictive exclusion area boundary (EAB) designs from better source term estimates, an important consideration for some markets.

It is also important to recognize that the bounding assumption of neglecting fission-product retention in the PHTS may not always be "conservative"[1]. For example, assuming fission products released from the fuel arrive instantaneously in containment can create high concentrations in the containment atmosphere early in an accident sequence. These high fission-product concentrations coincide with a period of high airborne water content resulting in efficient agglomeration and settling that cause a rapid reduction in amount of airborne fission products. On the other hand, a more protracted release can lead to higher airborne concentrations later in the accident sequence when less steam condensation and aerosol settling are occurring. It is for reasons such as these that the Light Water Reactor (LWR) community has been developing and using fission-product transport (FPT) codes.

Since LWR and CANDU reactors both use uranium oxide fuel, resulting in similar fission-product releases under accident conditions, a FPT code developed for LWR applications can be readily adapted to CANDU. The primary differences related to PHTS FPT phenomena are the more complicated piping of the CANDU PHTS, the use of carbon steel for CANDU feeder pipes, the presence of more liquid water in the PHTS during CANDU accident sequences, and the absence of control rod materials in CANDU fuel channels. These differences can be handled in part by the thermalhydraulic input to the FPT code, and by additions to the LWR FPT code. Therefore, the recommended approach for meeting the need for a CANDU FPT code is to adapt an LWR code.

Two LWR FPT codes, VICTORIA and SOPHAEROS were assessed for application to CANDU safety analysis. The USNRC code VICTORIA[2] has been the tool used for modelling fission product transport in CANDU applications. Ontario Hydro used VICTORIA for a set of scoping analyses in support of an equipment qualification study. VICTORIA was also used to model fission-product transport in Blowdown Test Facility (BTF)[3] and hot-cell fission-product release and transport experiments. In recognition of the need for a FPT code for use in CANDU safety analysis, VICTORIA was tentatively identified as one of the industry standard safety codes to be validated[4].

The IPSN (France) code SOPHAEROS[5] has many features that make it attractive for use in CANDU safety analysis. SOPHAEROS has been developed to modern Software Quality Assurance (SQA) standards and has the full suite of associated documentation. SOPHAEROS is undergoing active development. GRS (Germany) is also contributing to SOPHAEROS development, in particular in an area that will improve its ability to model FPT in the presence of water. SOPHAEROS appears to match, if not better, VICTORIA in terms of technical features. One feature that is very attractive is the use of modern numerical solution techniques that allow SOPHAEROS to solve complex problems in a fraction of the time taken by VICTORIA. (If recent experience on an International Standard Problem on aerosol transport is a good indication, SOPHAEROS can require less than 1/100 of the computer time to solve the same problem as VICTORIA[6].)

SOPHAEROS and VICTORIA were assessed for their ability to meet our needs for a FPT code with consideration being given to: (1) ability to model FPT in CANDU reactors, (2) ability to meet SQA requirements, and (3) relative cost. The assessment of the first point was based on the codes' phenomena coverage for CANDU accident scenarios and on benchmark cases under conditions representative of the following CANDU accident sequences: stagnation feeder break and LOCA/LOECI (loss-of-coolant accident (LOCA) with additional loss of emergency coolant injection). The scope of the SOPHAEROS documentation is similar to the requirements of the CSA N286.7 SQA standard, resulting in lower costs for our application. This paper presents the results of our technical assessment of the suitability of SOPHAEROS and VICTORIA for use in CANDU safety analysis.

2. PHENOMENA COVERAGE

The physical and chemical phenomena that affect fission-product transport and deposition in the PHTS under CANDU reactor accident conditions were described in the fission-product release and transport validation matrix.[4] Rankings of the importance of the FPT phenomena in CANDU accident scenarios were also included in the validation matrix. Table 1 shows a comparison of the phenomena simulated in the SOPHAEROS and VICTORIA codes with the list of PHTS FPT phenomena of primary importance in CANDU safety and licensing analysis. The information in Table 1 was obtained from the available code manuals and applies to VICTORIA v92-01[2] and SOPHAEROS version 1.3[5]. Information on later code versions and ongoing development plans was obtained from recent presentations and publications[7,8,9] and discussions with the developers. Most of the phenomena are treated similarly in the two codes with the exceptions discussed below.

Fuel particulate suspension is an important phenomenon for CANDU PHTS FPT analysis, especially during the rewet (termination) phase of some accident scenarios when high-velocity steam and water may shatter the oxidized fuel elements and entrain the smaller fragments. Neither SOPHAEROS nor VICTORIA includes a model for this phenomenon. Both codes are capable of simulating transport of fuel fragments entrained in steam by inputting appropriate aerosol source rates and initial size distributions.

Aerosol deposition by diffusiophoresis in condensing steam flows is calculated by SOPHAEROS but not by VICTORIA. This gives SOPHAEROS a clear advantage in the wetter environment of the PHTS in CANDU accident scenarios.

SOPHAEROS contains a curvature-angle-dependent model for inertial deposition in bends. VICTORIA only models inertial deposition in 90° bends in pipes but it also includes models for inertial deposition in sudden contractions, cyclone steam separators and steam dryers. SOPHAEROS appears to have advantages for simulating the geometry of CANDU feeder pipes but changes would be required in either code to treat details of inertial aerosol deposition in the complex geometry of a CANDU end fitting.

Both VICTORIA and SOPHAEROS (version 2.0) include models for physical resuspension of deposited aerosols under turbulent flow conditions. The time dependence of aerosol resuspension is captured correctly by the VICTORIA model but the timestep selection appears to influence the total amount resuspended[6]. The aerosol resuspension model in SOPHAEROS appears to calculate the total amount of resuspended material correctly but early implementations did not mirror the detailed time dependence observed in the STORM single-effects full-scale aerosol resuspension experiments[6]. The improved model implemented in version 2.0 allows SOPHAEROS to capture the detailed time dependence of aerosol resuspension[8].

Neither VICTORIA nor SOPHAEROS includes a model for fission-product vapour and aerosol retention in partially water-filled components by the pool scrubbing phenomenon, but there are plans to couple SOPHAEROS to the SPARC-B pool scrubbing code in the near future[8]. Pool scrubbing in feeders and end-fittings may lead to discharge of most of the fission products in bulk water and wet aerosols when the emergency coolant injection system fires, rather than as dry aerosols at an earlier stage in the accident.

Neither VICTORIA nor SOPHAEROS includes a model for transport of fission products in the liquid water phase. Fission-product partitioning between liquid and vapour phases, and transport in the liquid phase are areas for possible future development.

VICTORIA uses a larger set of chemical species than SOPHAEROS but additional chemical species can be added easily to a SOPHAEROS calculation, either through a modification to the database or through the input file. VICTORIA performs a full Gibbs energy minimization to determine the equilibrium chemical speciation in different regions (bulk gas, aerosol, structure film and clad film). In SOPHAEROS, chemical reactions in condensed phases are neglected and a solution scheme based on a quasi-kinetic approach to equilibrium driven by the deviation from the equilibrium state is used. The VICTORIA code assumes that all species in the condensed phase coexist in a single phase and that their vapour pressures are proportional to their equilibrium vapour pressure multiplied by their molar concentration in the condensed phase (ideal solution approximation). VICTORIA version 2.0[7,9] relaxes this assumption to the extent of forming three separate condensed phases: (1) oxides (including all oxygen bearing species), (2) metals (including tellurides, borides and hydrides) and (3) iodides. The SOPHAEROS code assumes that each species forms its own separate condensed phase and its vapour pressure is only related to the equilibrium vapour pressure of the pure compound (and local mass transfer characteristics).

There are indications that the approach in SOPHAEROS matches the experimental observations more closely, especially for cases where there is a large amount of another species co-condensed with the species of interest[8].

In summary, the fission-product transport phenomena simulated by SOPHAEROS and VICTORIA are similar. VICTORIA takes a more complicated approach to modelling certain phenomena but, based on the available experimental data, the additional complication does not appear to be justified under most circumstances. SOPHAEROS has the additional capability of simulating aerosol deposition by diffusiophoresis and there are plans to add a pool scrubbing capability through coupling with the SPARC-B code. As a result, in terms of FPT phenomena coverage, the SOPHAEROS code has a slight edge over VICTORIA for use in CANDU safety analysis.

3. CANDU ACCIDENT SCENARIOS SIMULATED

Two benchmark cases of fission-product transport and retention in the PHTS were performed under conditions representative of the stagnation feeder break and LOCA/LOECI CANDU accident scenarios. These cases were simulated with both the VICTORIA and SOPHAEROS codes.

3.1 LOCA/LOECI

A CANDU LOCA/LOECI accident scenario is initiated by a large break in the PHTS (large LOCA), e.g., a break in the inlet header, outlet header or pump inlet piping. The accident severity is compounded when the emergency core coolant injection system fails to operate on demand (LOECI).

The thermalhydraulic conditions in a single channel for the LOCA/LOECI FPT simulation were calculated using the CATHENA code based on a detailed header-to-header model including the feeder pipes, end fittings and fuel for a single CANDU-6 fuel channel. After the initial blowdown, a steady flow of about 8 g/s of steam was obtained at the inlet to the fuel channel using the inlet and outlet header conditions from a CATHENA simulation of the full PHTS. To get better estimates of the feeder pipe wall temperatures for the purposes of the FPT simulation, more detailed models of the heat losses from the feeder pipes were included than are normally used for LOCA/LOECI safety analyses. Fission-product release rates were calculated using a developmental version of the VICTORIA code (version 1.3) with improved models for fuel oxidation and its effect on fission-product releases. These fission-product release rates were supplied as input to the VICTORIA and SOPHAEROS FPT simulations.

A 7-node geometric idealization constructed for the FPT simulations included the last three bundles in the fuel channel, the end fitting and the feeder pipe. Node 1 represented a section of the fuel channel containing the three bundles at the end of the channel that was downstream during the transient. Node 2 represented the empty portion of the pressure tube between the last bundle and the front face of the shield plug. Node 3 represented the annular flow portion of the end fitting. Nodes 4-7 represented sections of the outlet feeder pipe. Nodes 3, 5, 6 and 7 included bends.

A comparison of the fission-product retention in the PHTS in the LOCA/LOECI scenario simulated with SOPHAEROS and VICTORIA is presented in Table 2. The amounts entrained in the gas flow (either as vapours or aerosols), deposited on the pipe walls and discharged through the break are expressed as a percentage of the cumulative inlet elemental mass at t = 2000 s. The entrained, deposited and discharged percentages do not sum to 100% for some of the elements in the VICTORIA simulation because of mass balance errors (up to 10% of the total mass for some of the elements). These mass balance errors in the VICTORIA LOCA/LOECI calculation are likely due to accumulation of convergence errors in the large number of time steps required to satisfy the Courant criterion (the flow must spend at least one time step in each node). SOPHAEROS is not Courant limited. There are no major differences between the fission-product retention predictions of SOPHAEROS and VICTORIA for this case, except for Sr which had significantly different speciation in the two codes (see below for discussion).

The aerosol mass median diameters (MMD), geometric mean diameters (GMD) and geometric standard deviations (GSD) for the VICTORIA and SOPHAEROS LOCA/LOECI simulations are given in Table 3 at simulation times of 250 and 1500 s. The lack of a simple relation between the mass median diameter and geometric mean diameter indicates that the aerosol size distributions were not simple log-normal distributions. The deposition velocities given in the VICTORIA output file (m/s) and the deposition rates in the SOPHAEROS output (s^{-1}) were used to assess the relative importance of the aerosol deposition mechanisms (see Table 3). The importance of inertial deposition in bends relative to the other deposition mechanisms could not be determined directly from the VICTORIA output file, because bend deposition was given as a rate rather than a velocity.

In the VICTORIA simulation, the aerosol MMD values were largest for the high-release period at 250 s and decreased for the lower-release periods at 1500 s. Inertial deposition in bends was of the greatest importance in Node 6. At 250 s, the gravitational deposition velocity was higher than the thermophoretic deposition velocity by factors between 1.5 and 3 in all but Node 7. At 1500 s, the thermophoretic deposition velocity was the highest by factors between 14 and 100. The decreasing importance of gravitational deposition over time correlates with the decreasing aerosol size. In all nodes at both times (except Node 1 at 1500 s), laminar and turbulent deposition phenomena were of secondary importance; their deposition velocities were usually two orders of magnitude less than the highest deposition velocity.

In the SOPHAEROS simulation, the aerosol MMD values were higher and did not change as much as in the VICTORIA simulation. Bend deposition gave the highest deposition rate in Node 6 at 250 s, but its rate was usually lower than either thermophoretic deposition or gravitational deposition. Because the MMD values were higher, a greater importance of gravitational deposition would have been expected. However, the thermophoretic deposition rate calculated by SOPHAEROS was higher than the gravitational deposition rate by factors between 1.5 and 25, except in Node 7 at all times and Node 5 at 250 s, where the gravitational deposition rate was higher by factors between 1.1 and 9. As in the VICTORIA simulation, the laminar and turbulent deposition phenomena were of secondary importance. SOPHAEROS calculated overall deposition during the transient as 56% by thermophoresis, 31% by gravitational settling, 12% by bend impaction, and 0.66% by all other mechanisms.

The speciation of deposits and vapours in the LOCA/LOECI simulations was examined at different times with nearly-pure hydrogen (containing 0.013 mol% of H_2O) and nearly-pure steam (containing 1.9 mol% of hydrogen), spanning most of the range of oxygen potential experienced in this scenario.

Many of the speciation differences between the SOPHAEROS and the VICTORIA LOCA/LOECI simulations can be accounted for by the different assumptions concerning the mixing of solid phases. VICTORIA assumes that all deposited solid phases are in a single ideal solution, while SOPHAEROS assumes that all solid phases are completely segregated from each other. This gives rise to much higher I, Ba, and Mo vapour content in most nodes of the SOPHAEROS simulation. In Node 1 of the SOPHAEROS simulation, no deposited species of I were present at either time and no Ba and Mo species were present at 1500 s, while significant quantities of these elements were deposited in Node 1 of the VICTORIA simulation.

While they are also affected by the solid-phase mixing assumption, four other speciation differences derive mainly from the species present in the chemical databases used in the codes. First, the species set for Sr in SOPHAEROS was very limited. The dominant solid-state species in the VICTORIA simulations (SrO and $Sr(OH)_2$) were not present in the SOPHAEROS database. Consequently, the Sr deposition was low and its pattern in the SOPHAEROS results was very different from the Ba deposition pattern (which it would be expected to resemble).

Second, the Cs_2Te vapour species was not present in the VICTORIA database. A study by McFarlane and LeBlanc indicates that the Cs_2Te vapour species is quite important in the volatilization of condensed-phase Cs_2Te[10]. The volatility of Te in the VICTORIA calculations was much lower than in the SOPHAEROS calculations. The BTF-104 experimental results are consistent with a higher volatility for Te species than appears in the results of the VICTORIA simulations[3].

Third, SnO_2 gas and condensed species are not present in the SOPHAEROS database. The absence of the SnO_2 solid species caused much higher volatility of Sn in the SOPHAEROS simulation.

Fourth, SOPHAEROS does not simulate the chemistry of Eu, which was released from the fuel in significant quantities; the SOPHAEROS simulation used La as an involatile substitute. In the VICTORIA simulation, more than one third of the total deposited Eu was deposited by vapour condensation on surfaces. At high temperatures in hydrogen-rich atmospheres, the volatility of Eu is significant, requiring its simulation using chemical species. Inclusion of the species $Eu_{(g)}$, $EuO_{(g,c)}$, and $Eu_2O_{3(c)}$ in the SOPHAEROS database would probably suffice, though $EuTe_{(g)}$ and $EuH_{2(g,c)}$ might also be significant under some circumstances.

Gibbs energies for most of the required Sn, Sr, Te and Eu species are available in the literature. The thermodynamic input capabilities of SOPHAEROS will allow the species to be added to the input file on an interim basis, during preparation of a more complete database for use in validation calculations. The absence of $Cs_2Te_{(g)}$ from the VICTORIA database would have to be addressed by changes to the code itself.

Another cause of differences was the different implementations of chemisorption on surfaces in the two codes. SOPHAEROS calculates the chemisorption of a much more extensive set of species, while VICTORIA only calculates the chemisorption of CsOH on stainless steel and Te on Zircaloy. The chemisorption of CsOH in Node 1 of the SOPHAEROS calculation dominated the Cs solid speciation in the node.

3.2 Stagnation Feeder Break

The initiating event for the stagnation feeder break (SFB) scenario is a break in an inlet feeder pipe which results in a near zero coolant flow in the fuel channel. Fuel cooling is significantly reduced and, since the reactor is still operating at full power, both the fuel and pressure tube heat up rapidly. The internal pressure in the fuel channel remains near the normal operating level of about 10 MPa. If the coolant flow is in the reverse direction, the fission products released from the fuel are transported toward the break location. Since the fuel temperatures increase rapidly to very high levels, significant fission-product releases are predicted. The scenario is terminated by pressure tube (and calandria tube) failure causing an increase in water flow from both headers into the channel. The increased flow cools the fuel and washes the fission products into the moderator.

The thermalhydraulic conditions for the FPT simulation of the stagnation feeder break scenario were calculated using the CATHENA code. The break size and location were adjusted to maximize the void fraction in the end fitting. Both VICTORIA and SOPHAEROS neglect the presence of liquid water. A sustained reverse flow of about 130 g/s of steam was obtained starting at about 1.5 s after the initiation of the break. The simulation was stopped at 11 s, when initial contact between a deformed fuel element and the pressure tube was predicted. Hence, only the period between 1.5 and 11 s was simulated with VICTORIA and SOPHAEROS (recast as $t = 0$ to 9.5 s for the FPT simulations).

Fission-product release rates were estimated using a simple methodology. The gap inventory was calculated with ELESTRES and assumed to be released with the failure of all of the fuel sheaths in the channel at the beginning of the accident. Subsequent releases from the fuel grains and grain boundaries were calculated with the Gehl model[11] augmented by releases caused by UO_2/Zircaloy interaction. The rate of tin release from the Zircaloy cladding was estimated using the correlation of Mulpuru, et al[12].

A 7-node model including part of the fuel channel and the end fitting was constructed for the FPT simulations. Node 1 was a hot fission-product source node, while Nodes 2 and 3 each contained 37 intact fuel elements. Node 4 represented the empty portion of the pressure tube between the last bundle and the front face of the shield plug. Nodes 5, 6 and 7 represented the annular flow portion of the end fitting.

A comparison of the fission-product retention in the PHTS in the stagnation feeder break scenario simulated with SOPHAEROS and VICTORIA is presented in Table 4. The amounts entrained in the gas flow (either as vapours or aerosols), deposited on the pipe walls and discharged through the break are expressed as a percentage of the total elemental mass. There are significant differences between the fission-product retention predictions of SOPHAEROS and VICTORIA for this case. The main difference is that VICTORIA calculated that a significant amount of material remained entrained in the gas flow at the end of the simulation. Even the noble gases Kr and Xe were predicted to remain inside the piping system (~90%). SOPHAEROS predicts that about 26% of the noble gases remain entrained in the gas flow at the end of the simulation. The SOPHAEROS result is consistent with the fission-product release rates and the gas transit time from the fuel to the break. This difference may be due to different treatments of gas transport between the bulk gas and the boundary layers in the two codes, highlighted by the short simulation time and high pressure of the stagnation feeder break scenario. Other differences between the amounts deposited and discharged can be understood in light of the chemical speciation differences discussed in the previous section.

4. CONCLUSIONS AND RECOMMENDATIONS

An assessment of VICTORIA and SOPHAEROS was conducted by comparing the features of the two codes with the requirements for CANDU PHTS fission-product transport software and performing simulations representative of the Loss-of-Coolant Accident with additional Loss-of-Emergency-Coolant Injection (LOCA/LOECI) and stagnation feeder break scenarios with both codes. Both codes calculate similar PHTS deposition (40-50% for most fission products) in a LOCA/LOECI accident scenario. However, the noble gas retention in the PHTS for the first 10 s of the stagnation feeder break scenario was higher in the VICTORIA simulation (~90%) than the SOPHAEROS results (~25%). A simple gas transit time assessment indicates that the SOPHAEROS result is more physically reasonable; the difference may be due to different treatments of gas transport in the boundary layers in the two codes.

The SOPHAEROS code has the following advantages: its documentation is similar to the requirements of the CSA N286.7 SQA standard; it has a diffusiophoresis model as required to calculate aerosol deposition under condensing steam conditions; and it runs about 100 times faster than VICTORIA, facilitating sensitivity analyses. VICTORIA, on the other hand, has a more extensive chemical thermodynamic database, simulates chemical reactions in the condensed phase, and includes models for aerosol deposition by impaction on complex structures, e.g., sudden changes in pipe diameter, as found in CANDU end-fittings.

Based on this assessment SOPHAEROS is better suited for simulating fission-product transport and retention in the PHTS for CANDU safety and licensing analysis, and VICTORIA should be retained to support more detailed calculations and R&D activities.

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TABLE 1

Coverage of Primary CANDU FPT Phenomena by VICTORIA and SOPHAEROS

Phenomena	VICTORIA	SOPHAEROS
Fuel Particulate Suspension	No	No
Vapour Deposition and Revaporization of Deposits	Yes	Yes
Vapour / Structure Interaction	Yes	Yes
Aerosol Nucleation	Yes	No[1]
Brownian Motion Agglomeration (Diffusion)	Yes	Yes
Turbulent Agglomeration	Yes	Yes
Aerosol Growth / Revaporization	Yes	Yes
Thermophoretic Deposition	Yes	Yes
Diffusiophoretic Deposition	No	Yes
Gravitational Deposition	Yes	Yes
Turbulent Deposition	Yes	Yes
Inertial Deposition	Yes	Yes
Aerosol Resuspension	Yes	No[1]
Pool Scrubbing	No	No
Transport of Deposits by Water	No	No
Chemical Speciation	Yes	Yes
Transport of Structural Materials	Yes	Yes

[1] - Models for these phenomena will be included in SOPHAEROS version 2.0.

TABLE 2

Comparison of Fission-Product Retention in LOCA/LOECC Predicted by SOPHAEROS and VICTORIA
(as a percentage of total elemental mass at t = 2000 s)

Element	I		Cs		Te		Sr	
Code	SOPH	VIC	SOPH	VIC	SOPH	VIC	SOPH	VIC
Entrained (%)	0	0	0	0	0	0	0	0
Deposited (%)	46	36	37	33	46	37	19	62
Discharged (%)	54	65	63	69	54	66	81	48
Total Mass (g)	2.67	2.70	54.8	55.1	1.30	1.30	12.3	12.3

Element	Sn		Ba		La/Eu		Mo	
Code	SOPH	VIC	SOPH	VIC	SOPH	VIC	SOPH	VIC
Entrained (%)	0	0	0	0	0	0	0	1
Deposited (%)	39	43	34	49	51	63	59	58
Discharged (%)	61	61	66	59	49	48	40	42
Total Mass (g)	32.0	32.1	5.97	5.97	0.67	0.73	5.6E-5	4.3E-5

TABLE 3

Aerosol Sizes and Dominant Aerosol Deposition Mechanisms for Simulations of LOCA/LOECI

	VICTORIA				SOPHAEROS			
Time = 250 s								
Node	MMD (μm)	GMD (μm)	GSD	Mechanisms	MMD (μm)	GMD (μm)	GSD	Mechanisms
1	1.4	0.1	3.4	grav > therm	1.7	0.4	1.8	therm >> grav
2	1.7	0.1	2.4	grav > therm	4.0	1.7	1.8	therm > grav
3	1.2	0.2	1.9	grav > therm, bend	4.6	2.5	1.6	therm > grav
4	1.2	0.3	1.9	grav > therm	4.6	2.6	1.5	therm ~ grav > bend
5	1.2	0.3	1.9	grav > therm, large bend	4.7	2.8	1.5	grav ~ therm > bend
6	1.2	0.3	1.9	grav > therm, large bend	4.8	3.0	1.4	bend > therm > grav
7	1.2	0.3	1.8	grav >> therm, large bend	5.1	3.3	1.4	grav > bend > therm
Time = 1500 s								
Node	MMD (μm)	GMD (μm)	GSD	Mechanisms	MMD (μm)	GMD (μm)	GSD	Mechanisms
1	0.19	0.06	2.4	grav ~ lam	1.8	0.4	2.0	therm > grav
2	0.19	0.05	2.6	therm >> grav ~ lam	1.8	0.4	2.0	therm > grav
3	0.38	0.04	2.4	therm >> grav, small bend	1.9	0.9	1.7	therm >> grav
4	0.39	0.04	2.4	therm >> grav	1.9	1.0	1.6	therm >> grav ~ bend
5	0.39	0.04	2.3	therm >> grav, large bend	2.0	1.1	1.5	therm >> grav > bend
6	0.38	0.05	2.3	therm >> grav, med bend	2.1	1.3	1.4	therm > bend >> grav
7	0.39	0.07	2.2	therm >> grav, small bend	4.2	2.3	1.5	grav > therm >> bend

MMD = mass median diameter, GMD = geometric mean diameter, GSD = geometric standard deviation,
Deposition mechanisms: grav = gravitational, therm = thermophoretic, lam = laminar, bend = bend inertial

TABLE 4

Comparison of Fission-Product Retention in Stagnation Feeder Break
Predicted by SOPHAEROS and VICTORIA
(as a percentage of total elemental mass at t = 9.5 s)

Element	I		Cs		Te		Sr	
Code	SOPH	VIC	SOPH	VIC	SOPH	VIC	SOPH	VIC
Entrained (%)	24	66	20	64	14	66	28	75
Deposited (%)	16	27	37	28	61	27	0	21
Discharged (%)	60	7	43	7	25	7	72	4
Total Mass (g)	1.75	1.75	3.77	3.77	0.05	0.05	17.3	17.3

Element	Sn		Kr		Xe	
Code	SOPH	VIC	SOPH	VIC	SOPH	VIC
Entrained (%)	22	89	26	88	27	87
Deposited (%)	71	11	0	2	0	2
Discharged (%)	7	1	74	10	73	10
Total Mass (g)	1.16	1.17	0.12	0.12	0.22	0.23