SIMULATION OF THE TRANSPORT OF VOLATILE FISSION PRODUCTS WITHIN THE FUEL-TO-SHEATH GAP OF DEFECTIVE CANDU REACTOR FUEL RODS

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1. INTRODUCTION

A numerical model has been developed for the prediction of the transport behaviour of volatile fission products within the gap between the fuel pellets and the sheath of fuel rods of CANDU Pressurized Heavy Water Reactors (PHWR). In this model, the volatile and radioactive fission products are produced within the fuel pellet in which they migrate. These fission products are partially released into the fuel-to-sheath gap with an isotopic production rate per unit volume, q (x,t), in moles m^{-3} s^{-1}, at axial position x and time t. This parameter can be determined from results of in-reactor and out-of-pile annealing experiments carried out at the Chalk River Laboratories.[1, 2]

2. GAP TRANSPORT MODEL

The mathematical equations of the model are based on mass balance equations as follows:

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} - \frac{\partial}{\partial x}(cv) - \lambda c + q(x,t) \tag{1}$$

where c(x,t) is the isotopic concentration, in moles m^{-3} s^{-1}, in the gap at axial position x and at time t, λ is the radioactive decay constant, and D is the volatile fission product diffusivity in the bulk gas. In this model, the fuel rod is assumed to be breached such that, at axial position x = L, where L is the length of the fuel rod, the end cap is completely missing leaving the gap fully exposed and in contact with the coolant for all azimuthal positions (Fig. 1). The model also assumes that the fuel rod is intact at position x = 0. A significant stable gas release q_S into the gap produces a bulk gas velocity profile given by:[3]

$$v(x) = q_s R T x \left| \frac{12 \mu q_s R T}{h^2} (L^2 - x^2) + P_{sys}^2 \right|^{-1/2} \tag{2}$$

where R is the gas constant, T is the average bulk gas temperature within the gap, μ the gas viscosity and P_{sys} is the bulk system pressure. One initial condition and two boundary conditions are required for the solution of Equation (1): the initial condition is for t = 0, n (x , 0) = 0 ($\forall$ x between 0 and L); the boundary condition at x = L (the damaged end) is, for all times, n (L , t) = 0, whereas at x = 0 (the intact end), the condition is:

$$-D \left| \frac{dc}{dt} \right|_{x=0} + c\,v(0) = 0 \quad . \tag{3}$$

Equation (3) implies an absence of flow at the intact end of the fuel rod and, when v (0) = 0, this condition becomes a simple reflexive condition. At the breached end of the fuel rod, the condition n (L , t) = 0 is interpreted as the volatile fission products being swept away into the primary coolant as soon as they reach the open end. Using Fick's Law, the rate of release of the fission products into the primary coolant may be given by the following equation:

$$R_c = \left| -DA \frac{dc}{dx} \right|_{x=L} \tag{4}$$

where A is the cross-sectional area of the open gap at x = L. For a constant isotopic production rate in the gap (q), the release fraction is given by:

$$F = \frac{R_c}{qAL} \quad . \tag{5}$$

3. NUMERICAL RESULTS

A one-dimensional numerical model was obtained by solving these equations, assuming a uniform concentration of the fission products in the azimuthal direction, and neglecting all variations in the radial direction since the gap thickness is very small. The model was tested for four different volatile fission products, ^{138}Xe, ^{85m}Kr, ^{133}Xe and ^{137}Cs, covering a range of half-lives from 14.12 minutes to 30.17 years. The model was run for these fission products for normal operating conditions, with a 50 kW m^{-1} linear power rating, 700 K average gas temperature, 1.0 × 10^7 Pa coolant pressure (P_{SYS}), giving an average bulk gas velocity of 1.37 × 10^{-7} m s^{-1}.[3] The model was also applied for a reactor accident situation for which the linear power rating was 50 kW m^{-1}, the average gas temperature was 1600 K, the coolant pressure was 1.0 × 10^5 Pa and the average bulk gas velocity was 1.55 × 10^{-2} m s^{-1}.[3] In addition, for each of the scenarios, the model was run for the actual bulk gas flow velocity profile as given by Equation (2) and for a constant value of this velocity as obtained from averaging Equation (2) over the length of the fuel rod.

For normal reactor operation, the release fractions for the shorter lived fission products were less than unity as this is expected since significant radioactive decay occurs before the nuclei reach the breached end of the fuel rod. The release fractions gradually increase with time to equilibrium values, in a matter of few minutes for the short-lived isotopes (^{138}Xe and ^{85m}Kr) and in about 120 hours for the other two fission products (Fig. 2a). The equilibrium release fractions for ^{138}Xe, ^{85m}Kr, ^{133}Xe and ^{137}Cs are 6.9%, 30.9%, 88.7% and 99.4% respectively. For the accident scenario (Fig. 2b), the kinetics are much more rapid and the release fractions saturate within 180 seconds as follows: 97.1% for ^{138}Xe and 98.3% for the other three isotopes. With this very rapid release due to the combination of high temperature and large pressure gradients, there is little time for radioactive decay which explains why even the shortest-lived fission product is essentially all released.

The two numerical approaches, using the variable, v(x), and constant, $\bar{v}$, velocity distribution produced results which were in good agreement with each other: the largest discrepancies observed were for ^{137}Cs for which the release fractions differed by at most 0.4% for normal reactor operation case and by a maximum of 2.5% for the reactor accident case. When the average value $\bar{v}$ was used for the bulk gas flow velocity, the numerical results could also be compared with an analytical solution for normal reactor operation.[3] Again, very good agreement was obtained as the largest discrepancy observed between methods was ~3% for the release fraction of ^{85m}Kr.

With the numerical modeling well established, the research continued on a sensitivity study aimed at determining the most important parameters of the model. For this analysis, the shortest-lived fission product (^{138}Xe) and the longest-lived one (^{137}Cs) were studied. The following parameters were varied in turn by ±10%: q_S, T, D, μ, P_{SYS}, q and h. For the normal reactor operation (Fig. 3), it was found that, for ^{138}Xe, the diffusivity (D) was the most sensitive of the parameters, producing a ±5.4% variation of the release fraction at 720 minutes. Similar variations of the other parameters produced variations of the release fraction of only about ±0.05%, and as little as ±0.002% for parameters such as q and h. The results for ^{137}Cs were even less pronounced, with the largest variation of the release fraction (at 600 h) obtained as about ±0.03% for T, P_{SYS} and q_S. The importance of the diffusivity D for the shortest-lived fission product in normal operation conditions is readily explained considering that the nuclei remain within the gap for a longer period of time relative to their half-life as they diffuse in the gap since bulk flow is no longer important.

For reactor accident conditions (Fig. 4), all parameters for ^{138}Xe have a comparable sensitivity, producing variations in the release fraction of about ±0.15%, except for the parameter q which produces variations of only ±0.01%. For ^{137}Cs, again, all parameters, except for q, have comparable effects, producing variations of ±0.25% on the average, only slightly higher than for ^{138}Xe. In this case, the variations of the isotopic production rate q are almost not detected in the model, yielding variations of the release fraction of only ±0.005%. This analysis leads to the conclusion that none of the parameters are especially sensitive and that the model appears quite sound.

4. OXYGEN POTENTIAL IN THE FUEL-TO-SHEATH GAP

As shown in Section 3, during a reactor transient an enhanced fission-gas release can lead to an important convective contribution for transport in the fuel-to-sheath gap. In order for fuel oxidation to occur, steam must diffuse into the breached element against any counter-current flow of non-condensable fission gases, and out-flowing hydrogen that is produced from the internal reaction of the in-coming steam with the Zircaloy sheathing or urania. As such, it is important to determine the local hydrogen-to-steam molar ratio (i.e., oxygen potential) along the gap as this ratio directly affects the fuel oxidation state. The fuel oxidation state, in turn, significantly influences the rate of fission-product diffusion in the fuel matrix and the subsequent release into the gap.[2] In addition, the oxygen potential in the gap will affect the chemical form of the fission product, which will dictate the amount of vaporization of low-volatile products from the fuel surface.[4, 5] For instance, the fission product release kinetics were observed to differ in annealing experiments conducted at high temperature in steam with bare fuel fragments versus mini-elements (i.e., short-length Zircaloy-sheathed fuel specimens), even after the Zircaloy sheath had been completely oxidized.[6] This observation can be attributable to a reduced transport in the gap and a lower oxygen potential as a result of inhibited steam penetration into the mini-elements.

4.1 *Development of the gap transport equations.*

The one-dimensional transport equations for the multi-component flow of steam, hydrogen and stable fission gases in the thin, annular, fuel-to-sheath gap are developed as follows. Consider a species *i* with molar concentration c_i (mol m^{-3}) in which one applies a conservation of mass through the volume element ΔV (= $S\,\Delta x$) in the gap (see Fig. 1):

$$\textit{time rate of change of number of moles of i in volume element} = \frac{\partial c_i}{\partial t} S \, \Delta \, x \tag{6}$$

$$\textit{input of i across face at } x = N_{ix}|_x \, S \tag{7}$$

$$\textit{output of i across face at } x + \Delta x = N_{ix}|_{x+\Delta x} \, S \tag{8}$$

$$\textit{rate of production of species } i = q_i \, S \, \Delta x \tag{9}$$

$$\textit{rate of loss of species } i = r_i \, S \, \Delta x \tag{10}$$

where S is the (constant) cross sectional area of the gap, N_{ix} is the molar flux of species *i* in the *x*-direction (mol m^{-2} s^{-1}) (resulting from diffusion and a total bulk molar flow), q_i is the production rate of species *i* (mol m^{-3} s^{-1}) and r_i is the loss rate of species *i* (mol m^{-3} s^{-1}). Hence, applying a mass balance:

$$\frac{\partial c_i}{\partial t} S \, \Delta x = \left\{ \begin{matrix} \textit{rate of moles} \\ \textit{of species i in} \end{matrix} \right\} - \left\{ \begin{matrix} \textit{rate of moles} \\ \textit{of species i out} \end{matrix} \right\} + \left\{ \begin{matrix} \textit{rate of production} \\ \textit{of species i} \end{matrix} \right\} - \left\{ \begin{matrix} \textit{rate of loss} \\ \textit{of species i} \end{matrix} \right\}$$

$$\frac{\partial c_i}{\partial t} S \, \Delta x = N_{ix} \, |_x \, S - N_{ix} \, |_{x+\Delta x} \, S + q_i \, S \, \Delta x - r_i \, S \, \Delta x \tag{11}$$

Thus, dividing Eq. (11) by $S\,\Delta x$, and taking the limit as Δx goes to zero, yields

$$\frac{\partial c_i}{\partial t} = - \frac{\partial N_{ix}}{\partial x} + q_i - r_i \tag{12}$$

For a flux resulting from both diffusion and a total molar bulk flow in a multi-component mixture of *n* components. [7]

$$N_{ix} = -cD_{im} \nabla x_i + x_i \sum_{j=1}^{n} N_j \tag{13}$$

where c is the total molar concentration

$$c = \sum^{n} c_j \tag{14}$$

The parameter x_i is the mole fraction of species i ($= c_i / c$), and $N_j = c_j\, v_j$ where v_j is the velocity of species j (m s^{-1}) . The parameter D_{im} is an "effective" binary diffusivity (m^2 s^{-1}) for the diffusion of

$$\nabla x_i = \sum_{j=1}^{n} \frac{c_i\, c_j}{c^2\, D_{ij}} \left(v_j - v_i\right) = \sum_{j=1}^{n} \left(\frac{1}{cD_{ij}}\right) \left(x_i N_j - x_j N_i\right) \tag{15}$$

species i in a mixture m. This quantity can be derived from the Stefan-Maxwell equations: [7] Hence, solving for ∇x_i in Eq. (13) and equating this to Eq. (15) gives:

$$\frac{1}{cD_{im}} = \frac{\sum_{j=1}^{n} \left(\frac{1}{cD_{ij}}\right) \left(x_j N_i - x_i N_j\right)}{N_i - x_i \sum_{j=1}^{n} N_j} \tag{16}$$

If $i = 1$, Eq. (16) can therefore be written as

$$\frac{1}{cD_{1m}} = \frac{\sum_{j=1}^{n} \left(\frac{x_j}{cD_{1j}}\right) \left(v_1 - v_j\right)}{v_1 - \sum_{j=1}^{n} x_j\, v_j} = \frac{\sum_{j=2}^{n} \left(\frac{x_j}{cD_{1j}}\right) \left(v_1 - v_j\right)}{v_1 - x_1\, v_1 - \sum_{j=2}^{n} x_j\, v_j} \tag{17}$$

where the second relation follows since the numerator will equal zero when $j = 1$. Now if the components 2, 3, ... n move with the same velocity, i.e., $v_2 = v_3 = \ldots = v_n = V$, Eq. (17) yields

$$\frac{1}{c\, D_{1m}} = \frac{\sum_{j=2}^{n} \left(\frac{x_j}{c\, D_{1j}}\right) \left(v_1 - V\right)}{v_1 - x_1 v_1 - V \sum_{j=2}^{n} x_j} \tag{18}$$

Since $\sum_{j=2}^{n} x_j = 1 - x_1$, Eq. (18) reduces to

$$\frac{1 - x_1}{c\, D_{1m}} = \sum_{j=2}^{n} \left(\frac{x_j}{c\, D_{1j}}\right) \tag{19}$$

Hence, in the present case, if all components move with a bulk velocity $V(x)$:

$$\frac{1 - x_i}{c\, D_{im}} = \sum_{\substack{j=1 \\ j \neq i}}^{n} \left(\frac{x_j}{c\, D_{ij}} \right) \tag{20}$$

The simple binary diffusivities D_{ij} (cm^2 s^{-1}) in Eq. (20) can be calculated from the Chapman-Enskog kinetic theory: [7]

$$c\, D_{AB} = 2.2646 \times 10^{-5} \, \frac{\sqrt{T\left(\frac{1}{M_A} + \frac{1}{M_B} \right)}}{\sigma^2_{AB}\, \Omega_{D_{AB}}} \tag{21}$$

where T is the temperature (K), M is the molecular weight (g mol^{-1}) and σ_{AB} is the collision diameter (Å). The collision integral $\Omega_{D_{AB}}$ is a function of the Lennard-Jones force constant ϵ_{AB}/κ (in K) : [5]

$$\Omega_{D_{AB}} = \frac{1}{0.7049 + 0.2910 \ln(T\kappa \,/\, \epsilon_{AB})} \tag{22}$$

The combined quantities for the force constants can be evaluated as

$$\sigma_{AB} = \frac{\sigma_A + \sigma_B}{2} \quad , \quad \frac{\epsilon_{AB}}{\kappa} = \sqrt{\frac{\epsilon_A}{\kappa}\,\frac{\epsilon_B}{\kappa}} \tag{23}$$

where the individual quantities for the gas components are given in Table 1.

Finally, substituting Eq. (13) into Eq. (12) yields the one-dimensional transport equation in the x-direction for species i

$$\frac{\partial c_i}{\partial t} = \frac{\partial}{\partial x}\left| cD_{im} \frac{\partial x_i}{\partial x} \right| - \frac{\partial}{\partial x}\left| x_i \sum_{j=1}^{n} N_j \right| + q_i - r_i \tag{24}$$

In the particular case that all components move with the same velocity $V(x)$ so that $x_i \sum_{j=1}^{n} N_j = \frac{c_i}{c} \sum_{j=1}^{n} c_j\, v_j \approx c_i\, V(x)$, Eq. (24) becomes

$$\frac{\partial c_i}{\partial t} = \frac{\partial}{\partial x}\left| cD_{im} \frac{\partial (c_i/c)}{\partial x} \right| - \frac{\partial}{\partial x}\left[c_i V(x) \right] + q_i - r_i \tag{25}$$

where cD_{im} is calculated from Eq. (20). The bulk flow velocity $V(x)$ follows from a Hagen-Poiseuille law: [2]

$$V(x) = -\frac{h^2}{12\mu}\left(\frac{dP}{dx}\right) \tag{26}$$

where R is the ideal gas constant, P is the pressure, and h is the radial gap thickness. For a gas mixture the gas viscosity μ in Eq. (26) can be determined from [4, 7]

$$\mu = \sum_{i=1}^{n} \frac{x_i\ \mu_i}{\sum_{j=1}^{n} x_i\ \phi_{ij}} \tag{27}$$

in which

$$\phi_{ij} = \frac{1}{\sqrt{8}}\left(1 + \frac{M_i}{M_j}\right)^{-1/2}\left|1 + \left(\frac{\mu_i}{\mu_j}\right)^{1/2}\left(\frac{M_j}{M_i}\right)^{1/4}\right|^2 \tag{28}$$

The individual viscosity μ_i (in g cm^{-1} s^{-1}) for each component can be calculated from

$$\mu_i = 2.6693 \times 10^{-5}\ \frac{\sqrt{M_i T}}{\sigma_i^2\,\Omega_{\mu_i}} \tag{29}$$

where T is in K, M_i is in g mol^{-1} and σ_i is in Å. The parameter $\Omega_{\mu i}$ can similarly be calculated from

$$\Omega_{\mu_i} = \frac{1}{0.6641 + 0.2581\ \ln(T\kappa/\epsilon_{AB})} \tag{30}$$

Using the ideal gas law:

$$c = \frac{P}{RT} \tag{31}$$

Eq. (26) becomes

$$V(x) = -\frac{h^2 R T}{12 \mu} \left(\frac{dc}{dx} \right) \tag{32}$$

Thus, as follows from Eqs. (14) and (25), the corresponding system of equations for the stable fission gas (e.g., Xe), steam (H_2O) and hydrogen (H_2) is:

$$\frac{\partial c_{Xe}}{\partial t} = \frac{\partial}{\partial x} \left[c D_{Xe,m} \frac{\partial (c_{Xe}/c)}{\partial x} \right] - \frac{\partial}{\partial x} \left[c_{Xe} V(x) \right] + q_{Xe} \tag{33}$$

$$\frac{\partial c_{H_2O}}{\partial t} = \frac{\partial}{\partial x} \left[c D_{H_2O,m} \frac{\partial (c_{H_2O}/c)}{\partial x} \right] - \frac{\partial}{\partial x} \left[c_{H_2O} V(x) \right] - r_{H_2O}^{Zr\,ox} - r_{H_2O}^{Fuel\,ox} \tag{34}$$

$$\frac{\partial c_{H_2}}{\partial t} = \frac{\partial}{\partial x} \left[c D_{H_2,m} \frac{\partial (c_{H_2}/c)}{\partial x} \right] - \frac{\partial}{\partial x} \left[c_{H_2} V(x) \right] + q_{H_2}^{Zr\,ox} + q_{H_2}^{Fuel\,ox} \tag{35}$$

where

$$c = c_{Xe} + c_{H_2O} + c_{H_2} \tag{36}$$

The source and loss terms in Eqs. (33) to (35) are known from physical models developed elsewhere (see discussion below). The effective diffusivity $D_{i,m}$ can also be evaluated from Eq. (20) for each gas constituent (i.e., i = Xe, H_2O and H_2). Hence, given that there are five unknows (c_{Xe}, c_{H_2O}, c_{H_2}, c, V) and five equations (Eqs. (32) to (36)), the system of equations can be uniquely solved by standard numerical methods.The parameter q_{Xe} in Eq. (33) is simply equal to the stable fission gas release q_s from Section 2. The production rate of hydrogen and the loss rate of steam are equal to one another for a given chemical process, i.e., $q_{H_2}^{Zr\,ox} = r_{H_2O}^{Zr\,ox}$ and $q_{H_2}^{Fuel\,ox} = r_{H_2O}^{Fuel\,ox}$. This result arises since the molar quantities of hydrogen and steam are balanced in each oxidation reaction for the Zircaloy and fuel:

$$Zr + 2H_2O \leftrightarrow ZrO_2 + 2H_2 \tag{37}$$

$$x H_2O + UO_2 \leftrightarrow UO_{2+x} + x H_2 \tag{38}$$

where x is the stoichiometry deviation in UO_{2+x}. The hydrogen production rate for the Zircaloy oxidation process is: [2]

$$q_{H_2}^{Zr\,ox} = \frac{1}{M_{Zr}} \sqrt{\frac{k_w}{t}} \frac{S_{Zr}}{V_{gap}} = \frac{1}{M_{Zr} h} \sqrt{\frac{k_w}{t}} \qquad (39)$$

where S_{Zr} (m^2) is the internal surface area of the sheath, V_{gap} is the gap volume (m^3), M_{zr} is the molecular weight of zirconium (= 0.091 kg mol^{-1}) and t is the time (s). The parameter k_w ($kg^2\ m^{-4}\ s$) is the parabolic rate constant:

$$k_w = k_{w0} \exp \left\{ - \frac{Q}{R\,T} \right\} \qquad (40)$$

where, from the experiments of Baker and Just, $k_{wo} = 3.33 \times 10^3\ kg^2\ m^{-4}\ s$ and $Q = 190\ kJ\ mol^{-1}$. [8] The hydrogen production rate for the fuel oxidation process is: [2]

$$q_{H_2}^{Fuel\,ox} = c_U\, \alpha \left\{ x_e - x(t) \right\} \left(\frac{S_{fuel}}{V_{gap}} \right) = \frac{C_U\, \alpha}{h} \left\{ x_e - x(t) \right\} \qquad (41)$$

where c_U is the molar density of uranium (mol of uranium m^{-3}), S_{fuel} is the fuel surface area (m^2), α is a surface exchange coefficient (= 0.365 exp{-23500/T(K) m s^{-1}}), and x_e is the equilibrium stoichiometry deviation (as determined with the methodology in Ref. 5).

In order to solve the system of equations, one requires three initial conditions and six boundary conditions for Eqs. (33) to (35). For example, typical conditions for the defect geometry shown in Fig. 1, which can arise in accident situations, can be mathematically represented as follows:

(i) *initial conditions*:

$$c_{Xe} = 0, \qquad t = 0, \qquad 0 < x < L \qquad (42)$$

$$c_{H_2O} = \frac{P_{sys}}{R\,T}, \qquad t = 0, \qquad 0 < x < L$$

$$c_{H_2} = 0, \quad t = 0, \quad 0 < x < L$$

(ii) boundary conditions:

$$\frac{\partial c_{Xe}}{\partial x} = 0, \quad x = 0, \quad t > 0 \qquad\qquad c_{Xe} = 0, \quad x = L, \quad t > 0 \quad \textbf{(43)}$$

$$\frac{\partial c_{H_2O}}{\partial x} = 0, \quad x = 0, \quad t > 0 \qquad\qquad c_{H_2O} = \frac{P_{sys}}{RT}, \quad x = L, \quad t > 0$$

$$\frac{\partial c_{H_2}}{\partial x} = 0, \quad x = 0, \quad t > 0 \qquad\qquad c_{H_2} = 0, \quad x = L, \quad t > 0$$

The initial conditions in Eq. (42) assume that only steam is present in the gap at the start of the transient ($t = 0$), with a molar concentration resulting from the given system pressure P_{sys}. At the intact end of the rod ($x = 0$), a simple reflexive condition is assumed in Eq. (43) where no flow occurs (i.e., the bulk flow velocity in Eq. (32) is also equal to zero in this situation). Finally, at the defect end of the rod ($x = L$), the fission gas and hydrogen concentrations are zero since these products are continually being swept away by the bulk-gas atmosphere flowing past the fuel element. On the other hand, there is a constant supply of steam as this exposed end from the bulk atmosphere in the reactor coolant system (RCS) (i.e., this condition implicitly assumes that there is no hydrogen in the RCS, i.e., $x_{H2O} = 1$).

Thus, solving the system of equations, one is able to obtain the hydrogen-to-steam partial pressure ratio p_{H2} / p_{H2O} ($= c_{H2} / c_{H2O}$) as a function of distance and time along the gap. It is important to realize for this solution that there is a feedback effect where the source term (q_{Xe}) in Eq. (33) depends on the state of fuel oxidation which, in turn, is affected by the ratio c_{H2} / c_{H2O} (see Refs. 2, 4 and 5). These equations are presently being solved for analysis of the mini-element experiments. Other future developments of this model include the use of variable isotopic production rates and the investigation of the effects of gap collapse and swelling. Multi-dimensional models to consider azimuthal effects will also be developed for more realistic modelling of actual defect cases.

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TABLE 1 : INTERMOLECULAR PARAMETERS FOR VARIOUS GAS CONSTITUENTS[(a)]

Gas Component	Molecular Weight, M (g mol^{-1})	Lennard-Jones Parameters	
		σ (Å)	ϵ / κ (K)
H_2	2.016	2.915	38.0
He	4.003	2.576	10.2
H_2O	18.015	2.65	380
Xe	131.3	4.055	229

(a) Taken from Refs. 2 and 7.

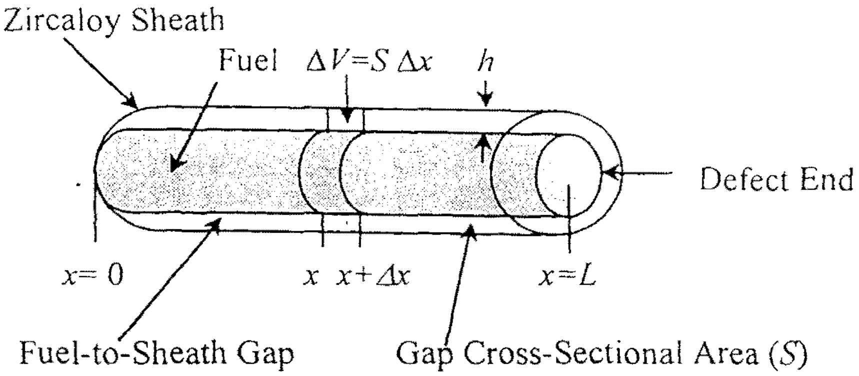

FIGURE 1 : SCHEMATIC OF A DEFECTIVE FUEL ROD.

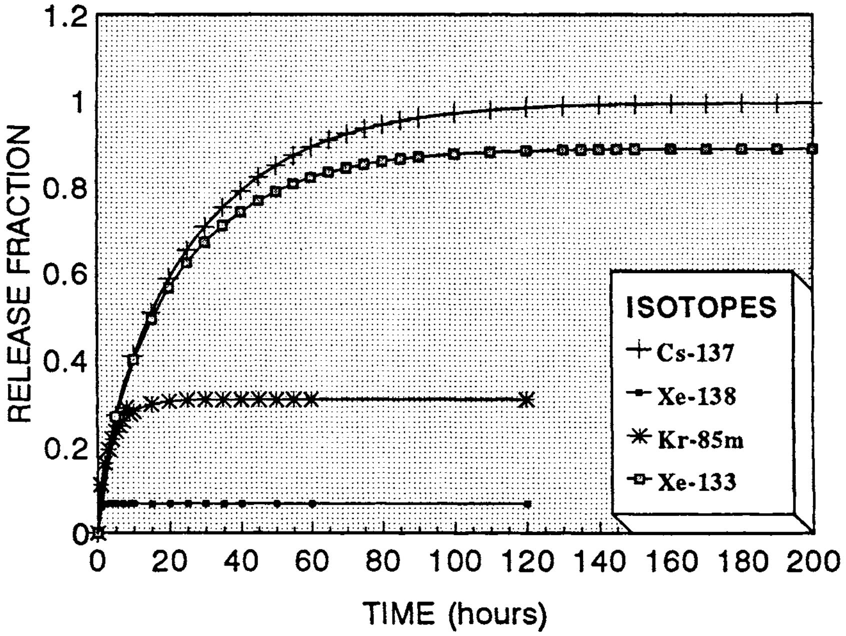

Fig. 2a: NORMAL REACTOR OPERATION

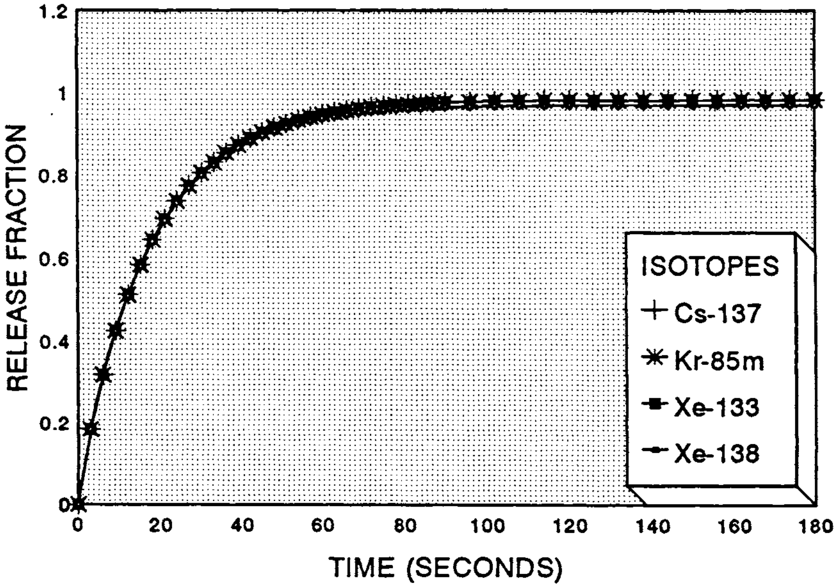

Fig. 2b: ACCIDENT CONDITIONS

Figure 2: VOLATILE FISSION PRODUCT RELEASE FRACTION

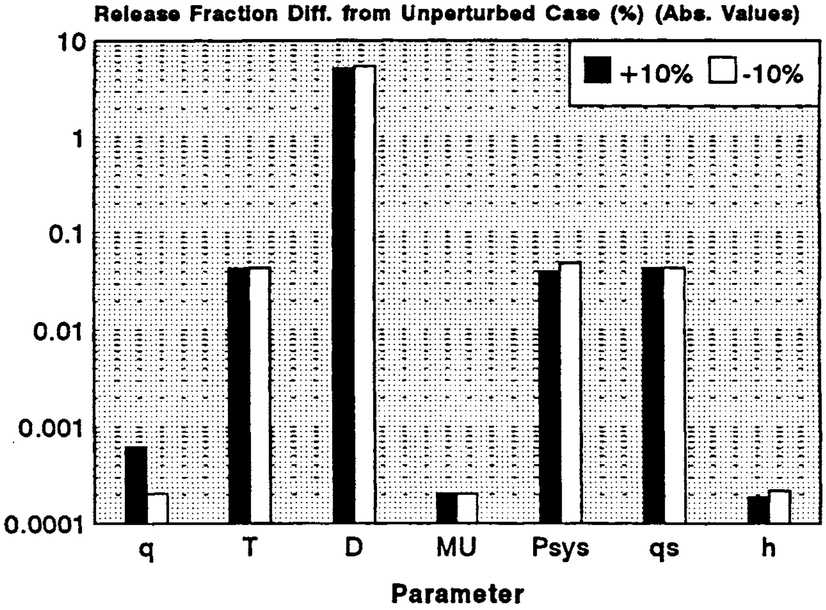

Fig. 3a: Sensitivity Analysis for Xe-138

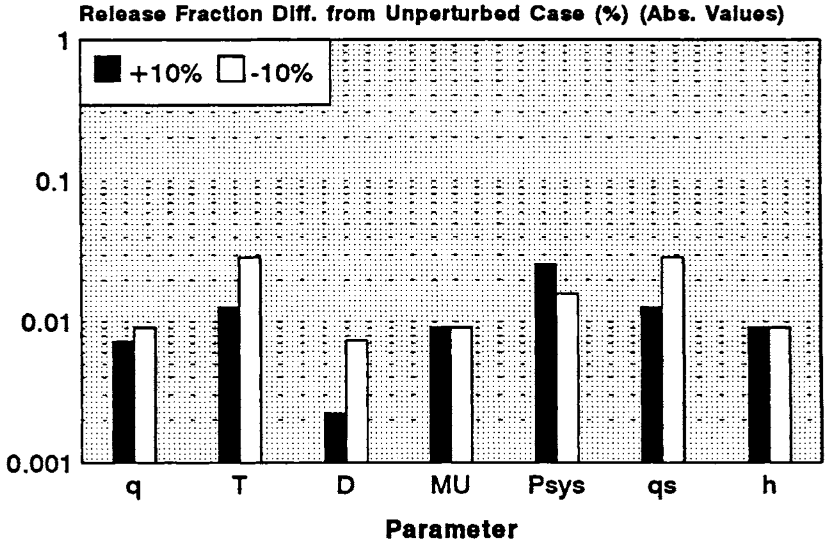

Fig. 3b: Sensitivity Analysis for Cs-137

Figure 3 : Sensitivity Analysis for Normal Reactor Operation

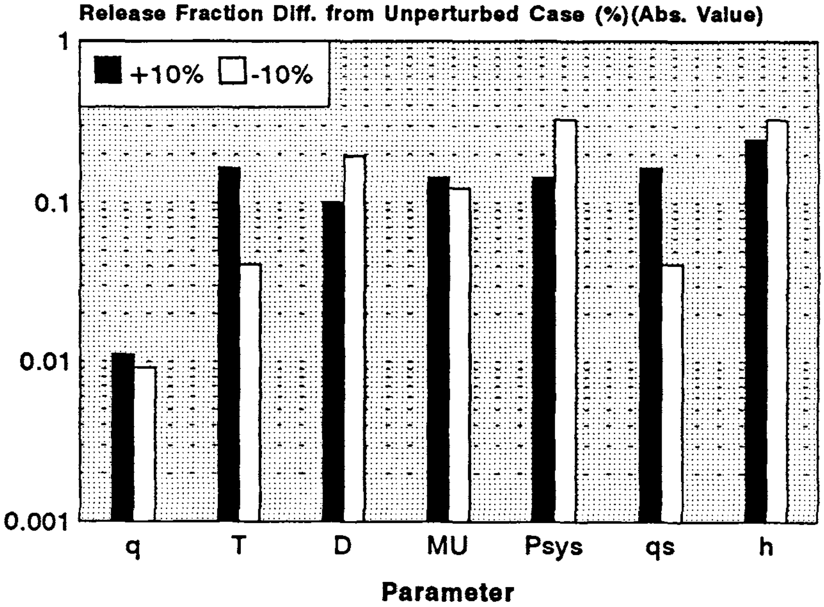

Fig 4a : Sensitivity Analysis for Xe-138

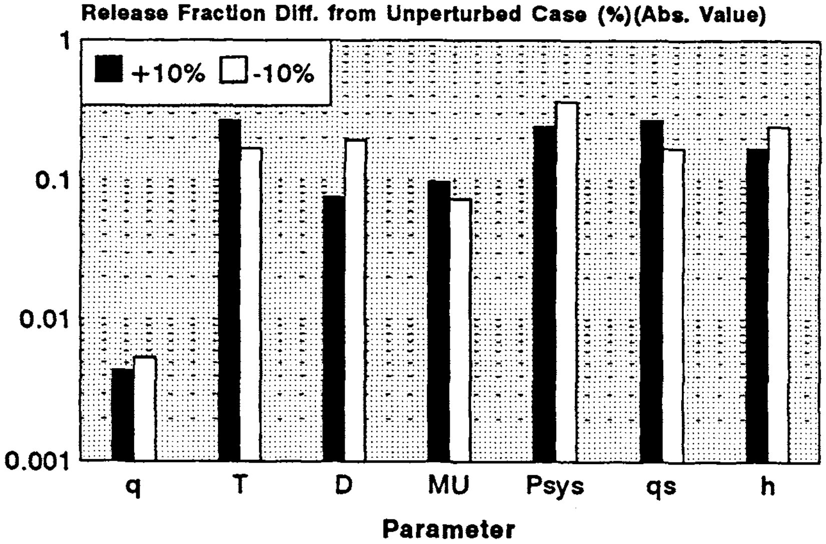

Fig. 4b : Sensitivity Analysis for Cs-137

Figure 4: Sensitivity Analysis for Reactor Accident Conditions