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Fission-Gas Release at Extended Burnups: Effect of Two-Dimensional Heat Transfer

Rejet des gaz de fission à des combustions nucléaires prolongées : effet du transfert de chaleur bidimensionnel

M. Tayal, S.D. Yu, J.H.K. Lau

Paper presented at IAEA International Seminar on Fission Gas Behaviour in Water Reactor Fuels, Cadarache, France, 2000 September 26-29

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Résumé

Afin de mieux simuler les performances du combustible CANDU à combustion élevée, un modèle bidimensionnel relatif au transfert de chaleur entre la pastille et la gaine a été ajouté au code de calcul ELESTRES. Le modèle porte sur quatre orientations relatives de la pastille et de la gaine et sur leurs conséquences sur le transfert de chaleur et le rejet de gaz de fission. Les prévisions du code ont été comparées à une base de données de 27 irradiations expérimentales comprenant des combustions nucléaires prolongées et des combustions normales. Les valeurs calculées du rejet de gaz de fission correspondaient aux mesures, en moyenne à 94 %. Ainsi, le modèle de transfert de chaleur bidimensionnel augmente la polyvalence du code ELESTRES pour mieux simuler les combustibles tant aux combustions normales que prolongées.

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Abstract

To better simulate the performance of high-burnup CANDU® fuel, a two-dimensional model for heat transfer between the pellet and the sheath has been added to the computer code ELESTRES. The model covers four relative orientations of the pellet and the sheath and their impacts on heat transfer and fission-gas release. The predictions of the code were compared to a database of 27 experimental irradiations involving extended burnups and normal burnups. The calculated values of fission gas release matched the measurements to an average of 94%. Thus, the two-dimensional heat transfer model increases the versatility of the ELESTRES code to better simulate fuels at normal as well as at extended burnups.

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1. INTRODUCTION

To enhance the economy of nuclear energy, activities are underway at Atomic Energy of Canada Limited (AECL) to increase core-average burnup of CANDU® fuel by a factor of about 3, to 20 GW•d/T U. To better simulate the performance of such fuels, some models in the computer code ELESTRES [References 1, 2] have been enhanced. This paper describes a model for two-dimensional heat transfer within the fuel element in the radial-circumferential plane (r-θ) as a result of on-power changes in the dimensions of the pellet and the sheath. This capability improves the predictions of fission-gas release at extended burnups while preserving the existing good match with measurements at normal burnups.

2. BACKGROUND

The main objective of the ELESTRES code is to calculate temperatures, fission-gas release, and hoop strains in a fuel element during normal operating conditions. The details of the code have been described elsewhere; see, for example, References 1 and 2. A brief summary is given here for completeness.

The code models thermal, microstructural, and mechanical behaviour of a nuclear fuel element. The original version used a one-dimensional (radial) finite-difference model for thermal simulations, a point model for microstructural simulations, and a two-dimensional (radial-axial) finite-element model for mechanical simulations. For normal-burnup CANDU fuel, ELESTRES calculations have shown excellent match with fission-gas release measurements in 98 normal-burnup irradiations [2]. The code is used extensively at AECL for fuel performance assessments. It was originally released in the 1970s and has been updated periodically.

In recent years, we have added a number of features to a developmental version of the code to facilitate simulation of high-burnup fuel. These features include: an updated model to reflect more recent data on the degradation of UO_2 thermal conductivity with burnup; variation of UO_2 diffusivity with burnup; variation of fission-gas bubble density with burnup; circumferential cracking of the pellet; larger range for the influences of burnup, enrichment, and element diameter on flux depression; updated model for solid fission-product swelling; incremental densification; rim effect; and two-dimensional model for heat transfer between the pellet and the sheath.

This paper describes the model for two-dimensional heat transfer in the radial-circumferential (r-θ) plane. This type of heat transfer is determined largely by the nature of pellet-to-sheath contact. Therefore, we start this discussion with an overview of the major processes that affect pellet-to-sheath contact.

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3. PELLET-TO-SHEATH CONTACT: THE PROCESS

Figure 1 shows some Canadian measurements of on-power variations in the diameter of a CANDU sheath during changes in power [3, 4]. These references provide explanations of the observations; a generalized description of the related processes is given below.

Pellet-to-sheath contact can occur because of pellet expansion, or because of sheath contraction, or because of a combination of the two processes. Figure 2 shows four possible stages of circumferential pellet-to-sheath contact in a horizontal fuel element, depending on the details of design and operating conditions. In this paper, the stages are called (a) full gap - Figure 2a; (b) elastic instability-Figure 2b; (c) partial wraparound - Figure 2c; and (d) full wraparound - Figure 2d. Note that the effects have been greatly exaggerated in the figure for visual clarity.

As fabricated, the fuel has a nominal diametral clearance (or radial gap) between the sheath and the pellet at room temperature. This feature leads to the configuration shown in Figure 2a. In this state, the contact occurs over a small part of the circumference at the bottom of the sheath, because the fuel bundle lies horizontally in a CANDU reactor.

During operation in the reactor, the pellet is significantly hotter than the sheath, and it also has a higher coefficient of thermal expansion. For these reasons, the pellet expands considerably more than the sheath does. Therefore, the nominal as-fabricated radial gap between the pellet and the sheath closes when the fuel is first brought to full power (Figure 2d). At this time, pellet-to-sheath contact extends uniformly around the full circumference, and the sheath is often stretched into the plastic region.

Subsequently, the pellet shrinks in response to densification or power reduction. The sheath, too, shrinks rapidly because of (i) recovery of elastic strains from the previous pellet expansion and (ii) compressive elastic strains from differential pressure, which means coolant pressure minus internal gas pressure.

Sometimes the sheath's shrinkage may not be as much as that of the pellet. This difference in shrinkage could potentially result in the nominal sheath circumference being greater than that of the pellet. In this situation, a nominal radial gap opens between the pellet and the sheath.

The differential pressure will induce compressive hoop stresses in a sheath with open gap. If the differential pressure is equal to or greater than the pressure for elastic instability of the sheath, the sheath will collapse and contact the pellet. The classical theory of elastic instability of thin cylinders suggests that at this time the contact can be expected over two small arches, as illustrated in Figure 2b [5, 6]. Over the remainder of the circumference, we can expect a local gap between the pellet and the sheath.

With further increase in differential pressure, local plastic deformation will tend to wrap the sheath more fully around the circumference of the pellet. This picture is based on Canadian

studies of sheath collapse, and the process is illustrated schematically in Figure 3. The sheath configuration at this stage is shown in Figure 2c.

With time, sheath will creep under the differential pressure, which will reduce - and sometimes eliminate - the nominal gap. Fission-product swelling will tend to have the same effect. The limiting situation of full wraparound is shown in Figure 2d.

Conversely, the pellet-to-sheath contact condition can temporarily move from a state of full wraparound (Figure 2d) to partial wraparound (Figure 2c) to elastic instability (Figure 2b) to full gap (Figure 2a) if, after the fission-gas pressure exceeds a certain level, the pellet shrinks because of a reduction in power or densification. Hence a complex dynamics of pellet-to-sheath contact can potentially be set up during the fuel's lifetime in the reactor depending on the details of element design, power history, and coolant conditions.

Some of the above dynamics are visible in the measurements shown in Figure 1. During the initial part of the power-increase, the slope of sheath expansion is driven by the free thermal expansion of the sheath [4]. After some time, however, the slope increases significantly, and is now governed by the thermal expansion of the pellet [4]. Intersection of the two slopes signifies the onset of interaction, or contact, between the sheath and the pellet—see Figure 1. This process illustrates that, even under hot coolant pressure, a nominally open gap can exist between the sheath and the pellet during some parts of the power history. In Figure 1, the gap closed after 20 kW/m during the power-increase because of additional thermal expansion of the pellet.

ELESTRES results for pellet and sheath dimensional changes suggest that more of these dynamics have also occurred in some other existing experimental irradiations, particularly in irradiations involving extended burnups and elevated powers. An illustrative example is given later in the section on "Verifications".

4. TWO-DIMENSIONAL HEAT TRANSFER: THE PROCESS

Under a condition of full wraparound (Figure 2d), the heat transfer from the pellet to the sheath is only along the radial direction. However, under conditions shown in Figures 2a to 2c—that is, full gap to elastic instability and then to partial wraparound—the heat flux will be comparatively higher at locations of pellet-to-sheath contact than at locations of pellet-to-sheath gap. Therefore, heat transfer will also occur circumferentially.

Figure 4 shows the results of a previous sensitivity study [7] of the possible magnitude of this effect. The study used the FEAT code [8] for a two-dimensional simulation of heat transfer between the pellet and the sheath. The fuel element was assumed to be operating at 50 kW/m; the pellet-to-sheath heat transfer coefficient was assumed to be 30 kW/m^2K in the region of contact, and 5 kW/m^2K in the region not in contact. The figure shows that the degree of contact can alter the central temperature by up to 400°C, or 24%.

To simulate the full ranges of available experimental data, we have added a model in ELESTRES for two-dimensional heat transfer. The details are described below.

5. PELLET-TO-SHEATH CONTACT: THE MODEL

The size of the total radial gap is calculated by ELESTRES as part of its normal calculation of circumferences of the sheath and the pellet. When the gap is closed, full contact is assumed, and the heat transfer coefficient is calculated using the Campbell model [9].

When the gap is open, the amount of sheath circumference that is in contact with the pellet depends on the following factors: the size of the on-power diametral gap between the pellet and the sheath; the differential pressure acting on the sheath; and the strength of the sheath (determined largely by thickness, modulus of elasticity, and yield strength at operating temperature).

We have used an empirical model to calculate the amount of sheath circumference that is in contact with the pellet during a nominally open gap. The model is based on the trends shown in Figure 3 and normalized to a selected set of data. The model assumes that if the calculated gap is open and the differential pressure is less than the pressure for elastic instability [5,6], pellet-to-sheath contact is limited to a small arch at the bottom (Figure 2a). Beyond that pressure, the degree of circumferential contact is assumed to increase in the manner shown in Figure 3.

At angular locations where the gap is locally open (Figures 2a to 2c), the local radial gap is calculated from the total circumferential difference by using simple trigonometric relationships.

6. TWO-DIMENSIONAL HEAT TRANSFER: THE MODEL

The following steps were taken to model two-dimensional heat transfer at each burnup step during a given power history:

The FEAT code was merged into the ELESTRES code as a subroutine. FEAT uses the finite-element method to model two-dimensional conduction of heat in solids of arbitrary shapes. Gap elements are used to simulate heat-transfer interfaces between the pellet and the sheath. The FEAT code has been validated independently [10].

Figure 5 shows the mesh pattern that has been included in ELESTRES as input to the FEAT routine. Symmetry about the vertical axis is assumed; this enables us to reduce computing time by simulating half the pellet cross-section in the FEAT mesh. The mesh pattern was guided by past studies on accuracy [11]. The level of nodalization was guided by past sensitivity studies on convergence [10]. For increased accuracy, the mesh uses a finer nodalization in areas where

sharper gradients of temperature are expected. Conversely, to reduce computing time, comparatively coarser nodalization is used in regions of shallow gradients of temperature.

The local heat generation rate in each finite element reflects the level of power, local flux depression, and skin effect. These are calculated automatically in the code at each burnup step using existing models for these effects [1]

Likewise, the thermal conductivity for each finite element is determined by relevant parameters at each calculation step, such as local temperature, local porosity, and burnup. Existing models for these processes are used [1].

The main part of ELESTRES passes all relevant inputs to the FEAT routine, which then calculates two-dimensional temperatures to reflect circumferentially non-uniform heat transfer in nominally open gap. An interfacing routine then averages the temperatures for each radial annulus, and passes them back to the rest of ELESTRES. The remaining ELESTRES calculations proceed as usual. This process is followed at each time step in the calculation. Thus the effect of two-dimensional temperatures is reflected in all calculations of fission-gas release, gas pressure, grain growth, pellet expansion, sheath strains, etc.

7. VERIFICATIONS

To confirm that the FEAT code has been accurately incorporated into ELESTRES, we compared results of the one-dimensional and two-dimensional versions of ELESTRES, for three test cases. In the first test, we forced both versions of the code to always use 10 kW/m^2K for all heat transfer calculations at all times. This test sets up a one-dimensional problem, which was solved in one-dimensional manner by the reference version of the code and in a two-dimensional manner by the latter (developmental) version of the code. Both versions of the code gave the same results. This suggests that the capture of FEAT into ELESTRES did not introduce any errors.

In the second test, we simulated an irradiation history in which the gap was naturally closed, essentially all the time. The two versions of the code were allowed to do their natural calculations. Both versions gave very similar results, suggesting that the changes had not inadvertently altered any calculation outside of the heat transfer package.

In the third test, a number of irradiations were simulated using the code's natural calculations of all parameters. Figure 6a shows an illustrative example for an irradiation that had a peak rating of 73 kW/m and burnup of 640 MW•h/kg U. Figure 6b shows the on-power variations in the nominal diametral gap between the sheath and the pellet. The nominal diametral gap is a measure of the excess circumference of the sheath; it represents the difference in the diameters of the sheath and the pellet had both been circular. It is obtained by calculating the difference in the on-power circumferences of the sheath and the pellet, and dividing that number by π. Figure 6b

illustrates the dynamics of the pellet-to-sheath gap discussed earlier; the gap closes, opens, increases, and decreases in response to variations in power, densification, fission-product swelling, differential pressure, and creep. At lower burnups, the two versions of the code give very similar results. Subsequently, high powers at intermediate burnups result in considerable fission-gas release and internal pressure. This reduces the differential pressure. A substantial reduction in power at 200 MW•h/kg U then shrinks the pellet. This opens a gap and sets up conditions for non-uniform heat transfer. The two-dimensional calculations capture this effect and increase the pellet temperature by 200-300°C during the later part of fuel life. This increase in pellet temperature, in turn, increases the final fission-gas release. The results of this case were reviewed in considerable detail for a number of intermediate and final calculations, and the trends were found to be reasonable.

8. COMPARISONS WITH EXPERIMENTAL DATA

We surveyed simulations of Canadian irradiations that predicted comparatively long periods (over 1 week) of significant open on-power gaps under conditions of relatively high internal gas pressures. Such irradiations would be most likely to be affected by two-dimensional heat transfer. Based on this survey, 27 irradiations were selected for further assessments. All involved relatively high peak powers (above 65 kW/m). Eight of the irradiations consisted of normal CANDU burnups (less than 300 MW•h/kg U); nineteen irradiations involved extended burnups (over 300 MW•h/kg U). The highest burnup was 660 MW•h/kg U. The sizes and durations of calculated gaps varied from case to case; the maximum gap was about 120 μm, and the maximum duration of the open gap was about 520 d. These 27 irradiations were not included in the original database of 98 irradiations mentioned earlier for normal burnups.

For these 27 irradiations, Figure 7 compares the measured gas releases to calculations. The figure shows volume of fission-gas release, rather than percentage, because the former is a more pertinent measure of the driving force for sheath stresses and pellet-to-sheath contact. In Figure 7, a slope of 1 would have shown perfect match between the simulations and the measurements. The best-fit line has a slope of 0.94. This value means that the code's calculations match these measurements to an average of 94%.

9. DISCUSSION

As noted earlier, the earlier version of ELESTRES had shown excellent match with fission-gas measurements in 98 normal-burnup irradiations. Therefore, when the gap is closed during the irradiation history, one-dimensional calculations of heat transfer are sufficient to give good predictions of fission-gas release. For this situation, the two-dimensional heat transfer calculations provide the same results as the one-dimensional calculations; hence both calculations are equally good.

When the gap is open for relatively long periods, two-dimensional calculations of heat transfer account for four relative orientations of the pellet and the sheath. This results in a good match between simulations and measurements of fission-gas release at extended burnups as well as at normal burnups at high ratings. Thus, the two-dimensional heat transfer model improves the versatility of the ELESTRES code to better simulate CANDU fuels at normal burnups as well as at extended burnups.

10. CONCLUSIONS

The original version of the ELESTRES code contained a one-dimensional model for heat transfer. Its calculations show an excellent match with 98 measurements of fission gas releases at normal CANDU burnups.

To continue getting good simulations of fuel performance at extended CANDU burnups, the code has now been updated to include a two-dimensional model for pellet-to-sheath heat transfer. The model covers four possible relative orientations of the pellet and the sheath and their effects on heat transfer and fission-gas release. The predictions of the model were compared to a database of 27 additional experimental irradiations involving extended burnups and normal burnups. The calculated values of fission gas release matched the measurements to an average of 94%. Thus, the two-dimensional model improves the versatility of the ELESTRES code to better simulate CANDU fuels at normal as well as extended burnups.

11. ACKNOWLEDGEMENTS

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[Data of Fehrenbach et al., AECL-7837, 1982]

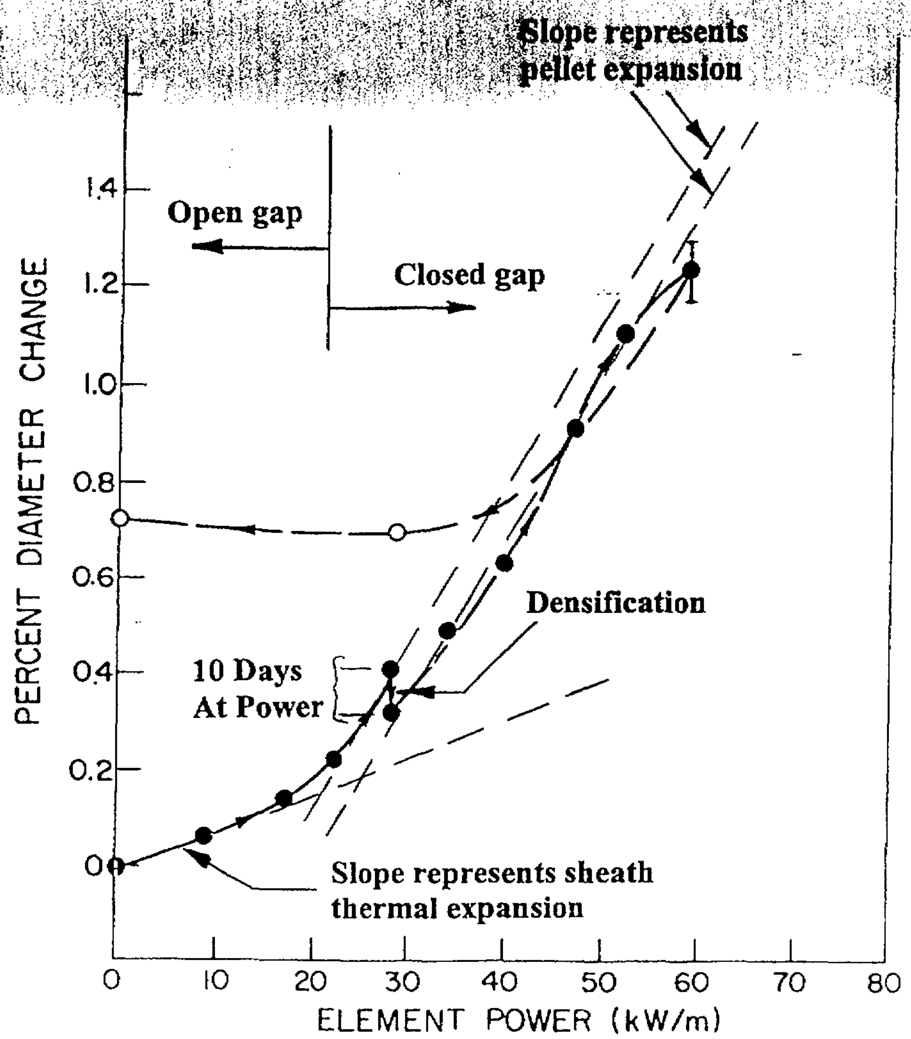
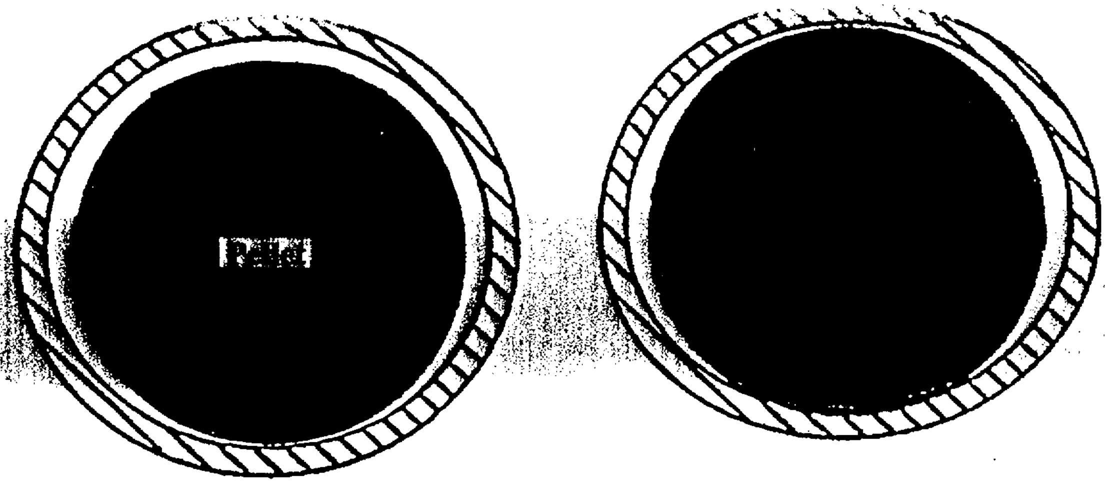
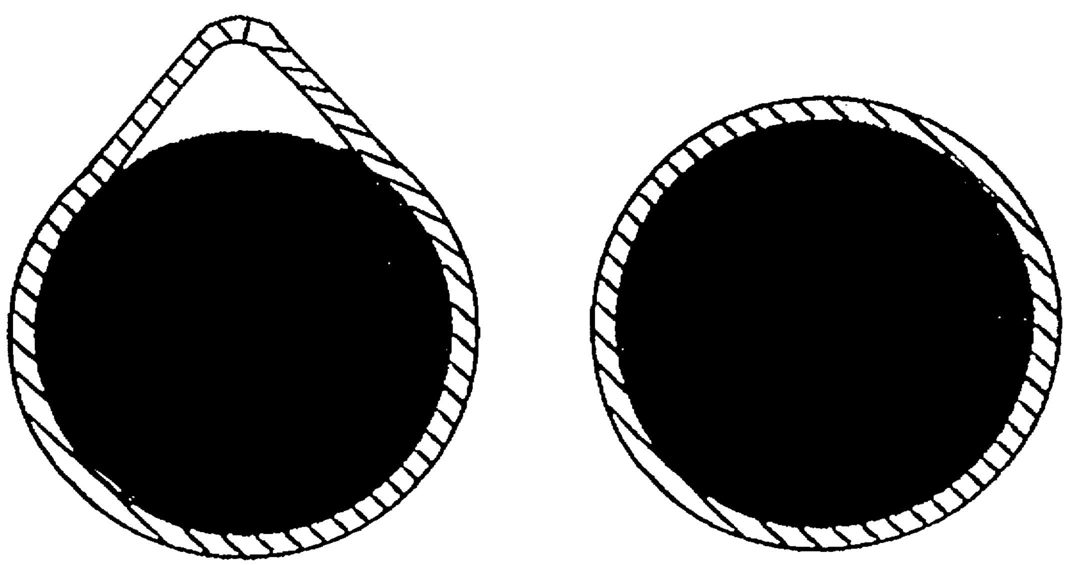


Figure 1: Sheath Diametral Expansion during a Power Change



(a) Full Gap **(b) Elastic Instability**



(c) Partial Wraparound (d) Full Wraparound

Figure 2: Stages of Pellet-to-sheath Contact

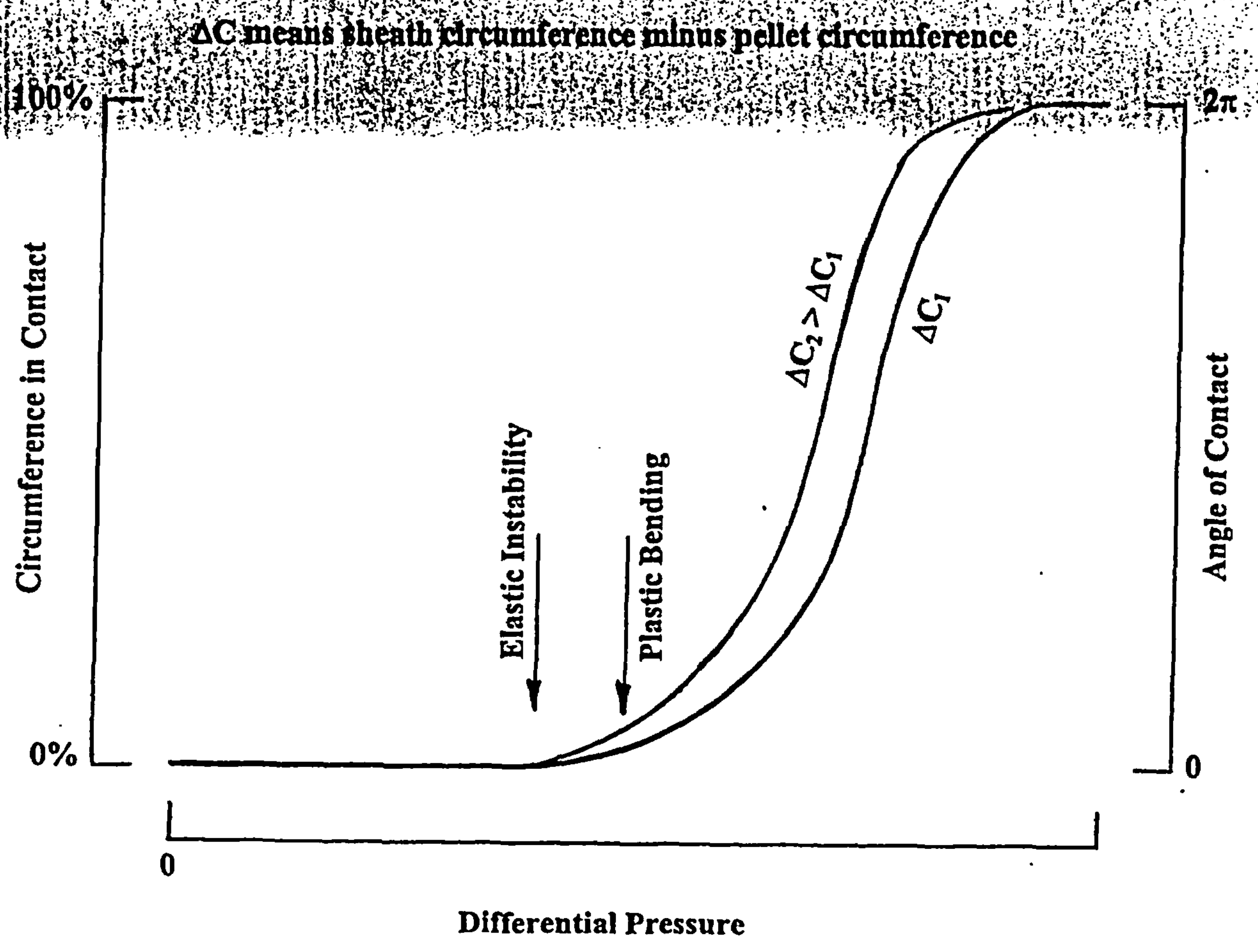


Figure 3: Sheath Collapse

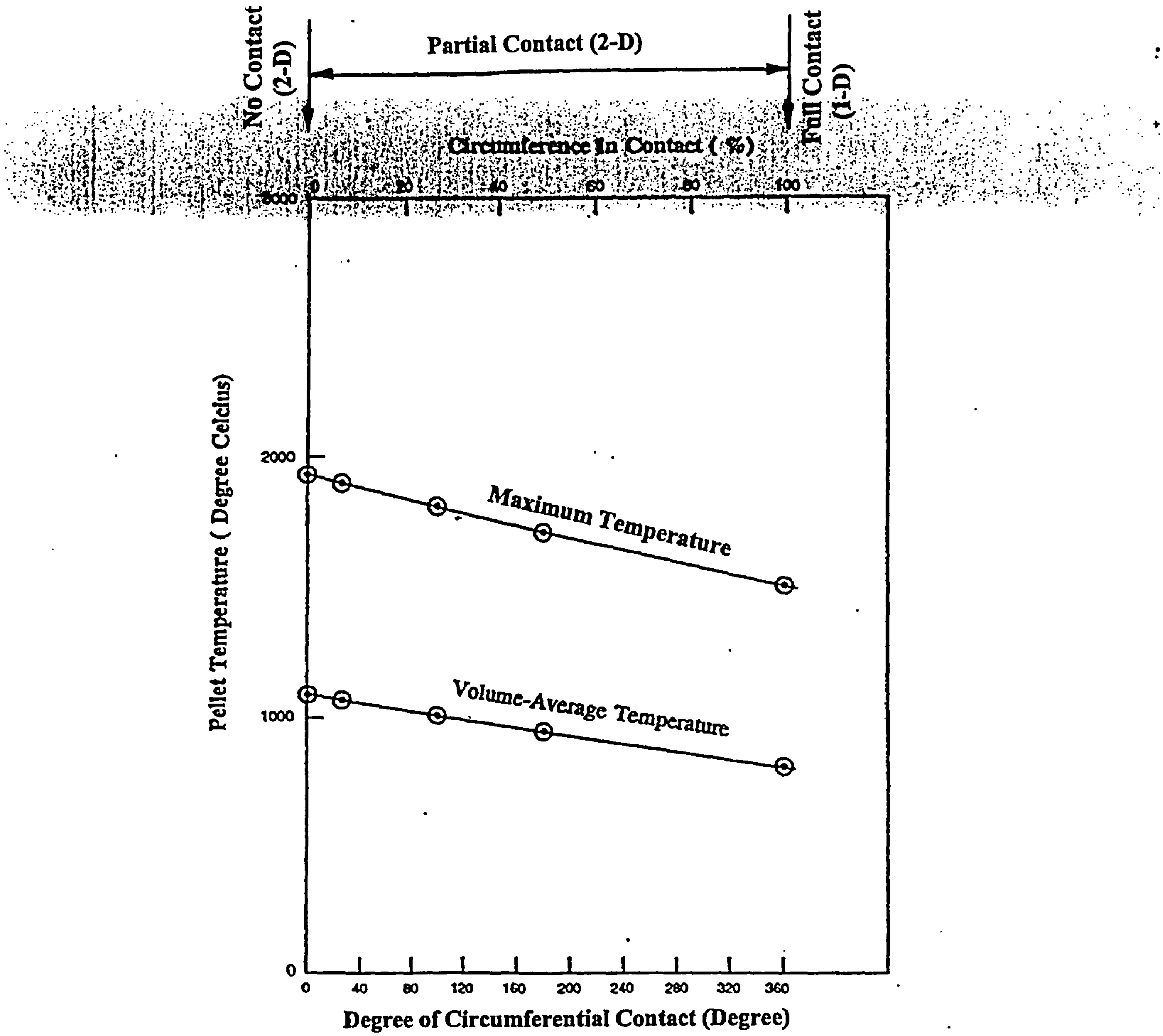


Figure 4: Pellet Temperatures for Various Levels of Contact

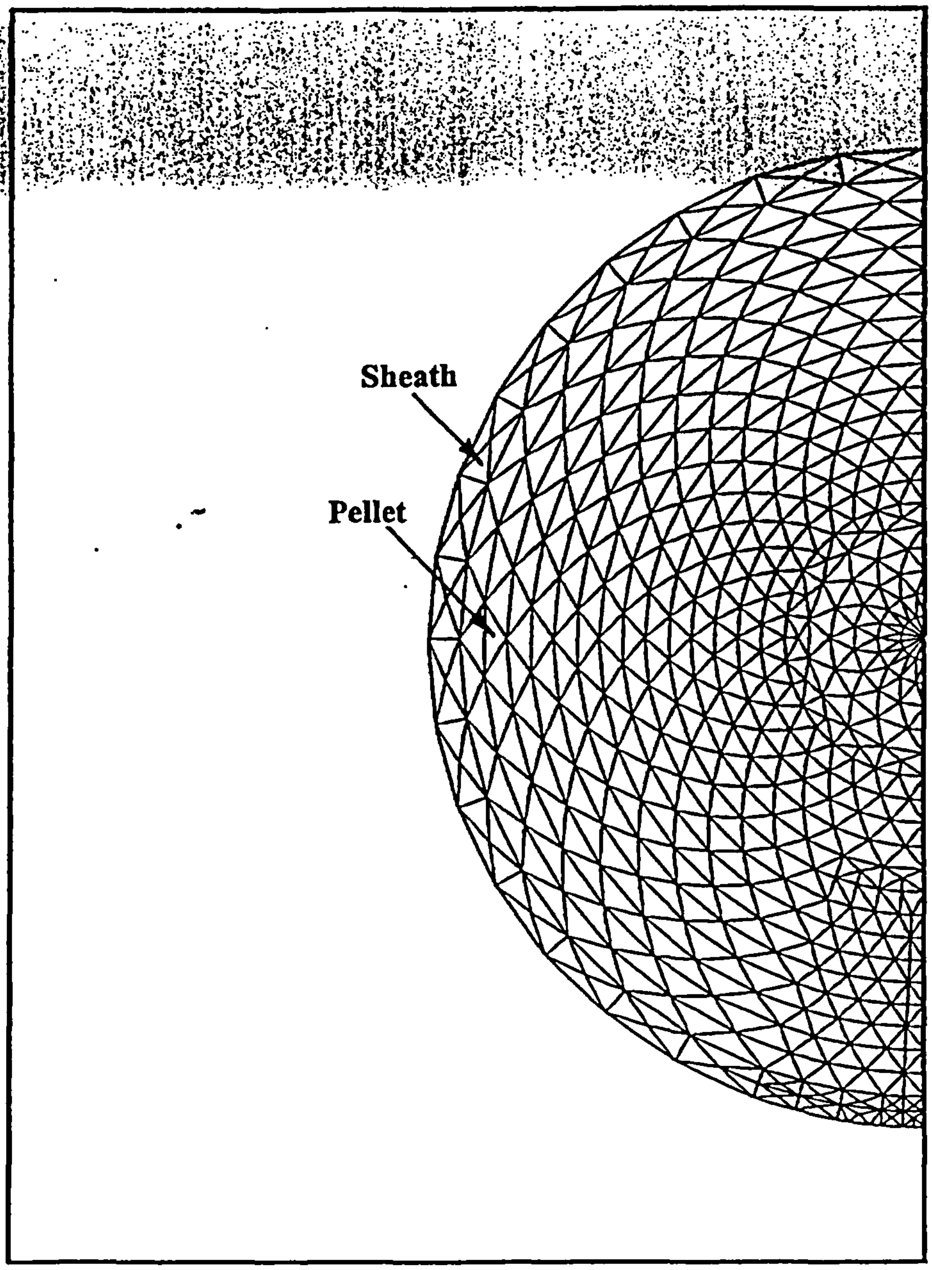
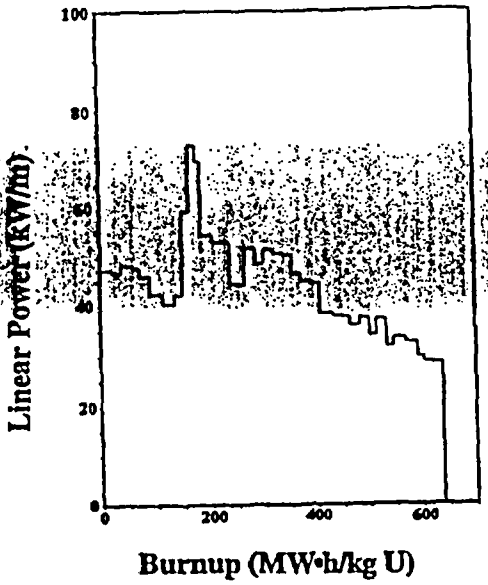
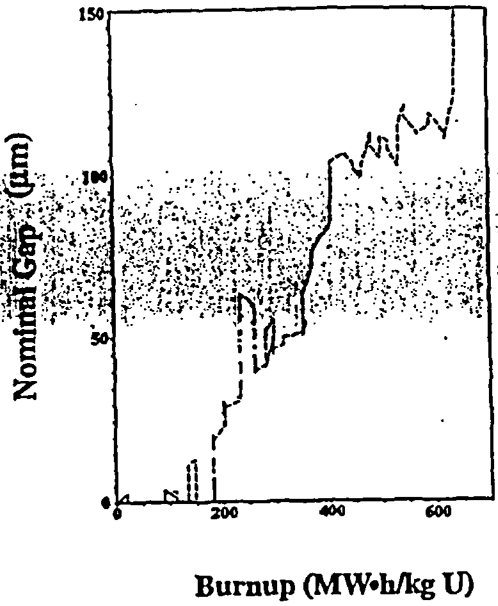


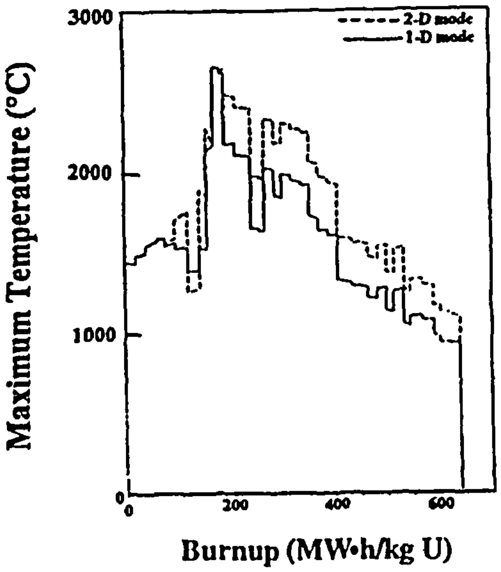
Figure 5: Finite-element Mesh for Two-Dimensional Heat Transfer



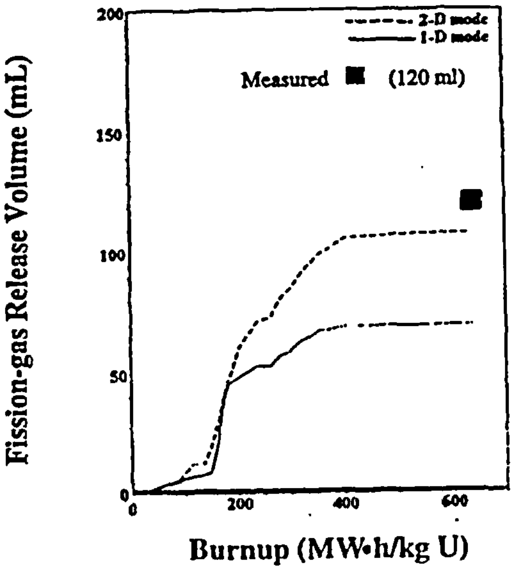
(a) Power History



(b) Nominal Gap



(c) Maximum Temperature



(d) Fission-gas Release

Figure 6: Illustrative Effects of Two-dimensional Heat Transfer

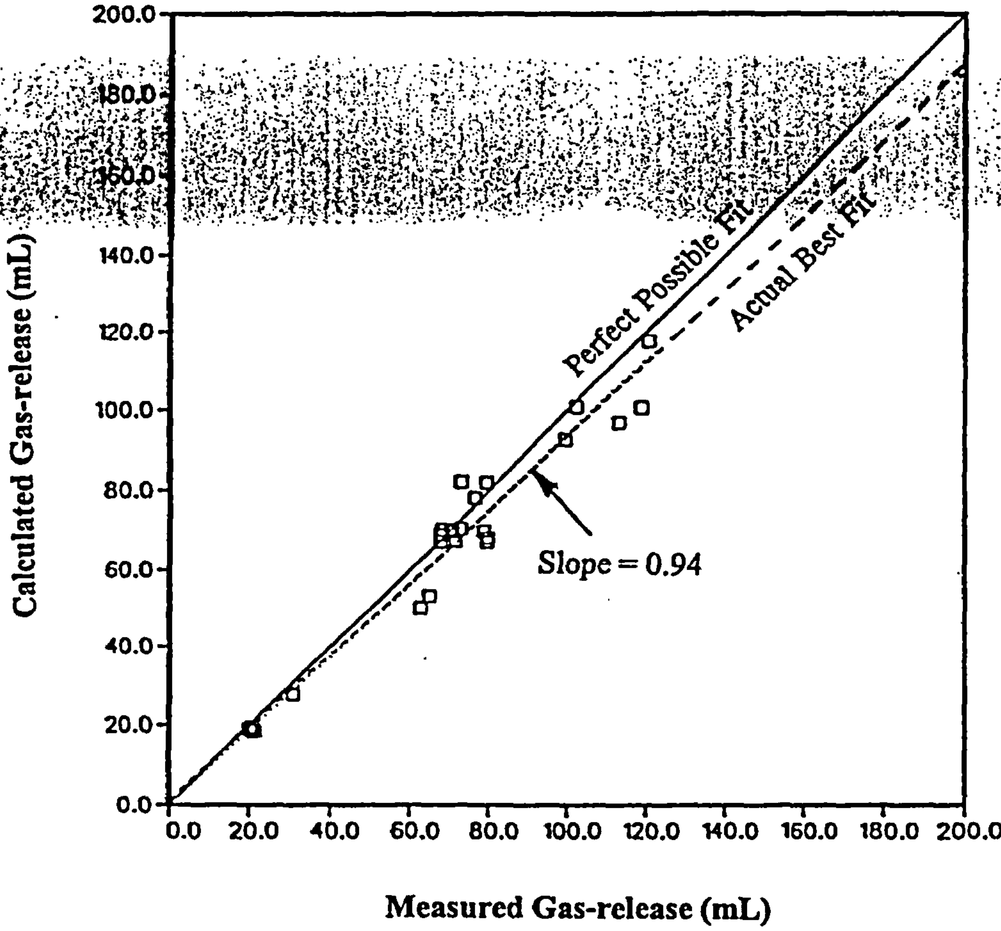


Figure 7: Fission-gas Release: Measurements vs. Calculations

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