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SWELLING AND GAS RELEASE IN OXIDE FUELS DURING FAST TRANSIENTS

(AWBA Development Program)

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BETTIS ATOMIC POWER LABORATORY
WEST MIFFLIN, PENNSYLVANIA

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SWELLING AND GAS RELEASE IN
OXIDE FUELS DURING FAST TEMPERATURE TRANSIENTS
(AWBA DEVELOPMENT PROGRAM)

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FOREWORD

The Shippingport Atomic Power Station located in Shippingport, Pennsylvania was the first large-scale, central-station nuclear power plant in the United States and the first plant of such size in the world operated solely to produce electric power. This program was started in 1953 to confirm the practical application of nuclear power for large-scale electric power generation. It has provided much of the technology being used for design and operation of the commercial, central-station nuclear power plants now in use.

Subsequent to development and successful operation of the Pressurized Water Reactor in the Atomic Energy Commission (now Department of Energy, DOE) owned reactor plant at the Shippingport Atomic Power Station, the Atomic Energy Commission in 1965 undertook a research and development program to design and build a Light Water Breeder Reactor core for operation in the Shippingport Station.

The objective of the Light Water Breeder Reactor (LWBR) program has been to develop a technology that would significantly improve the utilization of the nation's nuclear fuel resources employing the well-established water reactor technology. To achieve this objective, work has been directed toward analysis, design, component tests, and fabrication of a water-cooled, thorium oxide-uranium oxide fuel cycle breeder reactor for installation and operation at the Shippingport Station. The LWBR core started operation in the Shippingport Station in the Fall of 1977 and is expected to be operated for about 4 to 5 years or more. At the end of this period, the core will be removed and the spent fuel shipped to the Naval Reactors Expended Core Facility for a detailed examination to verify core performance including an evaluation of breeding characteristics.

In 1976, with fabrication of the Shippingport LWBR core nearing completion, the Energy Research and Development Administration, now DOE, established the Advanced Water Breeder Application (AWBA) program to develop and disseminate technical information which would assist U.S. industry in evaluating the LWBR concept for commercial-scale application. The program is exploring some of the problems that would be faced by industry in adapting technology confirmed in the LWBR program. Information being developed includes concepts for commercial-scale prebreeder cores which would produce uranium-233 for light water breeder cores while producing electric power, improvements for breeder cores based on the technology developed to fabricate and operate the Shippingport LWBR core, and other information and technology to aid in evaluating commercial-scale application of the LWBR concept.

All three development programs (Pressurized Water Reactor, Light Water Breeder Reactor, and Advanced Water Breeder Applications) are under the technical direction of the Office of the Deputy Assistant Secretary for Naval Reactors of DOE. They have the goal of developing practical improvements in the utilization of nuclear fuel resources for generation of electrical energy using water-cooled nuclear reactors.

Technical information developed under the Shippingport, LWBR, and AWBA programs has been and will continue to be published in technical memoranda, one of which is this present report.

ABSTRACT

Swelling and Gas Release in
Oxide Fuels During Fast Temperature Transients
(AWBA Development Program)

C. C. Dollins

The previously reported swelling and gas release model for oxide fuels has been modified to predict fission gas behavior during fast temperature transients. Under steady state or slowly varying conditions it has been assumed in the previous model that the pressure caused by the fission gas within the gas bubbles is in equilibrium with the surface tension of the bubbles. During a fast transient, however, net vacancy migration to the bubbles may be insufficient to maintain this equilibrium. In order to ascertain the net vacancy flow, it is necessary to model the point defect behaviour in the fuel. This model is reported herein. Knowing the net flow of vacancies to the bubble, the bubble size, the diffusivity can be determined and the long range migration of the gas out of the fuel can be calculated. The model has also been modified to allow release of all the gas on the grain boundaries during a fast temperature transient.

The gas release predicted by the revised model shows good agreement to fast transient gas release data from an EBR-II TREAT (Transient Reactor Test Facility) test. Agreement has also been obtained between predictions using the model and gas release data obtained by Argonne National Laboratory from out-of-reactor transient heating experiments on irradiated UO_2 . It was necessary to increase the gas bubble diffusivity used in the model by a factor

of thirty during the transient to provide agreement between calculations and measurements. Other workers have also found that such an increase is necessary for agreement and attribute the increased diffusivity to yielding at the bubble surface due to the increased pressure.

INTRODUCTION

When fission occurs, inert gas atoms are produced. In the design of nuclear reactors it is necessary to determine how much of this gas is retained in the fuel and how much escapes to the fuel rod plenum and the gap between the fuel and cladding. It is also necessary to determine how much swelling the retained gas and solid fission products will cause in the fuel. Gas which escapes from the fuel increases the temperature at which the fuel operates, due to a decrease in thermal conductivity across the fuel-clad gap, and increases the pressure inside the rod. Unacceptable proximity to fuel melting or unacceptable clad strains must be avoided both during normal operation and under fast transient (accident) conditions. During a fast temperature transient additional gas may be released. It is the purpose of this report to describe a model which can predict both gas release and swelling during a fast temperature transient ($\geq 10^\circ\text{C}/\text{sec}$). The model is also suitable for predicting gas behavior if the fuel is maintained at high temperature without fissioning.

Models to predict fission gas behavior during a fast temperature transient have been developed elsewhere (1-4) and features of those will be considered here.

Dias et al (1) modified the GRASS code (5) to employ higher bubble diffusivities at temperatures above $\sim 1800^{\circ}\text{C}$ independent of heating rate. Their model allows for bubble motion and coalescence. The pressure of the gas in the bubbles is assumed to be balanced by the surface energy and any externally applied hydrostatic stress.

Rest (4) also assumed higher bubble diffusivities during fast transients than those used during steady state conditions. The heating rate at which the higher diffusivity would be expected would depend on conditions. He calculated nonequilibrium bubble sizes.

The model proposed by Bogensberger and Ronchi (2) assumed that the gas bubbles are immobile. They allow gas to be knocked out of the bubble by fission fragments and then as individual atoms the gas can migrate to the grain boundaries where it is assumed to escape. They also assumed that the gas bubbles grow so rapidly that vacancies cannot flow into them fast enough to keep the gas pressure within the bubbles in equilibrium with the surface tension.

Gruber (3) has developed a fast transient model which is similar to the Dias et al (1) model in that bubble motion is allowed. The bubbles in this model are assumed to be in equilibrium with the surface tension.

The following model is based on previous work (6) which describes methods for predicting swelling and gas release in oxide fuels under either steady state or very slowly changing conditions. That model has been modified to predict gas behavior under out of pile and in-pile fast transient conditions. The modification is described here. In addition, comparisons are made between calculations based on the model and data.

THEORY

In previous work (6) it was shown that the approximate time between coalescent events between two bubbles containing n_g atoms is

$$t_c = \frac{0.063 r^2}{N'A} \quad (1)$$

where r is the bubble radius, N' is the number of bubbles per unit volume, and A is the numerator in the experimentally observed equation for the diffusion coefficient of a gas bubble (7):

$$D_{bu} = A/r^3. \quad (2)$$

The rate of change of gas atoms in a bubble originally containing n_g atoms as it coalesces with another bubble containing n_g atoms is given by

$$\frac{dn_g}{dt} = \frac{2n_g - n_g}{t_c} = \frac{n_g N'A}{0.063 r^2} \quad (3)$$

It is assumed that during a fast temperature transient a negligible amount of gas is knocked from the bubbles.

A bubble can be looked upon as a collection of vacancies. A bubble of radius r will have n_v vacancies in it where n_v is given by

$$n_v = \frac{4\pi r^3}{3\Omega} \quad (4)$$

where Ω is the atomic volume of the lattice atoms.

If a gas bubble is in equilibrium with the matrix, then the pressure of the gas in the bubble is equal to the applied hydrostatic pressure and the pressure caused by the surface energy of the bubble:

$$P_g = P + \frac{2\gamma}{r} \quad (5)$$

where P_g is the gas pressure in the bubble, P is the externally applied hydrostatic pressure, and γ is the surface tension of the bubble. In this report an equilibrium bubble size was not assumed.

The gas pressure within the bubble is calculated from a modified form of the Van der Waals equation and is given by

$$P_g = \frac{n_g kT}{\left(\frac{4}{3} \pi r^3 - \beta n_g\right)} \quad (6)$$

where β is Van der Waals constant, k is Boltzmann's constant and T is the absolute temperature

Immediately after two bubbles coalesce P_g is greater than $P + \frac{2\gamma}{r}$. The balance given by Equation (5) can only be restored if vacancies flow into the bubble from the matrix. In fissioning material there is a ready source of vacancies as is also the case at high temperatures. The fissioning creates interstitials which can also migrate to the bubbles and retard the attainment of equilibrium.

The rate of change of the net number of vacancies in a bubble with respect to time due to coalescence is given by

$$\left. \frac{dn_v}{dt} \right|_c = \frac{n_v N' A}{0.063 r^2} \quad (7)$$

where t is the time. Equation (7) is comparable to Equation (3).

The net rate of change of vacancies in a bubble due to interstitial absorption is given by

$$\left. \frac{dn_v}{dt} \right|_I = -4\pi r N_0 D_i C_i \quad (8)$$

where N_0 is the number of lattices sites per unit volume, D_i is the interstitial diffusion coefficient, and C_i is the interstitial concentration far from any defects.

The net rate of change of the number of vacancies in a bubble due to vacancy emission and absorption is given by

$$\left. \frac{dn_v}{dt} \right|_v = -4\pi r N_0 D_v \{ C_0 \exp \left[\frac{\Omega}{kT} \left(\frac{2\gamma}{r} - P_g \right) \right] - C_v \} \quad (9)$$

where D_v is the vacancy diffusion coefficient, C_v is the vacancy concentration far from any defects, and C_0 is the equilibrium vacancy concentration. The first term within the curly braces is due to vacancy emission and the second due to vacancy absorption by the bubble. The total change in the vacancy concentration within a bubble is given by

$$\frac{dn_v}{dt} = \frac{n_v N' A}{0.003 r^2} - 4\pi r N_0 D_i C_i$$

$$-4\pi r N_0 D_v \{C_0 \exp \left[\frac{\Omega}{kT} \left(\frac{2\gamma}{r} - p_g \right) \right] - C_v\}. \quad (10)$$

The change in the radius of a bubble is given by

$$\frac{dr}{dt} = \frac{\Omega}{4\pi r^2} \frac{dn_v}{dt}. \quad (11)$$

To use Equation (10) it is necessary to know C_v and C_i . Vacancies and interstitials are produced by the fission fragments. It will be assumed here that the damage cascade density has saturated at a relatively low level compared to the bubble density. Under the above assumption, vacancies and interstitials will be produced in equal numbers which are given by (3)

$$P_v = P_i = 10^4 \dot{f} \Omega \quad (12)$$

where $\dot{f}$ is the fission rate.

The loss rate of vacancies to dislocations is given by (8)

$$L_d^v = \frac{2\pi \rho' D_v}{\ln(r_1/b)} (C_v - C_0 \exp(-\frac{\Omega P}{kT})) \quad (13)$$

where ρ' is the dislocation density, $r_1 = (\pi\rho')^{-1/2}$ is half the distance between dislocations, and b is the Burgers vector. The effect of dislocations on the vacancy equation was not included in the Rest (4) analysis.

The loss rate of vacancies to bubbles is given by (8)

$$L_b^v = 4\pi r N' D_v \{C_v - C_0 \exp [\frac{\Omega}{kT} (\frac{2\gamma}{r} - p_g)]\}. \quad (14)$$

The loss rate of vacancies to interstitials through recombination is given by

$$L_k^v = \frac{5040 (D_i + D_v)}{a^2} C_v C_i \quad (15)$$

where a is the atomic jump distance.

Combining the above expressions we can obtain the rate of change of the vacancy concentration with respect to time and with respect to the distance ρ from the center of a grain which is given by

$$\frac{\partial C_v}{\partial t} = \frac{D_v}{\rho^2} \frac{\partial}{\partial \rho} (\rho^2 \frac{\partial C_v}{\partial \rho}) + 10^4 f \Omega - \frac{4\pi\rho' D_v}{2n(r_1/b)} (C_v - C_0 \exp (-\frac{\Omega}{kT} p))$$

$$+ 4\pi r N' D_v \{C_0 \exp [\frac{\Omega}{kT} (\frac{2\gamma}{r} - p_g)] - C_v\}$$

$$- \frac{5040 (D_i + D_v)}{a^2} C_v C_i \quad (16)$$

with boundary conditions $C_v = C_0 \exp \left(-\frac{\Omega P}{kT} \right)$ at $\rho = R$ where R is the grain radius and $\frac{\partial C_v}{\partial \rho} = 0$ at $\rho = 0$. An analogous equation exists for interstitials and is given by

$$\begin{aligned} \frac{\partial C_i}{\partial t} = & \frac{D_i}{\rho^2} \frac{\partial}{\partial \rho} \left(\rho^2 \frac{\partial C_i}{\partial \rho} \right) + 10^4 \cdot R \cdot \frac{4\pi \rho' D_i C_i}{\ln(r_1/(b+\Delta R))} \\ & - 4\pi N' D_i C_i - \frac{5040 (D_i + D_v)}{a^2} C_v C_i \end{aligned} \quad (17)$$

with boundary conditions $C_i = 0$ at $\rho = R$ and $\frac{\partial C_i}{\partial \rho} = 0$ at $\rho = 0$. In equation (17) ΔR is the increase in capture radius that a dislocation has for an interstitial over a vacancy and is given by (9,10)

$$\Delta R = 0.07 b a^2 \mu \epsilon / kT \quad (18)$$

where b is the Burgers vector of the dislocation, μ is the shear modulus of the fuel and ϵ is the misfit parameter of an interstitial in the lattice.

The radius of the bubble, r , is a function of the position, ρ , of the bubble in the grain. The larger bubbles tend to be in the center of the grain. When fissioning is occurring, the fission fragments limit the size the bubbles can grow to since the larger bubbles are more susceptible to fission gas resolution. A steady state bubble size can then be reached. In some

accidents, fast transients can occur without fissioning. Without fissioning nothing limits the bubble growth. Large bubbles can migrate into regions of small bubbles increasing the average bubble size and vice versa. The effect of long range bubble migration on the bubble size will now be considered.

The change in the number of vacancies in the bubbles per unit volume of fuel is given by the modified Laplacian equation

$$\frac{\partial n_v N'}{\partial t} = \frac{1}{\rho^2} \frac{\partial}{\partial \rho} \left(\rho^2 \frac{\partial n_v N' D}{\partial \rho} \right) \quad (19)$$

where D is the gas bubble diffusion coefficient to be discussed. The boundary conditions are

$$\frac{\partial n_v N' D}{\partial \rho} = 0 \quad \text{at} \quad \rho = 0, \text{ and}$$

$$n_v N' = 0 \quad \text{at} \quad \rho = R$$

The change in the number of bubbles per unit volume of fuel is given by

$$\frac{\partial N'}{\partial t} = \frac{1}{\rho^2} \frac{\partial}{\partial \rho} \left(\rho^2 \frac{\partial N' D}{\partial \rho} \right) \quad (20)$$

with boundary conditions

$$\frac{\partial N'D}{\partial \rho} = 0 \quad \text{at } \rho = 0 \quad \text{and}$$

$$N' = 0 \quad \text{at } \rho = R.$$

From the fact that

$$\frac{dN'n_v}{dt} = n_v \frac{dN'}{dt} + N' \frac{dn_v}{dt} \quad (21)$$

we obtain

$$\frac{dn_v}{dt} = \left(\frac{dn_v N'}{dt} - n_v \frac{dN'}{dt} \right) / N' \quad (22)$$

where $\frac{dn_v N'}{dt}$ is given by equation (19) and $\frac{dN'}{dt}$ is given by equation (20).

The $\frac{dn_v}{dt}$ of equation (22) must now be added to equation (10) to get the total rate of change of the number of vacancies in a bubble with respect to time.

The fission gas behavior has been described in detail elsewhere⁽⁶⁾. Certain points are reconsidered here.

The gas in the grain interior obeys the relationship

$$\frac{\partial C}{\partial t} = \frac{1}{\rho^2} \frac{\partial}{\partial \rho} \left(\rho^2 \frac{\partial CD}{\partial \rho} \right) + \dot{a} \quad (23)$$

where C is the fission gas concentration in atom fraction, D is the fission gas diffusion coefficient, and $\dot{a}$ is the gas generation rate. The boundary conditions for Equation (19) are $\frac{\partial CD}{\partial \rho} = 0$ at $\rho = 0$ and $C = 0$ at $\rho = R$. The gas concentration is related to N' and n_g by the relation

$$C N_0 = n_g N'. \quad (24)$$

The diffusion coefficient D is given approximately by

$$D = D_{bu} + D_{eff} \quad (25)$$

where D_{bu} is given by Equation (2) and D_{eff} is the effective enhancement of D by the presence of a temperature gradient and is given by

$$D_{eff} = \frac{2\pi A Q^* \nabla T R}{9kT^2 \Omega} \quad (26)$$

where Q^* is the heat of transport and ∇T is the temperature gradient. The bubble radius, r , used in Equation (2) is found by solving Equation (11).

The rate that gas goes to the grain boundaries is determined through the solution of Equation (19) which must be solved in conjunction with Equations (16) and (17).

Equations (16), (17) and (19) were solved numerically on a computer. It was found that very nearly the same answers could be obtained by setting $\frac{\partial C_v}{\partial t} = \frac{\partial C_i}{\partial t} = 0$ in Equations (16) and (17) with much shorter computer running

time. It was also found that not allowing point defect loss at grain boundaries had no effect on the answers with still greater saving of computer time. Equations (16) and (17) can then be written as

$$\begin{aligned}
 0 = 10^4 \dot{f}\Omega - \frac{4\pi\rho'D_v}{\ln(r_1/b)} (C_v - C_0) \\
 + 4\pi rN'D_v \{C_0 \exp [\frac{\Omega}{kT} (\frac{2\gamma}{r} + P - P_g)] - C_v\} \\
 - \frac{5040 (D_i - D_v)}{a^2} C_v C_i
 \end{aligned} \tag{27}$$

and

$$\begin{aligned}
 0 = 10^4 \dot{f}\Omega - \frac{4\pi\rho'D_i C_i}{\ln(r_1/(b+\Delta R))} - 4\pi rN'D_i C_i \\
 - \frac{5040 (D_i + D_v)}{a^2} C_v C_i.
 \end{aligned} \tag{28}$$

With the solution of Equations (19), (23), and (24) the bubble radius can be calculated using Equation (11). The bubble density can be calculated using Equation (20). The swelling due to the intragranular bubbles is given by

$$\frac{\Delta V}{V} = \frac{4}{3}\pi r^3 N'. \quad (29)$$

As in the case of Bogensberger and Ronchi⁽²⁾ and Gruber⁽³⁾, it will be assumed that any gas that migrates to the grain boundaries escapes. The grains break up along the grain boundaries because of the thermal stresses resulting from the rapid heating⁽⁴⁾. Such break up would prevent grain growth.

As was found by Dias et al⁽¹⁾ it was found that to get agreement between theory and data it was necessary to increase the bubble diffusion coefficient. The A of Equation (2) was increased from 1.19×10^{-22} to 3×10^{-21} cm⁵/sec. The resulting increased diffusion coefficient was used throughout this report. Rest⁽⁴⁾ attributes the increased diffusivity he must assume to yielding in the region of the bubble which is due to the overpressurized condition of the bubbles.

RESULTS AND DISCUSSION

Predictions made by the model were compared to experimental results obtained from the EBR-II TREAT test and reported by Stahl and Patrician⁽¹¹⁾. They irradiated UO₂-25 wt% PuO₂ to a burnup of 3.2 atomic percent. Prior to the transient, the fuel was operated at a maximum centerline temperature of 1800°C and a surface temperature of 600°C. The specimen cooled to 400°C and was then subjected to a 4 second transient to a centerline temperature of 2750°C. The surface rose to 1400°C. The specimen was then cooled so that after four additional seconds the centerline temperature was about 1500°C and

the surface at 700°C. A second specimen was treated to the steady state irradiation but not to the fast transient. The non-transient tested specimen had a gas release of 57.8% at the specimen midplane and 47.5% for the entire rod, compared to a value of 52% predicted using the model. The transient tested specimen had 88.5% gas release at the midplane, but the authors state that this is "questionable" since the entire specimen had a measured gas release of 56.2%. Midplane gas release measurements are made by examining the retained gas at the midplane. The method used was to vaporize the fuel by a laser and then measure the released gas. The model predicts 59% gas release for the midplane. The rods were about 13" long. In both cases agreement between predictions and the data are good.

Comparisons were also made between calculations using the model and data for UO₂ specimens which were subjected to a fast temperature transient in an out-of-reactor direct electrical heating experiment conducted by Gehl et al⁽¹²⁾. The specimens in this test were initially irradiated to a burnup of 3.2 atomic percent. At the end of the irradiation the specimen centerline temperature was 1419°C and the surface temperature was 798°C. The fission rate at the end of irradiation was 0.58×10^{13} f/cm³ sec. The centerline temperature at the beginning of the fast transient was 1350°C and the surface temperature was 1100°C. It was assumed that the surfaces of the specimens were heated to a maximum temperature of 1400°C during the tests. The cooling rate of the specimens was assumed to be 40°C/sec in all experiments.

The specimen centerline heating rate, duration of test and maximum temperature are shown in Table I. From the test duration and heating rate the

peak centerline temperature reached during the test was calculated and is shown in the table.

Gehl et al assumed no gas release during the irradiation portion of the test; the present model also predicts no gas release. Table I shows the measured Xe gas release along with the model predicted values. Agreement between the model and the data is good in most cases. The main exception is test number 26 which had more gas release than any of the other specimens and yet was heated to one of the lowest temperatures making the data for this one specimen questionable.

A plot of the predicted gas release versus measured gas release for the Gehl et al data (solid circles) and the Stahl and Patrician data (X's) are shown in Figure 1. The X at 88.5% measured gas release is questionable as is the solid circle at 63.1% measured gas release.

Figures 2 through 11 show the effect of varying various parameters on both gas release and swelling under conditions which Gruber used to show the same things. The base conditions are 300°C/sec heating rate, 5000°C/cm thermal gradient, 10 μm grain diameter, 1×10^{20} gas atoms/cm³, 0.25 MPa pressure, initial temperature of 1365°C and final temperature of 2865°C. To obtain the curves shown a pre-irradiation at 1000°C was assumed. The computer runs were then made to the melting point. Figure 2 shows the effect of varying the grain size. Increasing the grain size decreases the amount of gas that is released. The present model predicts less than half as much gas release as predicted by Gruber's model. Gruber's predictions were not compared to data. In all curves the broken lines are Gruber's predictions.

Figure 3 shows the effect of varying the gas atom concentration on the gas release. In both models, as the gas concentration is increased the gas bubble size is increased and the gas bubble diffusivity is decreased resulting in less and less gas escaping from the grain interior. In the present model gas that has accumulated on the boundary prior to the transient is released during the transient; therefore, the 4×10^{20} atom/cm³ curve starts out at a higher value.

Figure 4 shows the effect of heating rate on gas release. The slower the heating rate the longer the time at high temperatures and the greater the gas release. The gas bubbles were non equilibrium only at the 1000°C/sec heating rate. Rest⁽⁴⁾ predicted non equilibrium bubbles at much lower heating rates. The difference may very well be that he did not include the effect of dislocations as sources for vacancies. Since the bubbles are not overpressurized the yield model for enhanced diffusivity cannot be used. At this point we have no model for the enhanced diffusivity.

Figure 5 shows the effect of temperature gradient on gas release. The greater the temperature gradient the greater the amount of gas that is released.

Figure 6 shows the effect of pressure which under the present model is nonexistent.

Figures 7 through 11 show the swelling predicted by the model. The swelling values predicted by Gruber are orders of magnitude greater than the swelling predicted by the present model and, consequently, his values will not be shown. Bogensberger and Ronchi also observed swelling increases of 2 to 3% during fast transients.

CONCLUSIONS

A model has been developed to predict gas release and swelling during a fast temperature transient. The model allows for the coalescence of gas bubbles and for control of the bubble size by net vacancy migration to the bubbles. The model assumed 100% gas release for all gas on grain boundaries during the fast transient. Comparisons were made between the model and data obtained from the EBR-II TREAT test and from data obtained on out-of-reactor transient electrically heated UO_2 . In both cases good agreement was obtained; however, in order to obtain this agreement it was necessary to increase the bubble diffusivity by a factor of about 30. Other workers have also found that such an increase is necessary for agreement and attribute the increased diffusivity to yielding at the surface due to the increased pressure.

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TABLE IExperimental Conditions and Gas Release for Gehl et al Specimens

Test #	Duration of Test(s)	Avg. CL Heat Rate °C/sec	Peak Temp (°C)	Xe Gas Release (%)	Predicted Gas Release
21	68	25	3050	50.0	49.9
22	36	36	2646	13.1	24.8
23	28	41	2498	1-5	18.4
24	50	28	2750	12.0	32.2
25	58	25	2800	43.0	36.1
26	54	15	2160	63.1	13.1
27	54	22	2538	33.3	22.1
29	59	12	2058	2.	12.5
30	70	10	2050	0.4	12.5
32	60	22	2670	16.1	23.2
33	100	12	2550	42.6	20.7

FIGURE 1

Plot of predicted gas release versus measured gas release for both the Stahl and Patrician (x) and the Gehl et al (•) data.

FIGURE 2 Predicted gas release versus time into the transient for several grain sizes and for both the present model (-) and Gruber's model (---).

FIGURE 3

Predicted gas release versus time into the transient for several different fission gas atom concentrations.

FIGURE 4 Predicted gas release versus time into the transient for several heating rates.

FIGURE 5 Predicted gas release versus time into the transient for several temperature gradients.

FIGURE 6

Predicted gas release versus time into the transient for several externally applied pressures.

FIGURE 7 Predicted fission gas swelling versus time into the transient for several different grain sizes.

FIGURE 8 Predicted fission gas swelling versus time into the transient for several different gas atom concentrations.

FIGURE 9 Predicted fission gas swelling versus time into the transient for several different heating rates.

FIGURE 10

Predicted fission gas swelling versus time into the transient for several different temperature gradients.

FIGURE 11 Predicted fission gas swelling versus time into the transient for several different pressures.