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Model for Heat-Up of Structures in VICTORIA

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Abstract

VICTORIA is a mechanistic computer code that treats fission product behavior in the reactor coolant system during a severe accident. During an accident, fission products that deposit on structural surfaces produce heat loads that can cause fission products to revaporize and possibly cause structures, such as a pipe, to fail. This mechanism had been lacking from the VICTORIA model. This report describes the structural heat-up model that has recently been implemented in the code.

A sample problem shows that revaporization of fission products can occur as structures heat up due to radioactive decay. In the sample problem, the mass of deposited fission products reaches a maximum, then diminishes. Similarly, temperatures of the deposited film and adjoining structure reach a maximum, then diminish.

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1. Introduction

VICTORIA [1] is a mechanistic computer code that treats fission product behavior in the reactor coolant system (RCS) during a severe accident. It models release of fission products from fuel rods, transport within the RCS, chemical interactions, and aerosol physics. The heart of VICTORIA is its relatively sophisticated chemistry package, which currently models the equilibrium of 288 species composed of 26 elements. It also has a state-of-the-art aerosol physics package, which models condensation/evaporation from aerosol surfaces, agglomeration, deposition, and resuspension. VICTORIA does not model thermal-hydraulics for the RCS; rather, these data are required as part of the input to the program.

During a reactor accident, vapors and aerosols, which contain fission products, generally deposit onto structural surfaces. One consequence of such deposition is that decay heating due to radioactive decay of the fission products may cause structures to heat up. This heat-up may induce some revaporization of the deposited material and, in severe cases, may lead to failure of the structure. Revaporization of deposited fission products is a chief concern in the late stages of an accident when the reactor containment is likely to have failed, or alternatively, in the event of an accident in which containment is bypassed. If the containment has failed or bypassed, there is a direct path for fission products that are left in the RCS to reach the environment. Revaporization is the primary mechanism by which this can occur.

The current version of VICTORIA does account for vapor condensation and aerosol deposition onto structural surfaces. However, it does not analyze the amount of decay heat produced by the deposited radionuclides, nor does it couple the heat produced by decay heating with local temperatures. This report describes a new model to incorporate the effect of decay heating on thermal response in a simple way.

Data are generally available for the decay heat produced per mass of an isotope [2]. Data on the relative abundances of isotopes in a normally operating nuclear reactor are also available [3]. These data have been combined to describe the amount of decay heat per mass of each element as a function of time after reactor shutdown [4]. This information is the basis used here to prescribe the heat source resulting in the local heat-up of structures due to decay heating of deposited fission products.

Additional heat transfer information is needed to describe the transient thermal conditions caused by decay heating on a structure. These include density, heat capacity, and thermal conductivity of the condensate film and of the structure upon which it resides, thermal conductivity of the insulation surrounding the structure, the ambient temperature in the containment, a heat transfer coefficient for heat losses to gas flowing within the structure, and the temperature of that gas. Many of these parameters must be prescribed, either explicitly or implicitly, as part of the

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input data. However, much of the information needed to calculate the heat transfer to the gas is already embedded within VICTORIA.

With all of the relevant heat transfer parameters prescribed, the transient thermal response of the structure can be determined. If the structure exceeds a failure temperature, the geometry and response of the reactor coolant system (RCS) would undergo an abrupt change. Thus, it would make no sense to continue the analysis using the original geometry and flow conditions. Instead, the calculation is stopped in order to allow the user to restart the calculation with a different geometry and set of thermal-hydraulic conditions.

The following sections describe the mathematical model and implicit assumptions used to determine the thermal response of a structure containing deposited fission products, the data that are needed to perform the analysis, some practical aspects of the model, a sample calculation using the new model, and conclusions.

2. Assumptions and Mathematical Model

Several simplifying assumptions are made in the mathematical model described below and in the implementation of this model in VICTORIA. The major assumptions are as follows:

1. All isotopes of an element have the same diffusive and transport properties. Thus, the relative abundance of isotopes is the same everywhere in the RCS. This allows local decay heating to be determined as a function of the mass of each element (rather than the mass of each isotope) that has been deposited and the elapsed time since reactor shutdown.
2. Heat generated by gamma radiation is deposited within the surface film. Obviously, in many cases this is a bad assumption, but to determine where gamma radiation would be deposited is extremely complicated in all but the simplest of domains. While an overall recirculatory flow may exist in the RCS, recirculation does not occur within an individual cell. In other words, flow is unidirectional in all pipes and channels where decay heating occurs. This facilitates estimation of heat transfer conditions.
3. A uniform temperature exists within the structure. Likewise, a uniform temperature exists in the deposited fission product film.
4. Thermal conductivity of the insulation and thermal properties of the structure and film are independent of temperature.
5. The ambient temperature outside the external surface of the structure is constant.

6. Heat transfer to the gas has a negligible effect on the gas temperature. This implies that the throughput of thermal mass is great enough so that heat losses to the structure are negligible.
7. Radiation between the gas and the structure film is taken to be negligible. This is generally a good assumption unless the opacity of the gas is large due to suspended aerosol particles.

Some of these assumptions, especially those involving constant properties, could easily be eliminated. However, the benefit of keeping the input requirements and additional coding simple is viewed to outweigh the benefit of additional generality of the model.

The respective equations for modeling heat-up of the deposited film and structure are

$$\varepsilon \rho_F C p_F \frac{\partial T_F}{\partial t} = Q - L_1 - L_2 \quad \text{and} \quad (1)$$

$$w \rho_S C p_S \frac{\partial T_S}{\partial t} = L_2 - L_3 . \quad (2)$$

Here, ε is the thickness of the structural film, w is the wall thickness of the structure, ρ is density, Cp is heat capacity, T is temperature, t is time, Q is the rate of heat generation per unit area due to decay heating within the deposited film, L_1 is the heat flux to the gas flowing within the structure, L_2 is the heat flux from the surface film to the adjacent structure, and L_3 is the heat flux through a possible insulating layer surrounding the structure to the ambient. The subscript F indicates a film property and the subscript S indicates a structural property. Each of the fluxes are based on the surface area of the inside of the structure and are illustrated in Figure 1.

The rate of heat generation due to decay heating is

$$Q = \varepsilon \sum_j q_j(t) M_j \sum_i a_{ji} n_i . \quad (3)$$

Here, the first summation is over the set of elements and the second is over the set of species. $q_j(t)$ is the rate of heat generation by atomic decay per unit mass of element, j , as a function of time, and a_{ji} is the number of moles of element, j , contained in one mole of species, i . The data used for $q_j(t)$ are discussed in Section 3 below.

Assumptions and Mathematical Model

Figure 1. Schematic of the heat fluxes used in Equations 1 and 2

The heat loss to the flowing gas within the structure is

$$L_1 = h_1 (T_F - T_G) \quad . \quad (4)$$

Here, h_1 is a heat transfer coefficient that depends on thermal and geometric properties of the structure and T_G is the temperature in the gas. If the heat transfer is at a radial surface, then the following definition applies (see, e.g., [5]):

$$h_1 = \frac{1}{\log\left(\frac{r_{iS} - \epsilon}{r_{iS} - \epsilon - \delta}\right) \frac{r_{iS}}{k_G} + \log\left(\frac{2r_{iS} - \epsilon}{2r_{iS} - 2\epsilon}\right) \frac{r_{iS}}{k_F}} \quad ; \quad (5)$$

otherwise, if the heat transfer is along an axial surface (modeled as a flat plate), then

$$h_1 = \frac{1}{\frac{\delta}{k_G} + \frac{\epsilon}{2k_F}} \quad . \quad (6)$$

Assumptions and Mathematical Model

Here, r_{iS} is the inner radius of the structure, k_g is the thermal conductivity of the gas and δ is the thermal boundary layer thickness in the gas.

The heat loss from the film to the structure is

$$L_2 = h_2 (T_F - T_S) . \quad (7)$$

Here, h_2 is the heat transfer coefficient between the film and the structural material. On radial surfaces, it is

$$h_2 = \frac{1}{\log\left(\frac{2r_{iS}}{2r_{iS}-\epsilon}\right)\frac{r_{iS}}{k_F} + \log\left(\frac{r_{iS}+r_{oS}}{2r_{iS}}\right)\frac{r_{iS}}{k_S}} ; \quad (8)$$

on axial surfaces, it is

$$h_2 = \frac{1}{\frac{\epsilon}{2k_F} + \frac{\Delta z_S}{2k_S}} . \quad (9)$$

Here, r_{oS} is the outer radius of the structure and Δz_S is the axial thickness of the structure.

Finally, the heat loss through the structural insulation is

$$L_3 = h_3 (T_S - T_A) . \quad (10)$$

On a radial surface, h_3 is

$$h_3 = \frac{1}{\log\left(\frac{r_I}{r_{oS}}\right)\frac{r_{iS}}{k_I} + \log\left(\frac{2r_{oS}}{r_{oS}+r_{iS}}\right)\frac{r_{iS}}{k_S}} ; \quad (11)$$

on an axial surface it is

$$h_3 = \frac{1}{\frac{\Delta z_I}{k_I} + \frac{\Delta z_S}{2k_S}} . \quad (12)$$

Assumptions and Mathematical Model

Here, Δz_I is the axial thickness of the insulation, k_I is the thermal conductivity of the insulation, T_S is the temperature of the structure, T_A is the ambient temperature external to the structure, and r_i is the outer radius of the insulation.

Equations (1)-(4), (7), and (10), along with definitions of the heat transfer coefficients in (5), (6), (8), (9), (11), and (12), form a complete set of equations to describe the heat-up of a surface film and underlying structure. Normally, these equations would be solved numerically at each time step. However, explicit implementation of these equations proved to be unstable. The reason for this is that the initial mass of the film is very small, and thus its thermal mass is very small. Heat transfer to or from the gas or heat generation due to decay heating can cause substantial changes in temperature in the film over a single time step. There are three alternatives to the explicit implementation: (1) an implicit numerical implementation; (2) a numerical procedure using a sub-interval time step; and (3) an analytic solution of the equations. The third alternative was chosen because it is the most efficient and the most robust of the available choices.

Equations (1)-(4), (7), and (10) form a set of two coupled ordinary differential equations, which can be solved by standard methods. The solution has the following form:

$$T_F = c_1 e^{r_1 t} + c_2 e^{r_2 t} + d_1, \quad (13)$$

$$T_S = c_3 e^{r_1 t} + c_4 e^{r_2 t} + d_2. \quad (14)$$

The exponents in Equations (13) and (14) are defined as follows:

$$r_{1,2} = \frac{-(h'_1 + h'_2 + h''_2 + h'_3) \pm \sqrt{[h'_1 + h'_2 - h''_2 - h'_3]^2 + 4h'_2 h''_2}}{2}. \quad (15)$$

Here, the subscripts 1 and 2 refer to the plus and minus, respectively, and the primed quantities are related to the heat transfer coefficients defined above as follows:

$$h'_1 = \frac{h_2}{\epsilon \rho_F C p_F} \quad (16)$$

$$h'_2 = \frac{h_2}{\epsilon \rho_F C p_F} \quad (17)$$

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$$h''_2 = \frac{h_2}{w\rho_S C p_S} \quad (18)$$

$$h'_3 = \frac{h_3}{w\rho_S C p_S} \quad (19)$$

The coefficients in Equations (13) and (14) are defined as follows:

$$c_1 = \frac{h'_2 [T_S(t^n) - d_2] - (r_2 + h'_1 + h'_2) [T_F(t^n) - d_1]}{\sqrt{[h'_1 + h'_2 - h''_2 - h'_3]^2 + 4h'_2 h''_2}} ; \quad (20)$$

$$c_2 = \frac{-h'_2 [T_S(t^n) - d_2] + (r_1 + h'_1 + h'_2) [T_F(t^n) - d_1]}{\sqrt{[h'_1 + h'_2 - h''_2 - h'_3]^2 + 4h'_2 h''_2}} ; \quad (21)$$

$$c_3 = \frac{r_1 + h'_1 + h'_2}{h'_2} c_1 ; \quad (22)$$

$$c_4 = \frac{r_2 + h'_1 + h'_2}{h'_2} c_2 ; \quad (23)$$

$$d_1 = \frac{(h''_2 + h'_3) (Q' + h'_1 T_G) + h'_2 h'_3 T_A}{h'_1 h''_2 + h'_1 h'_3 + h'_2 h'_3} ; \text{ and} \quad (24)$$

$$d_2 = \frac{h''_2 (Q' + h'_1 T_G) + (h'_1 + h'_2) h'_3 T_A}{h'_1 h''_2 + h'_1 h'_3 + h'_2 h'_3} . \quad (25)$$

Here, $T_F(t^n)$ and $T_S(t^n)$ refer respectively to the film and structure temperatures at the beginning of a time step (in essence, the initial conditions) and

$$Q' = \frac{h_2}{\varepsilon \rho_F C p_F} . \quad (26)$$

3. Data Internal to the Code

Some of the parameters that appear in Equations (1) through (5) are given in data statements or are evaluated within the code; others must be prescribed by the user for each problem. This section describes the parameters that are defined within the code. Section 4 describes the additional input data needed for this model. The parameters are discussed in the order that they appear in the equations.

Table 1. Density, heat capacity, and thermal conductivity evaluated at 700 K for four structural materials and for the deposited film

Number	Name	Density (kg/m ³)	Heat Capacity (J/kgK)	Thermal Conductivity (W/mK)
1	Zircaloy-4 [6]	6550	340	18
2	Inconel 600 [7]	8420	900	15
3	Stainless Steel [7]	7930	800	15
4	Inert (ZrO ₂) [6]	5700	570	1.7
	Film (Fe ₂ O ₃) [6]		950	3.4

The thickness of the structural film, ϵ , in Equations (1) and (3) is defined in a data statement to be 0.5 mm [1]. Molar concentrations of species, n_i , which appear in Equation (3), are determined as part of the solution of thermodynamic equilibrium. Molecular weights of the species, M_i , which appear in Equation (2), are calculated within the code from the atomic weights of the elements, M_i , and from the coefficients, a_{ji} , which appear in Equation (3) and are defined in data statements. Densities, ρ , heat capacities, C_p , and thermal conductivities, k , of the film and structural materials are defined in data statements within the code. Their values are given in Table 1.

Values are tabulated in [4] for 29 elements that produce more than 99% of the decay heat in a LWR for the first two days after reactor shutdown. Only a subset of these elements are represented in VICTORIA. Data from [4] were extracted for each fission product in VICTORIA and for times after reactor shutdown from 0 to 20 hours. The values used in the code are reported in Tables 2 and 3.

Two points concerning Tables 2 and 3 are noteworthy. First, the data represent not only decay heat produced by the parent radionuclide, but also by daughters, granddaughters, etc. This is appropriate for VICTORIA since no explicit accounting of decay chains is performed. This also accounts for the fact that some of the data in the table do not decrease monotonically with time. Second, the data have been

Table 2. Normalized decay powers (W/kW_{th}) as a function of elapsed time since reactor SCRAM (s)

Time	0	6	12	18	30	60	120	240	600	1200
Element										
Cs	4.4	3.2	3.2	2.9	2.8	2.3	1.9	1.6	1.2	0.91
I	4.7	4.1	4.2	3.8	3.5	3.3	2.9	2.8	2.6	2.4
Ba	2.6	2.2	2.0	1.8	1.6	1.4	1.3	1.2	1.0	0.79
Sr	3.4	2.6	2.4	2.3	2.1	1.8	1.5	1.3	1.1	0.88
Zr	2.3	2.5	2.1	1.8	1.3	0.91	0.70	0.64	0.67	0.67
Sn	0.44	0.38	0.35	0.35	0.32	0.29	0.23	0.17	0.12	0.10
Te	2.1	1.8	1.7	1.6	1.4	1.3	1.2	1.1	1.1	1.0
U	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.1	0.91	0.70
Kr	2.4	1.9	1.7	1.6	1.5	1.3	1.1	0.97	0.79	0.76
Xe	2.4	2.1	1.9	1.8	1.7	1.5	1.2	0.94	0.70	0.53
Mo	1.9	2.1	2.1	2.1	2.0	1.8	1.5	1.2	0.85	0.61
Ru	0.53	0.53	0.56	0.56	0.59	0.59	0.56	0.50	0.44	0.38
Sb	1.8	1.6	1.6	1.5	1.5	1.4	1.2	1.0	0.67	0.50

normalized by decay power prior to reactor SCRAM. The rationale for this normalization stems from the following assertions that are made in [4]:

1. Unstable isotopes of fission products reach steady concentration levels within a few days after reactor start-up and remain level during normal reactor operation. These levels are insensitive to time during the annual operating cycle, the type of reactor (i.e., PWR versus BWR), or issues of fuel management history.
2. Stable isotopes gradually build up during the annual operating cycle. Their concentrations are sensitive to fuel management history and type of reactor.
3. Inventories of unstable isotopes of fission products depend mainly on operating power prior to reactor shutdown, provided that reactor power was held level long enough for a steady state to be achieved.

Additional Input Data

Table 3. Normalized decay powers (W/kW_{th}) as a function of elapsed time since reactor SCRAM (hr)

Time	1	1.5	2	4	6	8	10	12	15	20
Element										
Cs	0.38	0.23	0.15	0.07	0.06	0.06	0.06	0.06	0.06	0.06
I	1.9	1.6	1.5	1.0	0.82	0.70	0.62	0.53	0.47	0.38
Ba	0.47	0.38	0.35	0.27	0.25	0.26	0.27	0.29	0.32	0.35
Sr	0.76	0.73	0.70	0.62	0.53	0.44	0.39	0.32	0.27	0.21
Zr	0.73	0.79	0.79	0.82	0.79	0.76	0.70	0.67	0.62	0.56
Sn	0.07	0.05	0.04	0.01	0.007	0.004	0.004	0.003	0.003	0.003
Te	0.85	0.79	0.76	0.64	0.64	0.64	0.64	0.64	0.64	0.62
U	0.22	0.10	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Kr	0.70	0.62	0.53	0.32	0.18	0.11	0.07	0.04	0.02	0.01
Xe	0.29	0.20	0.15	0.09	0.08	0.08	0.07	0.07	0.07	0.06
Mo	0.25	0.19	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.16
Ru	0.35	0.35	0.32	0.29	0.28	0.26	0.25	0.23	0.23	0.22
Sb	0.26	0.18	0.13	0.08	0.06	0.05	0.04	0.03	0.03	0.02

It follows that the data in Table 2 must be scaled according to reactor power prior to shutdown and according to the abundances of each of the fission products. The manner in which these scalings are performed is described in Section 5 below.

4. Additional Input Data

Equations (1) through (5) use a number of parameters that are not currently available, either as part of the input or part of the internal data in VICTORIA. Some of these parameters, plus some information to tell VICTORIA where heat-up calculations are to be performed, must be included in the input file. The additional data needed to run the decay heat and structure heat-up calculations are discussed in this section.

Keeping with the current modular style of VICTORIA [1], heat-up of structures is treated as a new module named HEATUP. Thus the first input parameter that is required is a flag to tell the code whether or not heat-up calculations are to be included in the analysis. If the flag is set to zero, no decay heating calculations will be performed; if it is set to one, decay heating calculations will be performed; if it is set to two, decay heating and coupling between decay heating and local temperatures are both calculated.

When this flag is set to 1 or 2, some additional input data are expected by the code. When flag is set to 1, one additional line of data is required following the thermal-hydraulic input section. This line consists of four parameters: the ambient temperature inside containment, in units of K; elapsed time from reactor SCRAM to $t = 0$ for the VICTORIA calculation, in units of s; the mass of uranium per unit of thermal energy produced by the reactor just prior to reactor SCRAM, in units of kg uranium per kW thermal; and structure failure temperature, in units of K. Only the second and third of these parameters are used in the code when the decay heat flag is set to 1; all of them are used when it is set to 2. Guidance on the selection of appropriate values for structure failure temperatures is provided in [8].

Additional data are needed when the decay heat flag is set to 2. A flag array must be set to tell the code in which volumes to perform heat-up calculations. Usually heat-up calculations are needed in only a few of the volumes. Because of the thermal models that are used to determine heat losses to the ambient and to the gas flowing within the structure, heat-up of structures is allowed only along the perimeter of the domain. Thus the data needed for this and the following arrays should have as many values as the problem has perimeter cell edges (the data structure is the same as for boundary conditions [1]).

Structural materials, such as the those that are being considered here, can be specified to be made up of Zr-4, Inconel-600, 304 stainless steel, or inert material. The choice is specified by the structure identification flags that are part of the existing input file [1]. The choice of material will affect the heat capacity and density of the structural surface, as shown in Table 1. Although it is possible to select Zr-4 as a material on the perimeter of the domain, it is not recommended when performing heat-up calculations with this material for reasons explained below.

Three additional pieces of data are required at each perimeter cell edge. These are the thickness of the structural wall, w , expressed in m; the thermal conductivity of the insulation, k_i , in W/mK; and the insulation thickness in m.

All of the data needed to calculate the losses to the flowing gas, defined in (5), are already embedded within the code.

5. Practical Aspects of the Model Implementation

As mentioned in Section 3 above, the data in Table 2 need to be scaled before they can be used to calculate decay heating. This scaling is done in two parts. First the thermal power of the reactor prior to shutdown is calculated by taking the ratio of the mass of uranium initially in the fuel to the parameter defining the mass of uranium needed to generate a unit of thermal power. From this, the amount of decay heat produced by each fission product listed in Table 2 can be calculated. The second part of the scaling is simply to convert the total amount of decay heat produced by an element to that produced per unit mass. This is done by dividing the total decay heat produced by an element by its initial mass in the fuel. This tacitly makes the assumption that all fission products start out in the fuel at the beginning of a calculation. Once the data are scaled for the current problem, they are interpolated logarithmically to determine decay heat as a function of time.

Typical values for the amount of mass needed to produce a unit of thermal energy during normal power plant operation are 26×10^{-3} kg/kW for a PWR and 38×10^{-3} kg/kW for a BWR. However, if the plant is not operating normally prior to reactor shutdown, these values should be scaled to reflect the percent of capacity prior to shutdown.

Although there are four choices of structural materials, it is not advisable to perform heat-up calculations for structures made of Zircalloy-4. The problem is that both Zr and Sn, which are the main elements in Zircalloy-4, produce decay heat. VICTORIA has no mechanism for tracing the origin of an element and thus, does not distinguish between Zr and Sn that originated in the fuel and that which originated in the structure. This problem does not arise for the other three materials since they do not contain elements that produce decay heat.

When the decay heat flag is not set to 2, thermal transients for structures are determined by interpolating data from the input file. When the decay heating flag is set to 2, only the initial temperature is taken from the input file for the cells which where decay heating is calculated. Afterward, Equations (1) and (2) are used to calculate the transient thermal response of the film and structure.

As mentioned above, the calculation is stopped if the user specified structure failure temperature is reached. The reasoning for this is that the geometry and thermal-hydraulics would likely change dramatically at this point, so continuation of the calculation would probably not make sense. However, the user can overcome this feature by simply setting the failure temperature to be artificially high.

6. Data Available for Validation

To the best of the author's knowledge, no data are available to validate this model.

7. Sample Calculation

The sample calculation given here is primarily intended as an exercise to show the effects of decay heating in the context of a simple problem. It is based on the PHEBUS test bundle for FPT-0, which contains 21 trace irradiated fuel rods. The sample problem uses a total of eight cells with only one radial ring. The bottom five cells contain the fuel bundle; the top three consist of a conically shaped thermal gradient tube. Aerosols are injected just above the top of the fuel bundle to represent the presence of control rods, which are not explicitly modeled. For this test problem, the parameter specifying the mass of U needed to produce a kilowatt of heat has been chosen to be artificially low. This has been done in order to compensate for the small mass of fission products that are released by the test bundle. The amount of decay heat produced in this case is great enough to revaporize some of the deposited fission products. Coupling between decay heating and local thermal response is only activated in the upper three cells.

Appendix A.1 contains a complete input file and Appendix A.2 contains a partial output file for the sample problem. Notice that six elements have been edited out of the element masses portion of the output file since these elements did not exist in this calculation.

Release of fission products from the fuel occurs at 3000 s (which is the initial time of the calculation). Accumulated deposition of fission products reaches a maximum at about 3400 s, as shown in Figure 2. After this time, revaporization of the deposited fission products outstrips further deposition. Temperatures of the film and structure, on the other hand, reach a peak of 1099 K (for cell eight) at a later time, about 3800 s, as shown in Figure 3. Afterwards, the temperature begins to fall because both the mass and heat output of deposited fission products diminishes.

Notice that a section describing temperatures (fuel, gas, and structure) and gas pressure has been added to the output. This is especially useful for the film and structure temperatures since they can not be determined by interpolating input data when the structure heat-up model is active.

8. Conclusions

A simple model for decay heat and its effect on thermal transients of structures has been incorporated into VICTORIA. This model implicitly accounts for decay heating due to parents, daughters, granddaughters, etc., but does not explicitly account for decay chains. Heat losses are calculated to the ambient surroundings and to the gas flowing within the structure.

The sample problem in Section 7 illustrates the use of the structure heat-up model. In that problem, both mass of deposited radionuclides and temperature reach a

Conclusions

Figure 2. Transient behavior of deposited fission products (only those in Tables 2 and 3) in Cell 8

Figure 3. Transient behavior of film and structure temperatures

maximum then decrease again. The mass reaches a maximum because temperature gets high enough that some revaporization begins to occur. The loss of deposited radionuclides plus the decrease of decay heat with time causes the temperature to peak and then diminish. This relatively simple problem illustrates the phenomena that result from decay heating on structural surfaces.

The heat-up of structures model will be essential for analyzing some accident sequences, such as the steam generator tube rupture sequence. Decay heating is especially important in this sequence because large amounts of radionuclides are likely to be deposited in a small steam generator tube.

9. References

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2. *American National Standard for Decay Heat Power in Light Water Reactors*, ANSI/ANS-5.1-1979, August 29, 1979.
3. D. E. Bennett, *SANDIA-ORIGEN User's Manual*, SAND79-0299, NUREG/CR-0987, Sandia National Laboratories, Albuquerque, NM, October 1979.
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5. R. B. Bird, W. E. Stewart, and E. N. Lightfoot, *Transport Phenomena*, John Wiley and Sons, New York, NY, 1960.
6. J. K. Hohorst, editor, *SCDAP/RELAP5/MOD2 Code Manual, Volume 4: MAT-PRO--A Library of Materials Properties for Light-Water-Reactor Accident Analysis*, NUREG/CR-5273, EGG-2555 Vol. 4, EG&G Idaho, February 1990.
7. R. C. Schmidt, P. T. Giguere, T. J. Heames, and S. S. Dosanjh, *MELPROG PWR/MOD1 Models and Correlations*, SAND89-3123, NUREG/CR-5569, Sandia National Laboratories, May 1991.
8. B. L. Harris, V. N. Shaw, and G. E. Korth, *Creep Rupture Failure of Three Components of the Reactor Primary Coolant System During the TMLB' Accident*, EGG-EA-7431, EG&G Idaho, Inc., 1986.

APPENDIX A.1

Sample Problem Input File

```

$
$ Input deck for VICTORIA version 90NX
$
$ Job details
$ -----
$ Computer type :
'SUN SPARC 1+'
$ Calculation Description :
'Phebus - FP TMLB" Fresh Fuel bundle calculation'
$
$ Restart information
$   Read   Write
$     0     1
$
$ time step control input
$ -----
$ start time ; time step ; end time
$   3000.0   1.0   3200.0
$
$ Numerical Control data
$ -----
$ max chem. iterations ; convergence criterion ; max non-limited itera-
tions
$           500           1.e-8           50
$
$ Output control
$ -----
$ print control ; graphics control
$           100           1500
$ internal sub-module selection
$ -----
$ chemistry   aerosols   convection   rod release   decay
$           1           1           1           1           2
$
$ general cell input section
$ -----
$ axial ; radial ; fuel radial ; clad radial
$           8           1           2           1
$
$ Geometrical Data
$ -----
$ cell outer radii (m)
$   5*0.035, 0.03, 2*0.02
$ cell midpoints (m)

```

```

0.1,0.3,0.5,0.7,0.9,1.05,1.3,1.7
$ bend flags
8*0.
$ settling flags
8*0.
$ boundary condition flags (0=zero grad,1=a value)
8*0, 0, 1 , 8*0
$ axial cell areas
5*0.002428, 0.002828, 2*0.001257
$ hydraulic diameters
5*0.0109, 0.06, 2*0.04
$ floor area in cell
8*0.0
$ wall area (exclusive of rods) in cell
5*0.178, 0.018, 2*0.503
$ ceiling area in cell
5*0.0, 0.0008, 2*0.0
$ structure identification flag (Zirconia walls)
8*0
$
$ Fuel Data
$ -----
$ pellet diam. ; gap thick. ; clad thick. ; Helium pressure ; frac. the-
or.dens.
      8.20e-3      3.6e-4      5.70e-4      1.0e+5      0.931
$ number of fuel rods per radial ring
5*21.0,3*0.0
$
$ continuity input section
$ -----
$ initial condition values
1
H2Og
0.6059, 0.3633, 0.251, 0.242, 0.326, 0.326, 0.467, 0.373
$ boundary condition values
1
H2Og
8*0.0, 0.0,0.6135, 8*0.0
$
$ Initial fuel grain inventories and diffusion coefficients
$
$ Expected order is U,O,Cs,Ba,I,Sr,Zr,Sn,Te,Kr,Xe,Mo,Ru,Sb,Eu,He
$
$ U
$ Conc. ; dzero ; theta
38.127 , , ,
$ O
$ Conc. ; dzero ; theta
76.254 , , ,
$
$ Cs
$ Conc. ; dzero ; theta
3.03e-0 , , ,
$ Ba

```

```

$ Conc. ; dzero ; theta
  1.262e-0 , , ,
$ I
$ Conc. ; dzero ; theta
  5.1e-1 , , ,
$ Sr
$ Conc. ; dzero ; theta
  1.33e-0 , , ,
$ Zr
$ Conc. ; dzero ; theta
  4.85e-0 , , ,
$ Sn
$ Conc. ; dzero ; theta
  0.0 , , ,
$ Te
$ Conc. ; dzero ; theta
  6.8e-1 , , ,
$ Kr
$ Conc. ; dzero ; theta
  5.65e-1 , , ,
$ Xe
$ Conc. ; dzero ; theta
  4.3e-0 , , ,
$ Mo
$ Conc. ; dzero ; theta
  4.0e-0 , , ,
$ Ru
$ Conc. ; dzero ; theta
  2.5e-0 , , ,
$ Sb
$ Conc. ; dzero ; theta
  1.6e-2 , , ,
$ Eu
$ Conc. ; dzero ; theta
  1.0e-1 , , ,
$ He
  0. , , ,
$
$ *****
$ Input data file for the CHARM aerosol code
$ *****
$
$ Boundary layer data
$ *****
$
$ b.l. flag ; viscous b.l. ; diffusion b.l.
, , ,
$
$ Definition of collocation points
$ *****
$
$ ncoll ; spacing
, , ,
$

```



```

$      mlower      ;      mupper
      2.0e-18      ,      2.0e-7
$
$      element number
      ,
$
$ Tolerance specification
$ *****
$
$      eps      ;      maxcalls      ;      maxtrys
      1.e-4      ,      ,
$
$      eta      zeta
      ,
$
$ Aerosol physics data
$ *****
$
$
$      cshpfctr dshpfctr stickeff
      1.0 1.0 1.0
$      aknudweb qknudweb bknudweb
      1.37 0.4 1.1
$      cmbrock csbrock ctbrock
      1.0 1.37 1.0
$ multi or single component (use single or multi)
'single'
$ number of aerosol sources
      1
$ number of table entries
      2
$ time (sec) for aerosol source
      0.0      5000.0
$ Number of species in aerosol source
      2
$ Species name and fraction of aerosol
      Agc      0.15
      Snc      0.85
$ Fluid cell aerosol is input into
$      axial      radial
      6      1
$
$ Aerosol source rates vs time (kg/s) 1000 ppm (mass)
      6.e-6      1.e-6
$ Sigma radius (m)
      2.00      0.5e-7
$
$ Vapor Source
$ -----
$
$ number of vapor sources
      0
$
$ *****

```

```

$
$ Thermal Hydraulic Input
$ -----
$ number of time values for temperature arrays
    5
$ time values (s) for fuel temperatures
    0., 2000.0, 3000.0, 4000.0, 5000.
$ fuel temperature array (time,cell) degrees Kelvin
    900.0, 950.0, 1000.0, 1100.0, 1200.0
    1200.0, 1300.0, 1500.0, 1800.0, 2400.0
    1400.0, 1700.0, 2100.0, 2200.0, 2800.0
    1400.0, 1800.0, 2150.0, 2300.0, 2900.0
    1000.0, 1600.0, 2150.0, 2300.0, 2900.0
    5*0.0
    5*0.0
    5*0.0
$
$ fuel cladding failure temperature (K)
    2150.0
$
$ time values (s) for gas temperatures
    0., 2000.0, 3000.0, 4000.0, 5000.
$ gas temperature array (time,cell) degrees Kelvin
    800.0, 850.0, 900.0, 1000.0, 1100.0
    900.0, 1000.0, 1400.0, 1700.0, 2300.0
    1200.0, 1500.0, 2000.0, 2100.0, 2700.0
    1200.0, 1500.0, 2050.0, 2200.0, 2800.0
    1100.0, 1500.0, 2050.0, 2200.0, 2800.0
    1100.0, 1300.0, 1700.0, 1700.0, 2100.0
    1000.0, 1100.0, 1300.0, 1300.0, 1500.0
    900.0, 900.0, 900.0, 900.0, 900.0
$
$ time values (s) for wall temperatures
    0.0, 2000.0, 3000.0, 4000.0, 5000.0
$ wall temperature array (time,cell) (K)
    800.0, 850.0, 900.0, 1000.0, 1100.0
    800.0, 900.0, 1300.0, 1600.0, 2200.0
    1100.0, 1400.0, 1900.0, 2000.0, 2600.0
    1100.0, 1400.0, 1950.0, 2100.0, 2700.0
    1000.0, 1400.0, 1950.0, 2100.0, 2700.0
    1000.0, 1200.0, 1600.0, 1600.0, 2000.0
    900.0, 1000.0, 1200.0, 1200.0, 1400.0
    900.0, 900.0, 900.0, 900.0, 900.0
$
$ time values (s) for gas pressures
    0., 2000.0, 3000., 4000.0, 5000.
$ gas pressure array (time,cell) Pascals
    5*0.15e6
    5*0.15e6
    5*0.15e6
    5*0.15e6
    5*0.15e6
    5*0.15e6
    5*0.15e6

```

```

5*0.15e6
$
$ time values (s) for fluid flow velocities
    0.0, 2000.0, 3000.0, 4000.0, 5000.
$ radial time-dependent fluid flow velocities
40*0.
$ axial time-dependent fluid flow velocities
    1.34, 1.36, 1.09, 0.83, 0.43
    2.22, 2.47, 2.27, 1.95, 1.4
    3.21, 3.95, 3.64, 2.71, 1.46
    3.33, 4.32, 3.91, 2.77, 1.54
    2.47, 3.95, 3.64, 2.83, 1.56
    2.33, 2.97, 2.65, 1.80, 0.93
    4.05, 5.48, 4.23, 2.16, 1.15
    4.17, 4.64, 3.70, 2.39, 1.09
$
$ *****
$ input data for structure heat-up model
$ *****
$
$ amb. temp. (K) ; time after scram (s) ; kg U/kWt power ; struct. fail.
temp.
    300.                0.                .000026                2000.
$ heat-up flags--one for each boundary cell surface
    8*0, 0, 0, 5*0, 3*1
$ thicknesses of structure walls (m)
    18*0.005
$ thermal conductivity of the insulation (W/m/K)
    18*0.001
$ thicknesses of the insulation (m)
    18*0.05
$
$ *****
$ End of the input data file
$ *****
$

```

APPENDIX A.2

Sample Problem Output File

temperatures (K) and pressures (Pa) at time = 3.000E+03 s

i. j	fuel temp.	gas temp.	gas press.	film temp.	struc. temp.
1. 1	1.000E+03	9.000E+02	1.500E+05	9.000E+02	9.000E+02
1. 2	1.500E+03	1.400E+03	1.500E+05	1.300E+03	1.300E+03
1. 3	2.100E+03	2.000E+03	1.500E+05	1.900E+03	1.900E+03
1. 4	2.150E+03	2.050E+03	1.500E+05	1.950E+03	1.950E+03
1. 5	2.150E+03	2.050E+03	1.500E+05	1.950E+03	1.950E+03
1. 6		1.700E+03	1.500E+05	1.600E+03	1.600E+03
1. 7		1.300E+03	1.500E+05	1.200E+03	1.200E+03
1. 8		9.000E+02	1.500E+05	9.000E+02	9.000E+02

element masses (kg) in all cells at time = 3.000E+03 s

element	grains	pores	gap	clad	film	bulk gas	aerosol	structure	total	lost gas
Cs	4.158E-01	.	.	.	.	.	.	.	4.158E-01	.
I	6.682E-02	.	.	.	.	.	.	.	6.682E-02	.
H	.	.	.	.	1.289E-05	7.187E-04	.	4.330E-05	7.749E-04	.
Ba	1.789E-01	.	.	.	.	.	.	.	1.789E-01	.
O	1.260E+00	.	.	.	1.031E-04	5.749E-03	.	3.464E-04	1.266E+00	.
Sr	1.203E-01	.	.	.	.	.	.	.	1.203E-01	.
Zr	4.567E-01	.	1.820E-05	1.380E+00	2.245E-05	.	.	.	1.837E+00	.
Sn	.	.	2.959E-07	2.244E-02	3.651E-07	.	.	.	2.244E-02	.
Te	8.959E-02	.	.	.	.	.	.	.	8.959E-02	.
U	9.369E+00	.	.	.	.	.	.	.	9.369E+00	.
Kr	4.889E-02	.	.	.	.	.	.	.	4.889E-02	.
Xe	5.829E-01	.	.	.	.	.	.	.	5.829E-01	.
Mo	3.961E-01	.	.	.	.	.	.	.	3.961E-01	.
Ru	2.610E-01	.	.	.	.	.	.	.	2.610E-01	.
Sb	2.012E-03	.	.	.	.	.	.	.	2.012E-03	.
Eu	1.569E-02	.	.	.	.	.	.	.	1.569E-02	.
He	.	1.227E-05	3.260E-05	.	.	.	.	.	4.487E-05	.

element masses (kg) in all cells at time = 3.000E+03 s

element	lost aero	aero sce	initial	balance	bal/init
Cs	.	.	4.158E-01	.	.
I	.	.	6.682E-02	.	.
H	.	.	7.749E-04	.	.
Ba	.	.	1.789E-01	.	.
O	.	.	1.266E+00	.	.
Sr	.	.	1.203E-01	.	.
Zr	.	.	1.837E+00	.	.
Sn	.	.	2.244E-02	.	.
Te	.	.	8.959E-02	.	.
U	.	.	9.369E+00	.	.
Kr	.	.	4.889E-02	.	.
Xe	.	.	5.829E-01	.	.
Mo	.	.	3.961E-01	.	.
Ru	.	.	2.610E-01	.	.
Sb	.	.	2.012E-03	.	.
Eu	.	.	1.569E-02	.	.
He	.	.	4.487E-05	.	.

temperatures (K) and pressures (Pa) at time = 3.100E+03 s

i. j	fuel temp.	gas temp.	gas press.	film temp.	struc. temp.
1. 1	1.010E+03	9.099E+02	1.500E+05	9.099E+02	9.099E+02
1. 2	1.530E+03	1.430E+03	1.500E+05	1.330E+03	1.330E+03
1. 3	2.110E+03	2.010E+03	1.500E+05	1.910E+03	1.910E+03
1. 4	2.165E+03	2.065E+03	1.500E+05	1.965E+03	1.965E+03
1. 5	2.165E+03	2.065E+03	1.500E+05	1.965E+03	1.965E+03
1. 6		1.700E+03	1.500E+05	1.638E+03	1.634E+03
1. 7		1.300E+03	1.500E+05	1.232E+03	1.228E+03
1. 8		9.000E+02	1.500E+05	9.126E+02	9.084E+02

element masses (kg) in all cells at time = 3.100E+03 s

element	grains	pores	gap	clad	film	bulk gas	aerosol	structure	total	lost gas
Ce	3.651E-01	3.981E-02	1.136E-03	8.467E-05	1.169E-06	8.804E-05	2.069E-05	2.077E-04	4.065E-01	7.745E-03
I	4.992E-02	1.305E-02	2.170E-04	3.809E-05	5.236E-07	3.475E-05	1.379E-05	1.381E-04	6.341E-02	2.479E-03
H	.	7.213E-07	2.192E-06	2.812E-06	1.118E-05	5.724E-04	5.014E-08	3.360E-05	6.230E-04	1.435E-04
Ba	1.558E-01	2.305E-02	7.935E-06	1.379E-07	1.876E-09	8.703E-08	8.366E-08	1.222E-06	1.789E-01	7.084E-06
O	1.260E+00	8.241E-05	1.986E-05	4.133E-02	7.982E-05	3.520E-03	1.116E-06	2.221E-04	1.305E+00	-3.918E-02
Sr	1.194E-01	8.864E-04	2.911E-05	2.598E-07	3.511E-09	1.447E-07	2.552E-07	2.859E-06	1.203E-01	1.347E-05
Zr	4.562E-01	5.405E-04	1.820E-05	1.380E+00	2.245E-05	1.598E-17	9.677E-14	7.971E-12	1.837E+00	1.469E-11
Sn	2.704E-08	2.863E-09	1.508E-07	2.244E-02	3.651E-07	4.502E-07	1.691E-06	1.067E-05	2.245E-02	1.972E-05
Te	7.105E-02	1.853E-02	2.557E-07	5.287E-08	7.182E-10	4.768E-08	1.892E-08	1.178E-07	8.958E-02	1.991E-06
U	9.369E+00	1.273E-06	4.001E-15	7.840E-17	8.408E-19	3.623E-18	3.426E-16	5.785E-16	9.369E+00	1.251E-15
Kr	3.561E-02	8.227E-04	1.379E-03	8.846E-05	1.238E-06	1.156E-04	.	1.051E-05	3.803E-02	1.086E-02
Xe	4.249E-01	9.828E-03	1.645E-02	1.054E-03	1.480E-05	1.376E-03	.	1.252E-04	4.537E-01	1.292E-01
Mo	3.790E-01	1.709E-02	3.154E-13	3.378E-15	4.596E-17	1.548E-15	1.220E-14	4.997E-14	3.961E-01	1.544E-13
Ag	8.611E-22	4.598E-13	1.577E-13	9.429E-14	9.774E-14	7.029E-08	3.088E-07	1.955E-06	2.334E-06	3.072E-06
Ru	2.466E-01	1.440E-02	1.142E-12	1.224E-14	1.257E-16	1.530E-17	5.560E-14	1.796E-13	2.610E-01	3.681E-13
Sb	1.903E-03	1.090E-04	3.453E-08	1.894E-09	2.588E-11	1.150E-09	1.186E-09	1.938E-08	2.012E-03	1.063E-07
Bu	1.545E-02	2.348E-04	4.459E-06	4.150E-08	4.281E-10	1.939E-11	1.886E-07	5.870E-07	1.569E-02	1.207E-06
He	7.164E-06	4.433E-06	1.166E-05	3.801E-08	5.757E-10	5.259E-08	.	4.607E-09	2.336E-05	2.152E-05

element masses (kg) in all cells at time = 3.100E+03 s

element	lost aero	aero sce	initial	balance	bal/init
Ce	1.567E-03	.	4.158E-01	2.877E-08	0.000000
I	9.341E-04	.	6.682E-02	2.212E-08	0.000000
H	4.646E-06	.	7.749E-04	-3.693E-06	0.004766
Ba	4.995E-06	.	1.789E-01	6.035E-09	0.000000
O	9.334E-05	.	1.266E+00	-2.442E-05	0.000019
Sr	1.585E-05	.	1.203E-01	5.089E-06	0.000042
Zr	1.079E-10	.	1.837E+00	8.217E-11	0.000000
Sn	2.188E-04	2.508E-04	2.244E-02	4.190E-07	0.000019
Te	7.486E-07	.	8.959E-02	1.035E-10	0.000000
U	8.474E-15	.	9.369E+00	-3.553E-15	0.000000
Kr	.	.	4.889E-02	-4.649E-16	0.000000
Xe	.	.	5.829E-01	-1.332E-15	0.000000
Mo	6.148E-13	.	3.961E-01	4.824E-13	0.000000
Ag	3.907E-05	4.426E-05	.	2.215E-07	0.000000
Ru	2.610E-12	.	2.610E-01	1.969E-12	0.000000
Sb	7.859E-08	.	2.012E-03	3.025E-10	0.000009
Bu	8.564E-06	.	1.569E-02	6.459E-06	0.000412
He	.	.	4.487E-05	-4.005E-18	0.000000

temperatures (K) and pressures (Pa) at time = 3.200E+03 s

1, 3	fuel temp.	gas temp.	gas press.	film temp.	struc. temp.
1, 1	1.020E+03	9.199E+02	1.500E+05	9.199E+02	9.199E+02
1, 2	1.560E+03	1.460E+03	1.500E+05	1.360E+03	1.360E+03
1, 3	2.120E+03	2.020E+03	1.500E+05	1.920E+03	1.920E+03
1, 4	2.180E+03	2.080E+03	1.500E+05	1.980E+03	1.980E+03
1, 5	2.180E+03	2.080E+03	1.500E+05	1.980E+03	1.980E+03
1, 6	1.700E+03	1.500E+05	1.648E+03	1.646E+03	1.646E+03
1, 7	1.300E+03	1.500E+05	1.241E+03	1.238E+03	1.238E+03
1, 8	9.000E+02	1.500E+05	9.415E+02	9.337E+02	9.337E+02

element masses (kg) in all cells at time = 3.200E+03 s

element	grains	pores	gap	clad	film	bulk gas	aerosol	structure	total	lost gas
Ce	3.498E-01	4.757E-02	1.187E-03	7.365E-05	1.037E-06	8.027E-05	1.785E-05	3.655E-04	3.991E-01	1.374E-02
I	3.808E-02	2.149E-02	2.439E-04	3.164E-05	4.453E-07	3.004E-05	1.190E-05	2.680E-04	6.015E-02	4.812E-03
H	.	8.444E-07	2.522E-06	2.819E-06	1.116E-05	5.747E-04	4.356E-08	3.415E-05	6.263E-04	1.333E-04
Ba	1.436E-01	3.528E-02	1.347E-05	1.187E-07	1.646E-09	7.727E-08	7.479E-08	2.293E-06	1.789E-01	1.336E-05
O	1.260E+00	1.698E-04	2.573E-05	7.775E-02	7.984E-05	3.548E-03	1.009E-06	2.288E-04	1.342E+00	-7.581E-02
Sr	1.191E-01	1.134E-03	5.211E-05	2.518E-07	3.467E-09	1.440E-07	2.563E-07	5.351E-06	1.202E-01	2.523E-05
Zr	4.556E-01	1.071E-03	1.820E-05	1.380E+00	2.245E-05	2.932E-17	1.171E-13	8.287E-12	1.837E+00	1.529E-11
Sn	3.600E-08	3.157E-09	1.402E-07	2.244E-02	3.651E-07	4.641E-07	1.694E-06	2.026E-05	2.246E-02	3.982E-05
Te	5.973E-02	2.985E-02	6.768E-07	9.336E-08	1.296E-09	8.767E-08	3.479E-08	4.057E-07	8.958E-02	6.846E-06
U	9.369E+00	2.544E-06	1.466E-14	1.568E-16	1.723E-18	9.748E-18	7.307E-16	2.261E-15	9.369E+00	4.615E-15
Kr	2.925E-02	7.501E-04	1.562E-03	4.731E-05	6.913E-07	6.469E-05	.	5.883E-06	3.168E-02	1.721E-02
Xe	3.490E-01	8.958E-03	1.864E-02	5.642E-04	8.271E-06	7.713E-04	.	7.015E-05	3.781E-01	2.049E-01
Mo	3.782E-01	1.783E-02	6.033E-13	3.564E-15	4.946E-17	1.679E-15	1.352E-14	9.836E-14	3.961E-01	2.980E-13
Ag	3.784E-21	9.652E-13	2.191E-13	9.994E-14	1.034E-13	7.027E-08	3.116E-07	3.752E-06	4.134E-06	6.074E-06
Ru	2.457E-01	1.523E-02	2.210E-12	1.286E-14	1.338E-16	2.185E-17	6.165E-14	3.591E-13	2.610E-01	7.081E-13
Sb	1.897E-03	1.146E-04	5.625E-08	1.798E-09	2.505E-11	1.124E-09	1.173E-09	3.565E-08	2.012E-03	1.951E-07
Bu	1.541E-02	2.628E-04	9.050E-06	3.958E-08	4.134E-10	2.485E-11	1.902E-07	1.170E-06	1.569E-02	2.309E-06
He	7.446E-06	3.490E-06	9.143E-06	2.970E-08	4.685E-10	4.284E-08	.	3.754E-09	2.016E-05	2.472E-05

element masses (kg) in all cells at time = 3.200E+03 s

element	lost aero	aero sce	initial	balance	bal/init
Ce	2.942E-03	.	4.158E-01	5.217E-08	0.000000
I	1.861E-03	.	6.682E-02	4.124E-08	0.000001
H	7.898E-06	.	7.749E-04	-7.346E-06	0.009481
Ba	9.719E-06	.	1.789E-01	5.826E-09	0.000000
O	1.651E-04	.	1.266E+00	-4.999E-05	0.000019
Sr	3.029E-05	.	1.203E-01	9.361E-06	0.000078
Zr	1.131E-10	.	1.837E+00	8.619E-11	0.000000

Sn	4.317E-04	4.931E-04	2.244E-02	6.878E-07	0.000031
Te	2.664E-06	.	8.959E-02	3.487E-10	0.000000
U	3.536E-14	.	9.369E+00	1.954E-14	0.000000
Kr	.	.	4.889E-02	-5.065E-16	0.000000
Xe	.	.	5.829E-01	-3.997E-15	0.000000
Mo	1.285E-12	.	3.961E-01	1.016E-12	0.000000
Ag	7.718E-05	8.702E-05	.	3.744E-07	.
Ru	5.564E-12	.	2.610E-01	4.254E-12	0.000000
Sb	1.493E-07	.	2.012E-03	5.439E-10	0.000000
Eu	1.817E-05	.	1.569E-02	1.388E-05	0.000884
He	.	.	4.487E-05	-4.039E-18	0.000000

temperatures (K) and pressures (Pa) at time = 3.400E+03 s

i, j	fuel temp.	gas temp.	gas press.	film temp.	struc. temp.
1, 1	1.040E+03	9.399E+02	1.500E+05	9.399E+02	9.399E+02
1, 2	1.620E+03	1.520E+03	1.500E+05	1.420E+03	1.420E+03
1, 3	2.140E+03	2.040E+03	1.500E+05	1.940E+03	1.940E+03
1, 4	2.210E+03	2.110E+03	1.500E+05	2.010E+03	2.010E+03
1, 5	2.210E+03	2.110E+03	1.500E+05	2.010E+03	2.010E+03
1, 6	.	1.700E+03	1.500E+05	1.665E+03	1.664E+03
1, 7	.	1.300E+03	1.500E+05	1.257E+03	1.255E+03
1, 8	.	9.000E+02	1.500E+05	1.020E+03	1.011E+03

element masses (kg) in all cells at time = 3.400E+03 s

element	grains	pores	gap	clad	film	bulk gas	aerosol	structure	total	lost gas
Ce	3.347E-01	5.322E-02	1.255E-03	4.634E-06	8.393E-08	6.673E-06	8.502E-07	4.073E-04	3.896E-01	2.167E-02
I	2.830E-02	2.778E-02	2.180E-04	1.606E-06	2.914E-08	1.906E-06	7.227E-07	3.799E-04	5.668E-02	7.257E-03
H	.	1.000E-06	2.936E-06	2.833E-06	1.113E-05	5.803E-04	1.456E-09	3.448E-05	6.326E-04	1.160E-04
Be	1.340E-01	4.495E-02	2.219E-05	1.017E-08	1.590E-10	7.715E-09	7.778E-09	3.829E-06	1.789E-01	2.217E-05
O	1.260E+00	2.902E-04	3.461E-05	1.491E-01	7.927E-05	3.561E-03	3.195E-07	2.261E-04	1.413E+00	1.475E-01
Sr	1.187E-01	1.403E-03	8.296E-05	6.828E-08	9.731E-10	4.200E-08	6.803E-08	9.324E-06	1.202E-01	4.266E-05
Zr	4.546E-01	2.112E-03	1.820E-05	1.380E+00	2.245E-05	3.391E-15	1.387E-12	9.955E-12	1.837E+00	1.666E-11
Sn	4.454E-08	3.585E-09	1.298E-07	2.244E-02	3.651E-07	4.441E-07	1.739E-06	3.963E-05	2.248E-02	7.888E-05
Te	5.082E-02	3.874E-02	1.739E-06	3.593E-09	6.493E-11	4.213E-09	1.576E-09	9.614E-07	8.956E-02	1.741E-05
U	9.369E+00	5.096E-06	4.785E-14	8.128E-21	1.758E-21	6.395E-20	1.675E-15	8.945E-15	9.369E+00	1.327E-14
Kr	2.451E-02	7.221E-04	1.591E-03	8.529E-06	1.539E-07	1.342E-05	.	1.181E-06	2.685E-02	2.204E-02
Xe	2.926E-01	8.630E-03	1.900E-02	1.015E-04	1.836E-06	1.596E-04	.	1.405E-05	3.205E-01	2.625E-01
Mo	3.767E-01	1.936E-02	1.094E-12	1.959E-16	2.705E-18	1.165E-16	8.254E-16	1.795E-13	3.961E-01	5.206E-13
Ag	1.689E-20	1.697E-12	2.732E-13	1.203E-13	1.171E-13	7.073E-08	3.152E-07	7.422E-06	7.807E-06	1.180E-05
Ru	2.450E-01	1.599E-02	4.072E-12	1.261E-19	5.095E-21	8.546E-20	8.734E-14	7.536E-13	2.610E-01	1.215E-12
Sb	1.893E-03	1.189E-04	8.469E-08	6.434E-11	1.163E-12	5.156E-11	5.027E-11	5.892E-08	2.012E-03	3.170E-07
Eu	1.537E-02	2.917E-04	1.635E-05	5.925E-13	1.227E-14	3.980E-13	2.229E-07	2.249E-06	1.568E-02	3.728E-06
He	6.915E-06	2.318E-06	6.038E-06	2.128E-08	3.612E-10	3.346E-08	.	2.949E-09	1.533E-05	2.955E-05

element masses (kg) in all cells at time = 3.400E+03 s

element	lost aero	aero sce	initial	balance	bal/init
Ce	4.540E-03	.	4.158E-01	4.005E-07	0.000001
I	2.881E-03	.	6.682E-02	1.997E-07	0.000003
H	1.221E-05	.	7.749E-04	-1.399E-05	0.018056
Be	1.682E-05	.	1.789E-01	-9.516E-09	0.000000
O	2.720E-04	.	1.266E+00	-9.815E-05	0.000078
Sr	5.320E-05	.	1.203E-01	1.596E-05	0.000133
Zr	1.460E-10	.	1.837E+00	1.192E-10	0.000000
Sn	8.328E-04	9.522E-04	2.244E-02	1.172E-06	0.000052
Te	7.070E-06	.	8.959E-02	1.298E-09	0.000000
U	1.558E-13	.	9.369E+00	1.243E-13	0.000000
Kr	.	.	4.889E-02	2.101E-07	0.000004
Xe	.	.	5.829E-01	2.503E-06	0.000004
Mo	2.377E-12	.	3.961E-01	1.868E-12	0.000000
Ag	1.491E-04	1.680E-04	.	6.470E-07	.
Ru	1.271E-11	.	2.610E-01	1.045E-11	0.000000
Sb	2.535E-07	.	2.012E-03	8.990E-10	0.000000
Eu	3.758E-05	.	1.569E-02	3.058E-05	0.001949
He	.	.	4.487E-05	1.338E-10	0.000003

temperatures (K) and pressures (Pa) at time = 3.600E+03 s

i, j	fuel temp.	gas temp.	gas press.	film temp.	struc. temp.
1, 1	1.060E+03	9.599E+02	1.500E+05	9.599E+02	9.599E+02
1, 2	1.680E+03	1.580E+03	1.500E+05	1.480E+03	1.480E+03
1, 3	2.160E+03	2.060E+03	1.500E+05	1.960E+03	1.960E+03
1, 4	2.240E+03	2.140E+03	1.500E+05	2.040E+03	2.040E+03
1, 5	2.240E+03	2.140E+03	1.500E+05	2.040E+03	2.040E+03
1, 6	.	1.700E+03	1.500E+05	1.676E+03	1.675E+03
1, 7	.	1.300E+03	1.500E+05	1.269E+03	1.268E+03
1, 8	.	9.000E+02	1.500E+05	1.078E+03	1.072E+03

element masses (kg) in all cells at time = 3.600E+03 s

element	grains	pores	gap	clad	film	bulk gas	aerosol	structure	total	lost gas
Ce	3.307E-01	5.340E-02	9.244E-04	3.523E-05	9.888E-07	6.454E-05	7.097E-06	3.506E-04	3.855E-01	2.520E-02
I	2.671E-02	2.825E-02	7.954E-05	9.992E-06	2.811E-07	1.578E-05	4.727E-06	3.200E-04	5.538E-02	8.156E-03

H		1.138E-06	3.524E-06	4.321E-06	1.110E-05	5.873E-04	1.925E-08	3.557E-05	6.429E-04	9.743E-05
Ba	1.329E-01	4.592E-02	1.800E-05	1.318E-07	3.707E-09	1.619E-07	9.840E-08	5.020E-06	1.789E-01	2.920E-05
O	1.260E+00	3.543E-04	4.593E-05	1.878E-01	8.679E-05	4.521E-03	8.345E-07	2.932E-04	1.453E+00	-1.874E-01
Sr	1.186E-01	1.538E-03	8.423E-05	1.856E-07	4.293E-09	1.753E-07	2.030E-07	1.172E-05	1.202E-01	5.316E-05
Zr	4.536E-01	3.073E-03	1.820E-05	1.359E+00	2.245E-05	7.065E-16	8.973E-13	1.639E-11	1.815E+00	1.818E-11
Sn	8.373E-08	1.060E-08	7.260E-08	1.496E-02	3.651E-07	4.277E-07	1.830E-06	5.596E-05	1.502E-02	1.127E-04
Te	4.984E-02	3.972E-02	3.082E-07	4.524E-08	1.269E-09	7.076E-08	2.034E-08	1.099E-06	8.956E-02	2.123E-05
U	9.369E+00	7.680E-06	6.726E-14	1.386E-16	2.666E-18	2.734E-17	2.010E-15	1.473E-14	9.369E+00	1.545E-14
Kr	2.199E-02	4.537E-04	7.994E-04	1.730E-05	4.853E-07	3.531E-05	.	2.843E-06	2.330E-02	2.559E-02
Xe	2.624E-01	5.432E-03	9.556E-03	2.067E-04	5.813E-06	4.218E-04	.	3.396E-05	2.781E-01	3.049E-01
Mo	3.753E-01	2.072E-02	1.191E-12	1.655E-15	4.175E-17	1.591E-15	1.059E-14	2.046E-13	3.961E-01	5.899E-13
Ag	3.418E-20	1.700E-12	1.657E-13	1.221E-13	1.190E-13	6.999E-08	3.299E-07	1.040E-05	1.080E-05	1.710E-05
Ru	2.444E-01	1.657E-02	4.714E-12	3.876E-15	7.331E-17	6.832E-16	5.707E-14	1.000E-12	2.610E-01	1.279E-12
Sb	1.889E-03	1.224E-04	2.586E-08	6.982E-10	1.959E-11	8.204E-10	5.553E-10	6.958E-08	2.011E-03	3.764E-07
Bu	1.535E-02	3.093E-04	1.961E-05	1.542E-08	2.661E-10	2.198E-11	2.324E-07	2.990E-06	1.568E-02	3.941E-06
He	3.480E-06	1.089E-06	2.647E-06	3.754E-08	1.006E-09	7.665E-08	.	6.177E-09	7.338E-06	3.754E-05

element masses (kg) in all cells at time = 3.600E+03 s

element	lost aero	aero sce	initial	balance	bal/init
Ce	5.123E-03	.	4.158E-01	4.087E-07	0.000001
I	3.282E-03	.	6.682E-02	2.056E-07	0.000003
H	1.368E-05	.	7.749E-04	-2.080E-05	0.026848
Ba	2.321E-05	.	1.789E-01	-4.518E-08	0.000000
O	3.429E-04	.	1.266E+00	-1.459E-04	0.000115
Sr	6.756E-05	.	1.203E-01	1.908E-05	0.000159
Zr	3.257E-10	.	1.837E+00	-2.138E-02	0.011641
Sn	1.208E-03	1.377E-03	2.244E-02	-7.479E-03	0.333257
Te	8.822E-06	.	8.959E-02	1.653E-09	0.000000
U	3.193E-13	.	9.369E+00	2.700E-13	0.000000
Kr	.	.	4.889E-02	2.101E-07	0.000004
Xe	.	.	5.829E-01	2.503E-06	0.000004
Mo	2.833E-12	.	3.961E-01	2.255E-12	0.000000
Ag	2.160E-04	2.430E-04	.	8.621E-07	.
Ru	1.960E-11	.	2.610E-01	1.729E-11	0.000000
Sb	3.125E-07	.	2.012E-03	1.055E-09	0.000001
Bu	5.889E-05	.	1.569E-02	5.143E-05	0.003277
He	.	.	4.487E-05	1.338E-10	0.000003

temperatures (K) and pressures (Pa) at time = 3.800E+03 s

i, j	fuel temp.	gas temp.	gas press.	film temp.	struc. temp.
1, 1	1.080E+03	9.799E+02	1.500E+05	9.799E+02	9.799E+02
1, 2	1.740E+03	1.640E+03	1.500E+05	1.540E+03	1.540E+03
1, 3	2.180E+03	2.080E+03	1.500E+05	1.980E+03	1.980E+03
1, 4	2.270E+03	2.170E+03	1.500E+05	2.070E+03	2.070E+03
1, 5	2.270E+03	2.170E+03	1.500E+05	2.070E+03	2.070E+03
1, 6	.	1.700E+03	1.500E+05	1.683E+03	1.682E+03
1, 7	.	1.300E+03	1.500E+05	1.277E+03	1.276E+03
1, 8	.	9.000E+02	1.500E+05	1.099E+03	1.099E+03

element masses (kg) in all cells at time = 3.800E+03 s

element	grains	pores	gap	clad	film	bulk gas	aerosol	structure	total	lost gas
Ce	3.259E-01	5.162E-02	8.874E-04	3.397E-05	1.007E-06	6.836E-05	7.412E-06	1.664E-04	3.787E-01	3.096E-02
I	2.636E-02	2.682E-02	9.093E-05	8.683E-06	2.578E-07	1.497E-05	4.790E-06	1.500E-04	5.346E-02	9.448E-03
H	.	1.185E-06	3.677E-06	4.345E-06	1.107E-05	5.966E-04	2.057E-08	3.691E-05	6.538E-04	7.746E-05
Ba	1.340E-01	4.486E-02	1.303E-05	7.439E-08	2.208E-09	9.834E-08	6.257E-08	6.513E-06	1.788E-01	3.758E-05
O	1.260E+00	4.813E-04	4.665E-05	1.976E-01	8.623E-05	4.568E-03	8.639E-07	3.051E-04	1.463E+00	-1.976E-01
Sr	1.183E-01	1.788E-03	8.242E-05	1.478E-07	4.126E-09	1.682E-07	1.778E-07	1.480E-05	1.202E-01	6.594E-05
Zr	4.528E-01	3.936E-03	1.820E-05	1.359E+00	2.245E-05	1.326E-14	9.512E-12	2.601E-11	1.815E+00	2.921E-11
Sn	9.098E-08	7.017E-09	6.818E-08	1.496E-02	3.651E-07	4.394E-07	1.887E-06	6.848E-05	1.503E-02	1.432E-04
Te	5.089E-02	3.866E-02	2.386E-07	5.789E-08	1.714E-09	9.907E-08	2.996E-08	1.040E-06	8.955E-02	2.774E-05
U	9.369E+00	1.030E-05	8.895E-14	2.497E-16	5.181E-18	7.460E-17	3.500E-15	2.243E-14	9.369E+00	2.222E-14
Kr	2.033E-02	3.474E-04	6.005E-04	6.353E-06	1.877E-07	1.412E-05	.	1.158E-06	2.130E-02	2.759E-02
Xe	2.425E-01	4.165E-03	7.191E-03	7.593E-05	2.249E-06	1.688E-04	.	1.384E-05	2.541E-01	3.288E-01
Mo	3.745E-01	2.161E-02	9.845E-13	4.448E-15	9.247E-17	3.608E-15	2.405E-14	2.873E-13	3.961E-01	8.126E-13
Ag	5.371E-20	1.701E-12	1.341E-13	1.389E-13	1.358E-13	6.981E-08	3.419E-07	1.271E-05	1.312E-05	2.190E-05
Ru	2.439E-01	1.702E-02	5.244E-12	5.549E-15	1.073E-16	9.470E-16	7.941E-14	1.188E-12	2.610E-01	1.432E-12
Sb	1.886E-03	1.256E-04	2.659E-08	7.900E-10	2.338E-11	9.913E-10	7.037E-10	8.100E-08	2.011E-03	4.362E-07
Bu	1.533E-02	3.279E-04	2.221E-05	1.773E-08	3.139E-10	3.794E-11	2.598E-07	3.642E-06	1.568E-02	4.368E-06
He	1.496E-06	4.913E-07	1.213E-06	1.110E-08	3.147E-10	2.475E-08	.	2.033E-09	3.239E-06	4.164E-05

element masses (kg) in all cells at time = 3.800E+03 s

element	lost aero	aero sce	initial	balance	bal/init
Ce	6.089E-03	.	4.158E-01	4.217E-07	0.000001
I	3.915E-03	.	6.682E-02	2.144E-07	0.000003
H	1.630E-05	.	7.749E-04	-2.735E-05	0.035294
Ba	3.171E-05	.	1.789E-01	-7.364E-08	0.000000
O	4.420E-04	.	1.266E+00	-1.914E-04	0.000151
Sr	8.745E-05	.	1.203E-01	2.311E-05	0.000192
Zr	6.247E-10	.	1.837E+00	-2.138E-02	0.011641
Sn	1.556E-03	1.768E-03	2.244E-02	-7.478E-03	0.333245
Te	1.208E-05	.	8.959E-02	2.307E-09	0.000000
U	5.561E-13	.	9.369E+00	4.796E-13	0.000000
Kr	.	.	4.889E-02	2.101E-07	0.000004

Xe	.	.	5.829E-01	2.503E-06	0.000004
Mo	4.403E-12	.	3.961E-01	3.549E-12	0.000000
Ag	2.781E-04	3.121E-04	.	1.087E-06	.
Ru	2.552E-11	.	2.610E-01	2.268E-11	0.000000
Sb	3.800E-07	.	2.012E-03	1.227E-09	0.000001
Eu	8.038E-05	.	1.569E-02	7.085E-05	0.004514
He	.	.	4.487E-05	1.338E-10	0.000003

temperatures (K) and pressures (Pa) at time = 4.000E+03 s

i, j	fuel temp.	gas temp.	gas press.	film temp.	struc. temp.
1, 1	1.100E+03	9.999E+02	1.500E+05	9.999E+02	9.999E+02
1, 2	1.800E+03	1.700E+03	1.500E+05	1.600E+03	1.600E+03
1, 3	2.200E+03	2.100E+03	1.500E+05	2.000E+03	2.000E+03
1, 4	2.300E+03	2.200E+03	1.500E+05	2.100E+03	2.100E+03
1, 5	2.300E+03	2.200E+03	1.500E+05	2.100E+03	2.100E+03
1, 6	.	1.700E+03	1.500E+05	1.689E+03	1.688E+03
1, 7	.	1.300E+03	1.500E+05	1.284E+03	1.284E+03
1, 8	.	9.000E+02	1.500E+05	1.074E+03	1.078E+03

element masses (kg) in all cells at time = 4.000E+03 s

element	grains	pores	gap	clad	film	bulk gas	aerosol	structure	total	lost gas
Ce	3.212E-01	5.011E-02	8.606E-04	3.283E-05	1.029E-06	7.353E-05	7.019E-06	3.422E-05	3.723E-01	3.647E-02
I	2.594E-02	2.567E-02	1.131E-04	7.744E-06	2.431E-07	1.477E-05	4.311E-06	2.578E-05	5.178E-02	1.053E-02
H	.	1.217E-06	3.814E-06	4.373E-06	1.104E-05	6.092E-04	2.160E-08	3.874E-05	6.684E-04	5.381E-05
Ba	1.353E-01	4.347E-02	1.610E-05	6.480E-08	2.032E-09	9.217E-08	6.268E-08	7.457E-06	1.788E-01	4.296E-05
O	1.260E+00	6.020E-04	4.810E-05	2.211E-01	8.141E-05	4.253E-03	7.977E-07	2.922E-04	1.486E+00	-2.209E-01
Sr	1.180E-01	2.008E-03	8.991E-05	1.450E-07	4.472E-09	1.835E-07	2.043E-07	1.747E-05	1.201E-01	7.578E-05
Zr	4.520E-01	4.692E-03	1.820E-05	1.359E+00	2.245E-05	1.072E-13	4.761E-11	9.315E-11	1.815E+00	1.087E-10
Sn	9.159E-08	7.002E-09	6.745E-08	1.496E-02	3.651E-07	4.810E-07	1.943E-06	7.846E-05	1.504E-02	1.734E-04
Te	5.221E-02	3.732E-02	2.724E-07	7.217E-08	2.260E-09	1.371E-07	4.032E-08	3.902E-07	8.953E-02	3.607E-05
U	9.369E+00	1.297E-05	1.269E-13	4.268E-16	9.961E-18	2.079E-16	5.396E-15	3.401E-14	9.369E+00	3.425E-14
Kr	1.937E-02	3.433E-04	5.989E-04	4.601E-06	1.433E-07	1.126E-05	.	9.432E-07	2.033E-02	2.856E-02
Xe	2.311E-01	4.116E-03	7.176E-03	5.488E-05	1.712E-06	1.342E-04	.	1.125E-05	2.426E-01	3.404E-01
Mo	3.741E-01	2.193E-02	9.355E-13	2.343E-15	7.224E-17	2.751E-15	1.490E-14	3.687E-13	3.961E-01	1.021E-12
Ag	7.572E-20	1.703E-12	1.467E-13	1.654E-13	1.617E-13	6.952E-08	3.587E-07	1.472E-05	1.514E-05	2.618E-05
Ru	2.436E-01	1.735E-02	6.004E-12	7.930E-15	1.455E-16	2.546E-16	1.055E-13	1.403E-12	2.610E-01	1.596E-12
Sb	1.883E-03	1.285E-04	3.302E-08	9.296E-10	2.910E-11	1.245E-09	9.541E-10	9.476E-08	2.011E-03	4.996E-07
Eu	1.531E-02	3.415E-04	2.539E-05	2.030E-08	3.681E-10	1.134E-10	2.729E-07	4.250E-06	1.568E-02	4.784E-06
He	1.145E-06	2.275E-07	5.517E-07	3.941E-09	1.186E-10	9.712E-09	.	8.164E-10	1.939E-06	4.294E-05

element masses (kg) in all cells at time = 4.000E+03 s

element	lost aero	aero sce	initial	balance	bal/init
Ce	7.020E-03	.	4.158E-01	4.341E-07	0.000001
I	4.503E-03	.	6.682E-02	2.225E-07	0.000003
H	1.898E-05	.	7.749E-04	-3.364E-05	0.043415
Ba	3.806E-05	.	1.789E-01	-1.108E-07	0.000001
O	5.349E-04	.	1.266E+00	-2.314E-04	0.000183
Sr	1.057E-04	.	1.203E-01	2.681E-05	0.000223
Zr	2.853E-09	.	1.837E+00	-2.138E-02	0.011641
Sn	1.873E-03	2.125E-03	2.244E-02	-7.478E-03	0.333234
Te	1.662E-05	.	8.959E-02	2.978E-09	0.000000
U	9.185E-13	.	9.369E+00	8.100E-13	0.000000
Kr	.	.	4.889E-02	2.101E-07	0.000004
Xe	.	.	5.829E-01	2.503E-06	0.000004
Mo	6.045E-12	.	3.961E-01	4.860E-12	0.000000
Ag	3.350E-04	3.751E-04	.	1.301E-06	.
Ru	3.303E-11	.	2.610E-01	2.931E-11	0.000000
Sb	4.648E-07	.	2.012E-03	1.438E-09	0.000001
Eu	1.021E-04	.	1.569E-02	8.999E-05	0.005734
He	.	.	4.487E-05	1.338E-10	0.000003

temperatures (K) and pressures (Pa) at time = 4.200E+03 s

i, j	fuel temp.	gas temp.	gas press.	film temp.	struc. temp.
1, 1	1.120E+03	1.020E+03	1.500E+05	1.020E+03	1.020E+03
1, 2	1.919E+03	1.819E+03	1.500E+05	1.719E+03	1.719E+03
1, 3	2.319E+03	2.219E+03	1.500E+05	2.119E+03	2.119E+03
1, 4	2.419E+03	2.319E+03	1.500E+05	2.219E+03	2.219E+03
1, 5	2.419E+03	2.319E+03	1.500E+05	2.219E+03	2.219E+03
1, 6	.	1.780E+03	1.500E+05	1.711E+03	1.707E+03
1, 7	.	1.340E+03	1.500E+05	1.296E+03	1.294E+03
1, 8	.	9.000E+02	1.500E+05	1.042E+03	1.045E+03

element masses (kg) in all cells at time = 4.200E+03 s

element	grains	pores	gap	clad	film	bulk gas	aerosol	structure	total	lost gas
Ce	3.193E-01	5.109E-02	9.004E-04	4.460E-06	1.505E-07	1.158E-05	4.205E-07	2.577E-06	3.713E-01	3.735E-02
I	2.482E-02	2.667E-02	1.721E-04	5.015E-07	1.688E-08	1.060E-06	2.735E-07	1.242E-06	5.166E-02	1.061E-02
H	.	1.228E-06	3.866E-06	4.345E-06	1.092E-05	6.060E-04	2.355E-09	3.873E-05	6.651E-04	3.928E-05
Ba	1.424E-01	3.640E-02	1.950E-05	4.942E-09	1.680E-10	8.514E-09	6.771E-09	7.450E-06	1.788E-01	4.438E-05
O	1.260E+00	6.135E-04	4.800E-05	2.534E-01	7.855E-05	4.061E-03	4.188E-07	2.814E-04	1.518E+00	-2.532E-01
Sr	1.179E-01	2.074E-03	8.557E-05	8.880E-08	2.924E-09	1.223E-07	1.198E-07	1.903E-05	1.201E-01	8.015E-05
Zr	4.511E-01	5.555E-03	1.820E-05	1.359E+00	2.245E-05	2.060E-11	5.647E-09	6.363E-09	1.815E+00	8.421E-10

Sn	9.176E-08	7.086E-09	6.715E-08	1.496E-02	3.651E-07	5.243E-07	1.832E-06	9.305E-05	1.506E-02	2.015E-04
Te	5.850E-02	3.103E-02	1.361E-07	5.024E-11	1.691E-12	1.078E-10	1.019E-10	7.135E-09	8.953E-02	3.656E-05
U	9.369E+00	1.583E-05	1.281E-13	3.300E-18	2.091E-19	7.530E-18	7.507E-15	5.069E-14	9.369E+00	3.473E-14
Kr	1.809E-02	4.382E-04	8.140E-04	6.582E-06	2.213E-07	1.766E-05	.	1.484E-06	1.936E-02	2.952E-02
Xe	2.158E-01	5.248E-03	9.741E-03	7.830E-05	2.637E-06	2.101E-04	.	1.765E-05	2.311E-01	3.518E-01
Mo	3.741E-01	2.200E-02	9.191E-13	1.535E-16	5.188E-18	2.168E-16	3.503E-16	3.724E-13	3.961E-01	1.031E-12
Ag	1.063E-19	1.703E-12	1.608E-13	2.158E-13	2.114E-13	7.357E-08	3.418E-07	1.742E-05	1.784E-05	3.011E-05
Ru	2.434E-01	1.759E-02	6.019E-12	9.516E-18	3.137E-19	1.062E-17	1.051E-13	1.687E-12	2.610E-03	1.598E-12
Sb	1.887E-03	1.310E-04	4.026E-08	1.847E-11	6.215E-13	2.874E-11	2.915E-11	9.405E-08	2.011E-03	5.041E-07
Bu	1.529E-02	3.569E-04	2.706E-05	1.420E-11	3.806E-13	1.306E-11	2.654E-07	4.976E-06	1.568E-02	4.788E-06
He	1.087E-06	1.230E-07	2.680E-07	1.841E-09	6.010E-11	4.975E-09	.	4.194E-10	1.486E-06	4.339E-05

element masses (kg) in all cells at time = 4.200E+03 s

element	lost aero	aero sce	initial	balance	bal/init
Cs	7.091E-03	.	4.158E-01	1.457E-08	0.000000
I	4.548E-03	.	6.682E-02	1.851E-07	0.000003
H	1.929E-05	.	7.749E-04	-5.118E-05	0.066055
Ba	3.990E-05	.	1.789E-01	-1.778E-07	0.000001
O	5.818E-04	.	1.266E+00	-3.354E-04	0.000265
Sr	1.144E-04	.	1.203E-01	2.812E-05	0.000234
Zr	1.442E-07	.	1.837E+00	-2.138E-02	0.011641
Sn	2.154E-03	2.449E-03	2.244E-02	-7.478E-03	0.333229
Te	1.694E-05	.	8.959E-02	2.957E-09	0.000000
U	1.405E-12	.	9.369E+00	1.315E-12	0.000000
Kr	.	.	4.889E-02	-2.490E-07	0.000005
Xe	.	.	5.829E-01	-2.961E-06	0.000005
Mo	6.116E-12	.	3.961E-01	4.900E-12	0.000000
Ag	3.856E-04	4.321E-04	.	1.418E-06	.
Ru	4.120E-11	.	2.610E-01	3.775E-11	0.000000
Sb	4.722E-07	.	2.012E-03	1.449E-09	0.000001
Bu	1.230E-04	.	1.569E-02	1.116E-04	0.007108
He	.	.	4.487E-05	1.338E-10	0.000003

temperatures (K) and pressures (Pa) at time = 4.400E+03 s

i, j		fuel temp.	gas temp.	gas press.	film temp.	struc. temp.
1, 1		1.140E+03	1.040E+03	1.500E+05	1.040E+03	1.040E+03
1, 2		2.039E+03	1.939E+03	1.500E+05	1.839E+03	1.839E+03
1, 3		2.439E+03	2.339E+03	1.500E+05	2.239E+03	2.239E+03
1, 4		2.539E+03	2.439E+03	1.500E+05	2.339E+03	2.339E+03
1, 5		2.539E+03	2.439E+03	1.500E+05	2.339E+03	2.339E+03
1, 6		.	1.860E+03	1.500E+05	1.756E+03	1.750E+03
1, 7		.	1.380E+03	1.500E+05	1.317E+03	1.314E+03
1, 8		.	9.000E+02	1.500E+05	1.014E+03	1.017E+03

element masses (kg) in all cells at time = 4.400E+03 s

element	grains	pores	gap	clad	film	bulk gas	aerosol	structure	total	lost gas
Cs	3.157E-01	5.372E-02	1.063E-03	4.769E-06	1.759E-07	1.322E-05	1.067E-06	6.971E-06	3.705E-01	3.814E-02
I	2.168E-02	2.946E-02	3.491E-04	1.356E-06	4.986E-08	3.160E-06	8.502E-07	5.275E-06	5.151E-02	1.071E-02
H	.	1.242E-06	3.894E-06	4.310E-06	1.079E-05	6.022E-04	3.404E-09	3.874E-05	6.612E-04	2.643E-05
Ba	1.488E-01	2.997E-02	2.750E-05	1.017E-09	3.752E-11	2.401E-09	2.969E-09	7.172E-06	1.788E-01	4.468E-05
O	1.260E+00	6.236E-04	4.714E-05	2.919E-01	7.481E-05	3.801E-03	3.872E-07	2.655E-04	1.556E+00	-2.916E-01
Sr	1.179E-01	2.127E-03	7.963E-05	1.386E-07	5.040E-09	2.134E-07	2.229E-07	2.225E-05	1.201E-01	8.647E-05
Zr	4.503E-01	6.405E-03	1.817E-05	1.359E+00	2.245E-05	1.480E-10	3.971E-08	9.980E-08	1.815E+00	5.636E-09
Sn	9.187E-08	7.188E-09	6.691E-08	1.496E-02	3.651E-07	6.191E-07	1.694E-06	1.139E-04	1.508E-02	2.316E-04
Te	6.401E-02	2.552E-02	2.744E-07	3.301E-10	1.205E-11	7.535E-10	2.060E-10	1.790E-09	8.953E-02	3.658E-05
U	9.369E+00	1.903E-05	1.335E-13	1.486E-17	5.211E-19	1.845E-17	1.085E-14	9.356E-14	9.369E+00	3.554E-14
Kr	1.625E-02	5.307E-04	1.055E-03	8.973E-06	3.301E-07	2.691E-05	.	2.273E-06	1.787E-02	3.101E-02
Xe	1.940E-01	6.352E-03	1.262E-02	1.067E-04	3.931E-06	3.200E-04	.	2.703E-05	2.134E-01	3.695E-01
Mo	3.740E-01	2.205E-02	8.843E-13	5.553E-16	2.047E-17	3.630E-16	9.750E-16	3.811E-13	3.961E-01	1.048E-12
Ag	1.562E-19	1.703E-12	1.938E-13	2.882E-13	2.824E-13	8.049E-08	3.255E-07	2.128E-05	2.169E-05	3.393E-05
Ru	2.432E-01	1.776E-02	6.099E-12	3.779E-17	1.586E-18	5.612E-17	8.598E-14	2.143E-12	2.610E-03	1.600E-12
Sb	1.878E-03	1.331E-04	6.446E-08	3.906E-11	1.436E-12	6.972E-11	5.253E-11	9.318E-08	2.011E-03	5.065E-07
Bu	1.527E-02	3.716E-04	2.976E-05	7.485E-11	2.429E-12	8.525E-11	2.009E-07	6.098E-06	1.568E-02	4.791E-06
He	9.031E-07	8.783E-08	1.745E-07	1.567E-09	5.617E-11	4.708E-09	.	3.984E-10	1.172E-06	4.370E-05

element masses (kg) in all cells at time = 4.400E+03 s

element	lost aero	aero sce	initial	balance	bal/init
Cs	7.173E-03	.	4.158E-01	-4.177E-07	0.000001
I	4.608E-03	.	6.682E-02	1.029E-07	0.000002
H	1.961E-05	.	7.749E-04	-6.762E-05	0.087273
Ba	4.028E-05	.	1.789E-01	-2.295E-07	0.000001
O	6.216E-04	.	1.266E+00	-4.240E-04	0.000335
Sr	1.284E-04	.	1.203E-01	3.053E-05	0.000254
Zr	1.455E-06	.	1.837E+00	-2.138E-02	0.011641
Sn	2.392E-03	2.738E-03	2.244E-02	-7.478E-03	0.333226
Te	1.695E-05	.	8.959E-02	2.958E-09	0.000000
U	2.077E-12	.	9.369E+00	2.030E-12	0.000000
Kr	.	.	4.889E-02	-1.002E-06	0.000021
Xe	.	.	5.829E-01	-1.192E-05	0.000020
Mo	6.163E-12	.	3.961E-01	4.915E-12	0.000000
Ag	4.290E-04	4.831E-04	.	1.473E-06	.
Ru	4.826E-11	.	2.610E-01	4.525E-11	0.000000
Sb	4.758E-07	.	2.012E-03	1.452E-09	0.000001
Bu	1.404E-04	.	1.569E-02	1.300E-04	0.008281
He	.	.	4.487E-05	1.338E-10	0.000003

temperatures (K) and pressures (Pa) at time = 4.500E+03 s

i, j	fuel temp.	gas temp.	gas prese.	film temp.	struc. temp.
1, 1	1.150E+03	1.050E+03	1.500E+05	1.050E+03	1.050E+03
1, 2	2.099E+03	1.999E+03	1.500E+05	1.899E+03	1.899E+03
1, 3	2.499E+03	2.399E+03	1.500E+05	2.299E+03	2.299E+03
1, 4	2.599E+03	2.499E+03	1.500E+05	2.399E+03	2.399E+03
1, 5	2.599E+03	2.499E+03	1.500E+05	2.399E+03	2.399E+03
1, 6		1.900E+03	1.500E+05	1.786E+03	1.779E+03
1, 7		1.400E+03	1.500E+05	1.331E+03	1.327E+03
1, 8		9.000E+02	1.500E+05	1.003E+03	1.006E+03

element masses (kg) in all cells at time = 4.500E+03 s

element	grains	pores	gap	clad	film	bulk gas	aerosol	structure	total	lost gas
Ce	3.139E-01	5.586E-02	1.203E-03	4.841E-06	1.874E-07	1.381E-05	1.558E-06	1.194E-05	3.700E-01	3.851E-02
I	1.910E-02	3.175E-02	4.918E-04	1.919E-06	7.417E-08	4.725E-06	1.305E-06	9.996E-06	5.136E-02	1.080E-02
H		1.249E-06	3.901E-06	4.289E-06	1.072E-05	6.002E-04	3.873E-09	3.875E-05	6.591E-04	2.054E-05
Ba	1.501E-01	2.867E-02	3.180E-05	1.080E-09	4.181E-11	2.682E-09	3.095E-09	7.032E-06	1.788E-01	4.478E-02
O	1.260E+00	6.282E-04	4.646E-05	3.138E-01	7.259E-05	3.645E-03	3.782E-07	2.557E-04	1.578E+00	-3.134E-01
Sr	1.178E-01	2.158E-03	7.598E-05	1.585E-07	6.072E-09	2.588E-07	2.903E-07	2.475E-05	1.201E-01	9.032E-05
Zr	4.500E-01	6.670E-03	1.814E-05	1.359E+00	2.245E-05	3.559E-10	7.468E-08	2.688E-07	1.815E+00	1.295E-08
Sn	9.202E-08	7.264E-09	6.664E-08	1.496E-02	3.651E-07	6.647E-07	1.631E-06	1.255E-04	1.509E-02	2.473E-04
Te	6.496E-02	2.457E-02	6.105E-07	1.151E-09	4.408E-11	2.776E-09	7.475E-10	4.714E-09	8.953E-02	3.661E-05
U	9.369E+00	2.076E-05	1.422E-13	2.791E-17	7.003E-19	2.443E-17	9.432E-15	1.236E-13	9.369E+00	3.608E-14
Kr	1.537E-02	5.353E-04	1.076E-03	9.123E-06	3.528E-07	2.908E-05		2.463E-06	1.702E-02	3.186E-02
Xe	1.835E-01	6.407E-03	1.287E-02	1.085E-04	4.201E-06	3.458E-04		2.930E-05	2.033E-01	3.796E-01
Mo	3.740E-01	2.207E-02	8.497E-13	1.243E-15	4.802E-17	2.034E-15	2.058E-15	3.948E-13	3.961E-01	1.069E-12
Ag	1.909E-19	1.704E-12	2.185E-13	3.363E-13	3.296E-13	8.558E-08	3.162E-07	2.347E-05	2.388E-05	3.583E-05
Ru	2.431E-01	1.782E-02	6.259E-12	7.386E-17	3.418E-18	1.221E-16	6.189E-14	2.355E-12	2.610E-01	1.602E-12
Sb	1.877E-03	1.340E-04	8.041E-08	5.567E-11	2.148E-12	1.073E-10	7.182E-11	9.300E-08	2.011E-03	5.083E-07
Eu	1.526E-02	3.792E-04	3.152E-05	1.667E-10	5.979E-12	2.116E-10	1.315E-07	6.581E-06	1.568E-02	4.794E-06
He	7.900E-07	7.927E-08	1.526E-07	1.487E-09	5.612E-11	4.741E-09		4.023E-10	1.029E-06	4.385E-05

element masses (kg) in all cells at time = 4.500E+03 s

element	lost aero	aero sce	initial	balance	bal/init
Ce	7.246E-03	.	4.158E-01	-6.425E-07	0.000002
I	4.668E-03	.	6.682E-02	2.242E-08	0.000000
H	1.980E-05	.	7.749E-04	-7.543E-05	0.097345
Ba	4.041E-05	.	1.789E-01	-2.473E-07	0.000001
O	6.399E-04	.	1.266E+00	-4.618E-04	0.000365
Sr	1.385E-04	.	1.203E-01	3.301E-05	0.000274
Zr	3.338E-06	.	1.837E+00	-2.138E-02	0.011639
Sn	2.497E-03	2.869E-03	2.244E-02	-7.478E-03	0.333225
Te	1.698E-05	.	8.959E-02	2.960E-09	0.000000
U	2.425E-12	.	9.369E+00	2.419E-12	0.000000
Kr	.	.	4.889E-02	-1.453E-06	0.000030
Xe	.	.	5.829E-01	-1.728E-05	0.000030
Mo	6.219E-12	.	3.961E-01	4.928E-12	0.000000
Ag	4.481E-04	5.064E-04	.	1.490E-06	
Ru	5.077E-11	.	2.610E-01	4.794E-11	0.000000
Sb	4.785E-07	.	2.012E-03	1.453E-09	0.000001
Eu	1.460E-04	.	1.569E-02	1.360E-04	0.008665
He	.	.	4.487E-05	1.338E-10	0.000003

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