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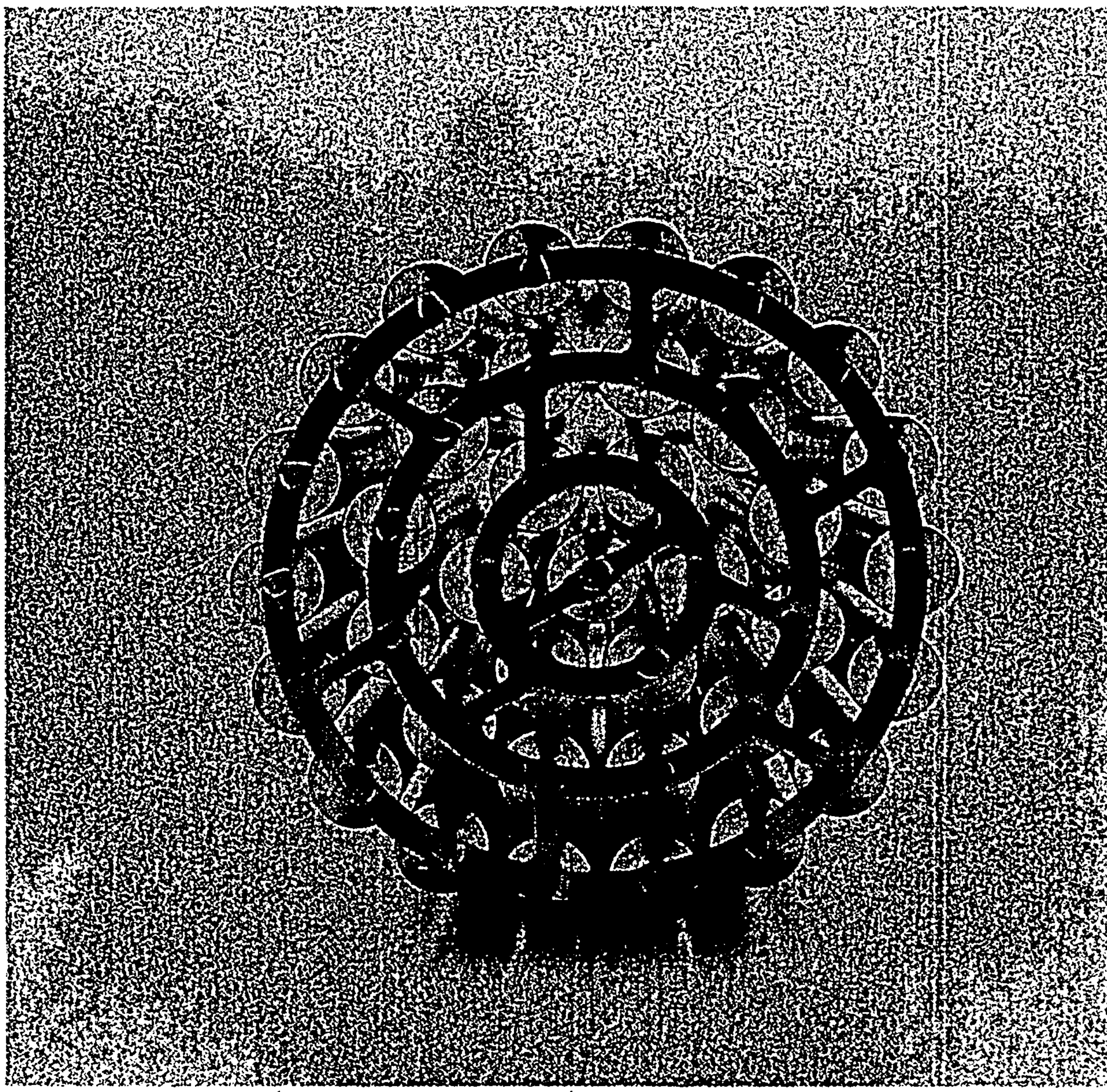
Evolution of the ELESTRES Code for Applications to Extended Burnups



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Evolution of the ELESTRES Code for Applications to Extended Burnups

By M. Tayal, A. Ranger,
N. Singhal, R. Mak

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EVOLUTION OF THE ELESTRES CODE FOR APPLICATIONS TO EXTENDED BURNUPS
AECL-9947

by
M. Tayal, A. Ranger, N. Singhal, R. Mak

SUMMARY

The computer code ELESTRES is frequently used at Atomic Energy of Canada Limited to assess the integrity of CANDU fuel under normal operating conditions. The code also provides initial conditions for evaluating fuel behaviour during high—temperature transients. This paper describes recent improvements in the code in the areas of pellet expansion and of fission gas release. Both of these are very important considerations in ensuring fuel integrity at extended burnups. Firstly, in calculations of pellet expansion, the code now accounts for the effect of thermal stresses on the volume of gas bubbles at the boundaries of UO_2 grains. This has a major influence on the expansion of the pellet during power-ramps. Secondly, comparisons with data showed that the previous fission gas package significantly underpredicted the fission gas release at high burnups. This package has now been improved via modifications to the following modules: distance between neighbouring bubbles on grain boundaries; diffusivity; and thermal conductivity. The predictions of the revised version of the code show reasonable agreement with measurements of ridge strains and of fission gas release. An illustrative example demonstrates that the code can be used to identify a fuel design that would (a) reduce the sheath stresses at circumferential ridges by a factor of 2-10, and (b) keep the gas pressure at very high burnups to below the coolant pressure.

AMÉLIORATION DU PROGRAMME DE CALCUL ELESTRES POUR APPLICATION AUX COMBUSTIONS MASSIQUES SUPÉRIEURES
EACL-9947

par
M. Tayal, A. Ranger, N. Sighal, R. Mak

RÉSUMÉ

Á Énergie atomique du Canada limitée, on utilise fréquemment le programme de calcul ELESTRES pour évaluer l'intéégreité du combustible CANDU dans des conditions d'exploitation normales. Le programme donne également les conditions initiales permettant d'évaluer le comportement du combustible durant les transitoires de température. Cette communication décrit les récentes ameliorations apportées au programme en ce qui conçerne le gonflement des postilles de conbustible et le relâchement des gaz de fission. Ces deux aspects sont très importants si l'on veut assurer l'intégrité du combustible á des combustions massiques supérieures. Premièrement, dans les calculs de gonflement des pastilles, le programme prend maintenant en considération l'effet des contraintes thermiques sur le volume des bulles de gaz aux joints des grains d'UO_2. Cet effet influe fortement sur le gonflement des pastilles pendant les rampes de puissance. Deuxièmement, la comparaison avec les données d'expérience montre que le progiciel de calcul des gaz de fission précedént avait sous-estimé considérablement la libération de gaz de fission aux combustions massiques supérieures. On a amélioré ce progiciel en apportant certaines modifications aux modules suivants: la distance entre des bulles voisines aux joints de grains, la diffusivité et la conductivité thermique. Les prévisions données par la nouvelle version du programme concordent assex bien avec les mesures de déformation de l'arête circonférentielle et de la libération des gaz de fission. On démontre, à l'aide d'un example, que le programme peut servir à déterminer un type de combustible qui permettrait de (a) réduire par un facteur 2-10 les contraintes présentes dans la gaine à l'endroit des arêtes et (b) maintenir la pression des gaz à une valeur inférieure à celle du caloporteur à des combustions massiques très élevées.

Atomic Energy of Canada Limited
Énergie atomique du Canada limitée

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EVOLUTION OF THE ELESTRES CODE FOR APPLICATIONS TO EXTENDED BURNUPS

1. INTRODUCTION

The performance of CANDU* fuel has been excellent to date: Over 600,000 fuel bundles have been irradiated in the current generation of CANDU reactors, and fuel bundle integrity is well over 99.8% [1].

Planned evolutions of the CANDU reactor include the 450 MWe CANDU-3 design, the 900 MWe CANDU design, the high-burnup version of the CANDU-6 design, and increased capabilities for load following. These are expected to place increased demands on the 37-element CANDU fuel, such as a combination of: peak element ratings of 60 kW/m; element burnups of 700-800 MW.h/kgU; power-ramps at high burnups; multiple power-ramps; and in-reactor residence times of 800-900 hot-coolant days. Experimental and analytical programs are underway in Canada to ensure fuel integrity under these conditions, including development of an advanced 43-element bundle called CANFLEX. Previous assessments have indicated [2,3] that under these conditions, the two most important considerations regarding the integrity of CANDU fuel under normal operating conditions are: Environmentally-Assisted Cracking (EAC) of the sheath; and Fission Gas Pressure. More detailed descriptions are available from references [2,3].

The computer code ELESTRES [4] is frequently used at Atomic Energy of Canada Limited to calculate the following parameters that have a major impact on the preceding defect mechanisms: temperatures; fission gas release/pressure; and pellet expansion at the midplane and at the endplane. Figure 1 illustrates the terms used in this paper.

The details of the code have been described previously [4]. The objective of this paper is to describe two recent enhancements of the ELESTRES code: improved calculations of fission gas release; and the effect of thermal stresses on the volume of gas bubbles at the boundaries of UO_2 grains.

This paper first provides background information on the mechanisms that lead to gas release, to EAC, and to fuel failures. Then we discuss the features of ELESTRES that relate to the above mechanisms. A detailed description is then given of the two recent improvements in ELESTRES noted earlier. Some predictions of the code are compared to experimental data. We also give an illustrative example that demonstrates the use of the code to improve the integrity of CANDU fuel at extended burnups. Finally, the long-range plan for further evolution of the code is outlined.

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* CANDU: Canada Deuterium Uranium

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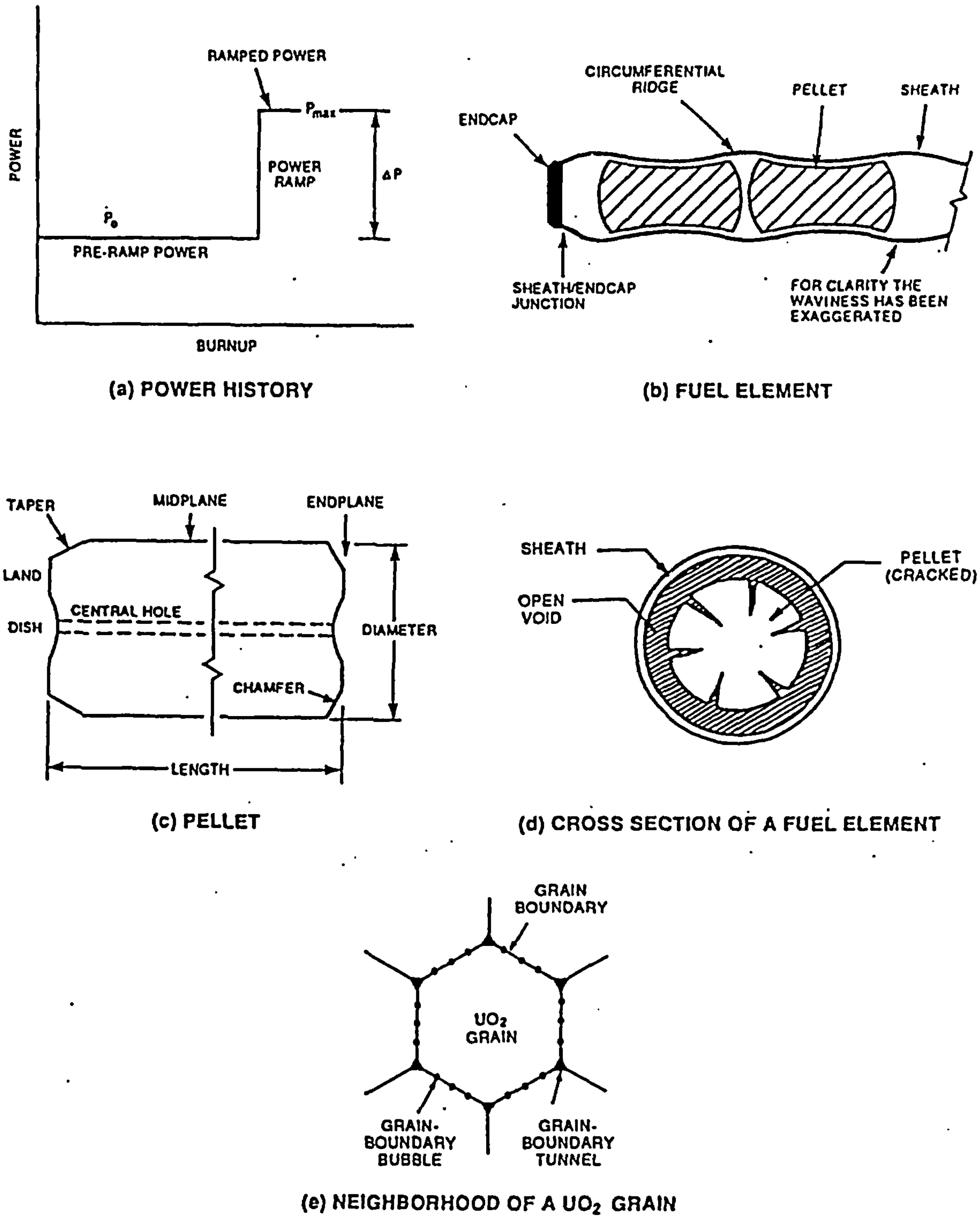

(a) POWER HISTORY

(b) FUEL ELEMENT

(c) PELLET

(d) CROSS SECTION OF A FUEL ELEMENT

(e) NEIGHBORHOOD OF A UO_2 GRAIN

FIGURE 1 DEFINITIONS OF TERMS

2. BACKGROUND

The most important factor affecting fuel integrity at high and at moderate burnups, is environmentally-assisted cracking (EAC) of the sheath [1,3]. This occurs when the irradiation-embrittled sheath experiences high tensile stresses, generally due to pellet expansion, in the presence of a corrosive internal environment provided by fission products. It may be aggravated by hydrides in the sheath, which can provide sites for crack initiation. As noted earlier, integrity of CANDU fuel has been excellent to date. In the few failures that have occurred, EAC has been a very dominant failure mechanism, accounting for a few hundred defects in over 600,000 bundles irradiated [1]. Other significant causes of fuel defects are fretting and manufacturing flaws [1].

The other factor influencing fuel integrity is fission gas pressure. During irradiation, several stable isotopes of the gases krypton and xenon are produced steadily, at rates that vary with operating power. While most of the fission products stay within the UO_2 matrix, some fraction does migrate to the open space between the pellets and the sheath, giving rise to gas pressure in the element. Gas pressure above the coolant pressure (~10 MPa) gives primary tensile stresses in the sheath, causing redistribution of zirconium hydrides. Further, the higher gas release at extended burnups also increases the concentration of fission products at the sheath surface. The combined effect can reduce sheath integrity. In CANDU reactor operation to date, gas overpressure due to high burnup may have contributed to the observed failure of zero to three fuel bundles out of the 600,000 irradiated [2,3]. In experimental reactors, two bundles have failed due to gas overpressure, out of the ~70 bundles tested to high burnups. Both the failed experimental bundles contained thoria pellets [3]. A conservative approach would be to keep the gas pressure below the coolant pressure.

3. THE ELESTRES CODE

The fuel performance code ELESTRES [4] predicts the behaviour of a CANDU fuel element for a given power history under normal operating conditions. It contains one- dimensional models of heat generation, temperature distribution, and fission gas release. A two-dimensional axisymmetric stress analysis of the fuel pellet is used in conjunction with a one-dimensional analysis for the sheath to compute the strains in the pellet and in the sheath. The major results from ELESTRES include: temperatures; fission gas release/ pressure; and two-dimensional axisymmetric deformation of the pellet. An estimate of the activity of radioactive isotopes in the free voidage is also provided. The code also generates the initial conditions needed for estimating fuel behaviour during high-temperature-transients.

ELESTRES was developed by combining two programs: ELESIM [5], a one-dimensional fuel performance code; and SAFE, a two-dimensional axisymmetric finite element stress analysis code. ELESTRES is thus an extension/replacement of the ELESIM code, which accounts for 30-40% of the ELESTRES coding. The balance (60-70%) is primarily SAFE.

The constituent submodels are physically (rather than empirically) based and include such phenomena as pellet-to-sheath heat transfer via solid-solid, gas, and radiative components; temperature- dependent densification of the pellet; temperature- and porosity-dependence of pellet thermal conductivity; temperature-dependent grain growth, both equiaxed and columnar; burnup-dependent neutron flux depression; burnup- and microstructure-dependent fission product gas release and fission product swelling; temperature- and burnup-dependent distribution of radioactive isotopes in the pellet/sheath gap; and stress-, dose-, and temperature-dependent constitutive equations for the sheath, including creep.

ELESTRES shares these features with ELESIM.

The two-dimensional finite element model for pellet deformation includes: thermal, elastic, plastic and creep strains; pellet cracking; interpellet interaction; pellet/sheath interaction; and rapid drop of UO_2 yield strength with temperature. The pertinent two-dimensional equations are solved simultaneously to account for multiaxial equilibrium, compatibility, and flow rule. These features are provided by the SAFE portion of ELESTRES.

The interactions and the feedbacks among the various parameters noted above are considered in the code in a dynamic manner throughout the irradiation history. The code uses the variable stiffness method for plasticity calculations and combines it with a modified Runge-Kutta integration scheme for rapid convergence and accuracy. For typical irradiation histories involving peak powers of 60 kW/m and discharge burnups of 200-700 MW.h/kgU, the code requires 10-30 s of CPU (Central Processing Unit) time on the CDC/CYBER-990 computer. Typical turnaround time is 5-10 minutes.

4. IMPROVEMENTS IN THE STRAIN CALCULATIONS

The expansion of the end of the pellet is the driving force behind the failure of fuel sheaths via EAC. An improvement has recently been made to a component of that calculation. It relates to the diametral swelling of grain-boundary bubbles. The model considers the influences of the following parameters: the number (mass) of atoms of gas at the grain boundary; the density (number) of the bubbles per unit surface area of the grain; the local temperature; the surface tension of the bubbles; and the hydrostatic stress acting on the bubbles which is assumed in the code to be equal to the local radial stress. In the previous version of the code, the calculation of the local radial stress on the bubble was based on the interfacial pressure between the pellet and the sheath and on the radial location of the bubble; the gas pressure was used if the interfacial pressure was very small. The thermal stresses were previously ignored in this calculation.

It was recently noted that during a change in power, the transient thermal stresses in the pellet can sometimes be an order of magnitude higher than the interfacial stresses. As an illustrative example, consider the following hypothetical scenario: The power is held constant until a moderate burnup; the initial thermal stresses in the pellet have relaxed completely; and the cracks have healed. A small ramp in power then increases the temperature gradient in the pellet by 110°C. Pellet expansion causes the pellet/sheath interfacial pressure to temporarily reach 10 MPa after which it relaxes.

Figure 2 shows the radial stresses [6] in an uncracked pellet for the above conditions. It is clear that near the centre of the pellet the local thermal stresses are far more important than the stresses due to interfacial pressure. For this reason we have now added in ELESTRES a calculation that considers the influence of thermal stresses on bubble radius. This is expected to provide in ELESTRES a more accurate prediction of the dynamics of bubble growth, resulting in improved predictions of the dynamics of sheath strains.

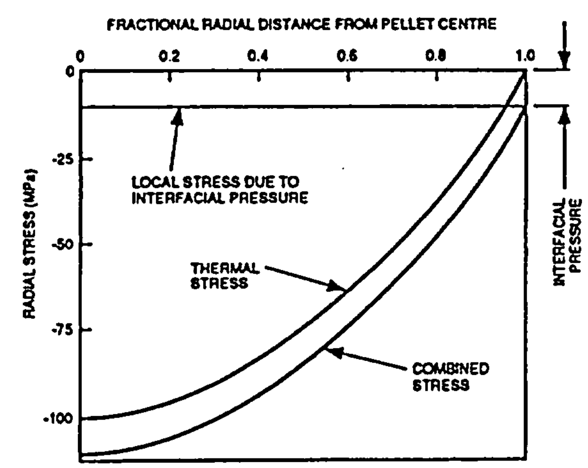

FIGURE 2 ELASTIC RADIAL STRESSES IN AN AXISYMMETRIC CYLINDER

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The following calculation procedure is used: At the beginning of the power-increase, the local values of stresses in the pellet are available from the finite element package [4]. They include the cumulative effects of, among others, elasticity, plasticity, creep, and cracking, up to that point in time.

To this, we add the incremental stresses due to the ramp. Assuming a parabolic temperature profile, the temperature increment for the current time-step is used to calculate the incremental elastic thermal stresses. The following equations [6] are used:

$$\sigma_r = \alpha E(\Delta T)\,[1 - (r^2/R^2)] / [4(1-\nu)];$$
$$\sigma_\theta = \alpha E(\Delta T)\,[1 - (3r^2/R^2)] / [4(1-\nu)];$$
$$\sigma_z = \alpha E(\Delta T)\,[1 - (2r^2/R^2)] / [2(1-\nu)].$$

Here, 'σ' represents the stress. 'r,θ,z' are polar co-ordinates. 'α' represents the coefficient of thermal expansion. 'E' is the Young's modulus. 'ΔT' represents the incremental temperature-gradient during the time-step.

Next, we add to the above stresses the effect of the interfacial pressure/gas pressure as a function of radial distance from the centre of the pellet. The fraction of this incremental stress which brings the stress state to yield (or the entire incremental stress if yield is not reached) is then added to the current stress state. This value of local stress now approximates the effects of thermal expansion, elasticity, plasticity, creep, cracking, interfacial pressure, and gas pressure, during the entire irradiation history including the current time-step. This stress is used to calculate the radius of the gas bubbles, which in turn is used to estimate the fission product swelling [5].

This estimate of fission product swelling is then fed to the finite element package to arrive at a more comprehensive final calculation of the stress/strain distribution in the pellet.

5. IMPROVEMENTS IN THE FISSION GAS RELEASE CALCULATIONS

As noted earlier, one consideration in fuel integrity is the additional gas release at extended burnups. It has been noted that the fission gas package, NOTPAT [5], of the ELESTRES code underpredicts gas release by about a factor of two at extended burnups. Accelerated gas release at extended burnups has also been noted in other countries [7]. Initial experiments and reviews have identified several factors that may have caused this [7-11]. More comprehensive experiments are in progress in Canada and around the world to quantify these parameters in more detail [7,11]. The detailed results are expected in a few years, at which time we intend to update ELESTRES as appropriate. To enable initial design studies in the meantime, optional ad-hoc modifications have been incorporated in the ELESTRES code, so that measured and predicted releases are, on average, now equivalent. The modifications are based on the information available now.

The NOTPAT model for gas release has been described previously [5]. To summarize: Irradiation generates fission products within the interior of UO_2 grains. Some of the fission products are gaseous. The gas diffuses through the UO_2 grains to the grain-boundaries, due to differences in local concentrations of the gas. The diffused gas amasses in bubbles at the grain boundaries. The bubbles grow as more gas reaches the grain boundary, either by diffusion or by grain-boundary sweeping due to grain growth. When the bubbles are big enough to touch each other (i.e., to interlink), any excess gas in the bubbles is assumed to be available for release to the grain-boundary tunnels. From the tunnels, it is released to the open void at the next change in reactor power. If the UO_2 temperature exceeds the UO_2 melting point, then the gas contained within the grains and within the grain-boundaries of the affected areas, is released directly to the open void.

The parameters which have the most influence on the above processes include: local heat generation rate as a function of distance along the pellet radius and of burnup; thermal conductivity of UO_2; heat transfer coefficient between the pellet and the sheath; pellet temperatures; diffusivity; rate of grain growth; efficiency of grain boundary sweep; density of intergranular bubbles; and fraction of grain surface covered by intergranular bubbles. Of these, we focused on the roles of the following three parameters, because experimental evidence suggests [8-10] their dependence on burnup: (a) bubble distance; (b) diffusivity; and (c) thermal conductivity of UO_2.

The approach consisted of parametric studies that compared predictions to measurements of gas release. The level of modification in each parameter was kept consistent with the available experimental data.

The data-base consisted of 98 irradiations that had been previously qualified for such use. These irradiations had a maximum linear heat generation rate of 110 kW/m, maximum burnup of 362 MW.h/kgU, and maximum gas release of 44%. Percent gas release refers to the gas released to the open void as a percent of the gas produced during the irradiation.

As noted earlier, a conservative approach in the design of CANDU fuel elements is to keep the gas pressure below the coolant pressure. For this reason, the above data-base was limited to irradiations in which pellet/sheath contact was maintained during the irradiation.

5.1 BUBBLE DISTANCE

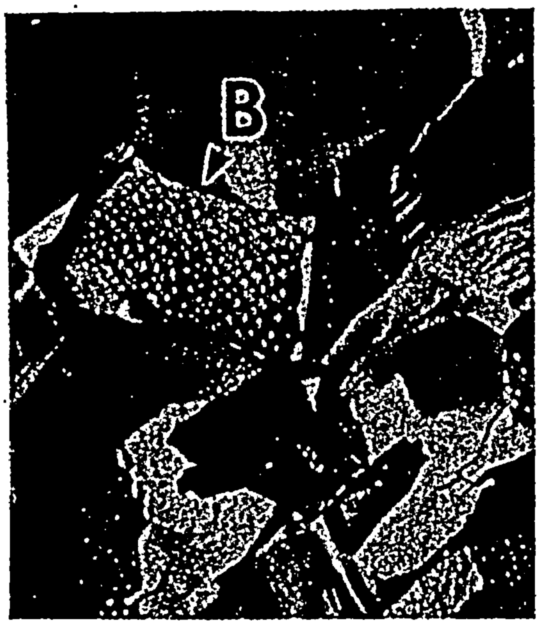
The NOTPAT model assumes that the centres of neighbouring intergranular bubbles are separated by 0.46 μm [5]. This number is considered in NOTPAT to be a constant. The basis for the assumption came from post-irradiation examinations of 6-10 fuel bundles, all irradiated in the Pickering reactor to very similar power histories: Burnups of 190-200 MW.h/kg, at linear heat generation rates of 44-50 kW/m.

Much more data are now available, and show a wide range of distances between the centres of neighbouring bubbles. For example, Figure 3 shows micrographs of fuel irradiated in Canadian reactors [12], in which the bubbles are up to 10 μm apart – that is, the bubble distance can be significantly higher than the previous number. Bubble distance of 5 μm has been reported by Turnbull [13], and of ~10 μm by Kleykamp [9]. Perhaps the details of the irradiation conditions and of fuel design/manufacture can change the bubble distance due to factors like: the effect of temperature and of temperature-gradient on the critical size of intergranular bubbles; and the collisional coalescence of intergranular bubbles [14].

Recently, Suk et. al showed [14] that the fission gas predictions can be improved by treating the bubble distance as changing during the irradiation. They used a sophisticated model that included detailed analytical treatments of, among others, the effect of thermal gradient on critical bubble size; and bubble size distribution from random coalescence. At present, ELESTRES uses a much simpler approach to account for the variable spacing of bubbles. The code allows the bubble distance to vary in the range 0.46 to 0.8 μm depending on burnup. This range is well within the experimental data noted earlier.

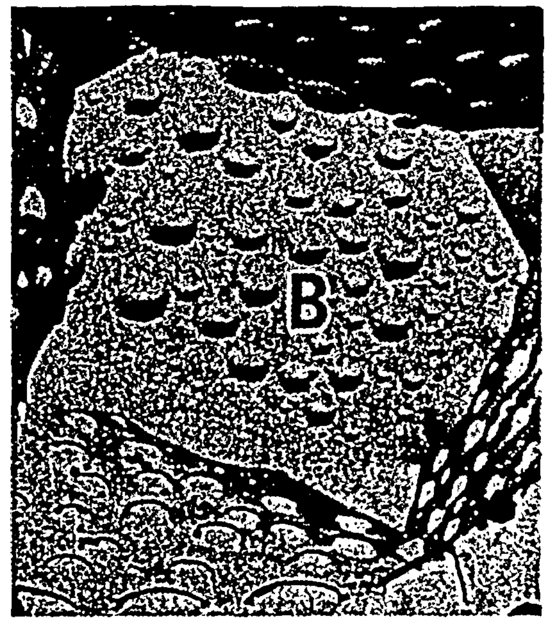
5.2 DIFFUSIVITY

The data on diffusivity show large scatter – typically an order of magnitude, see References [5] and [15]. For this reason, Notley and Hastings felt justified in multiplying the experimental 'mean' values of diffusivity by a factor of 3, in order to improve the match between the experimental measurements of gas release and the predictions of NOTPAT.



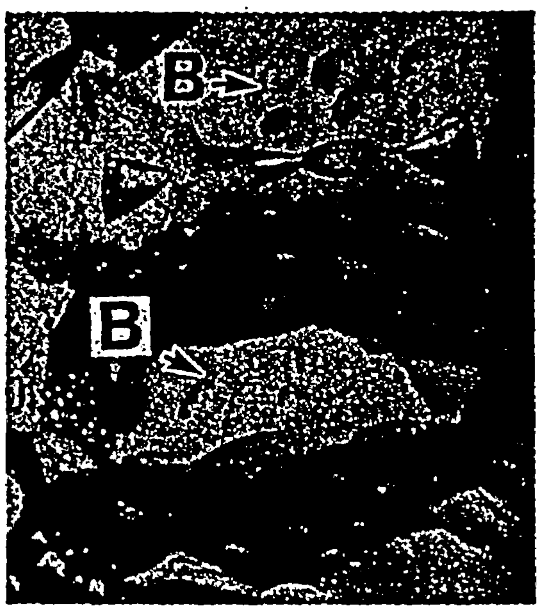
10 µm

BUBBLE DISTANCE : 0.3 TO 0.5 µm



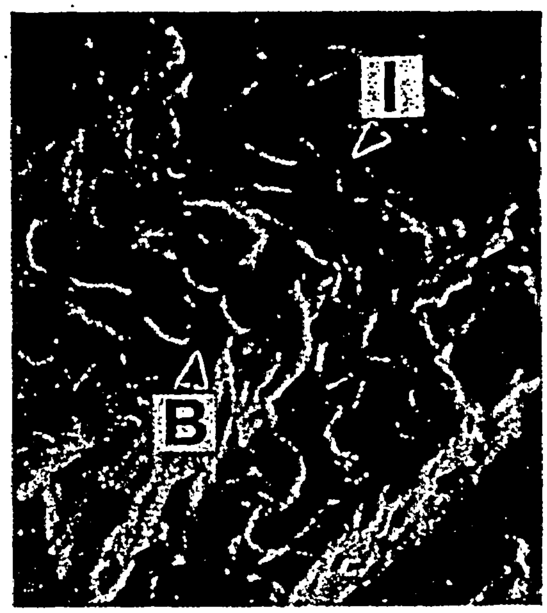
2 µm

BUBBLE DISTANCE : 0.4 TO 0.6 µm



10 µm

BUBBLE DISTANCE : 1 TO 2 µm



50 µm

BUBBLE DISTANCE : 10 TO 12 µm

NOTES: B – FISSION GAS BUBBLES ON GRAIN BOUNDARY
I – INTERLINKAGE OF BUBBLES
(PHOTOS COURTESY OF I. HASTINGS, AECL)

FIGURE 3 GRAIN BOUNDARY BUBBLES

The literature suggests [10,16-18] that irradiation can sometimes decrease and sometimes increase the diffusivity of Xe in UO_2. Matzke reports [16] that depending on the local temperature in the range 1400-1550°C, the diffusivity of gas in UO_2 after 2.0 to 2.6 x 10^{17} fissions/cm^3 is 3 to 20 times *lower* than that measured after 5 to 8 x 10^{14} fission/cm^3. MacEwan and Stevens also measured [17] decreases in diffusivity with increasing irradiation exposure. These results indicate that at the above temperatures, the gas atoms are trapped by irradiation – induced defects, resulting in retarded diffusion.

The highly-rated CANDU fuel operates at higher temperatures. At 1800°C, Frigerio's data [15] did not show any significant reduction in diffusivity, suggesting that perhaps the above effect is less important at higher temperatures.

On the other hand, it has been suggested that irradiation can *increase* the diffusivity via chemical effects like: increased concentration of soluble fission products; changing oxygen potential of the pellet; and changing O/U ratio of the pellet [11].

With irradiation (fission), some of the original U in UO_2 gets converted to lighter atoms, giving an 'excess' of oxygen, i.e., UO_{2+x}. But some of the lighter fission fragments use oxygen. The stoichiometry is further influenced by the stability of the lighter oxides at the operating temperatures. The complicated dynamics of the stoichiometry in a fuel element can best be known by a detailed chemical model; none are available at present. At this stage, it is therefore difficult to predict [18] the stoichiometry within an operating fuel element.

Recently, Walker and Mogensen measured [18] the stoichiometry of two irradiated fuel elements. One element showed a build-up of oxygen at the centre of the pellet; the O:U ratio there was 2.2. Une et. al have noted [10] that comparatively small changes in the O:U ratio of the pellet, $UO_2 \rightarrow UO_{2.001}$, increase the diffusivity by a factor of 3. Adding small amounts of Nb_2O_5 and TiO_2 increased the diffusivity by factors of 50 and 7 respectively [10]. To account for the above possible effects of irradiation, ELESTRES multiplies by two, the values of diffusivity contained in the NOTPAT routine. This variation is well within the ranges of Une's data noted above.

5.3 THERMAL CONDUCTIVITY

Many of the correlations suggested in the open literature for the thermal conductivity of UO_2 account for its dependence on temperature and on density. ELESTRES uses the MATPRO-11 correlation [19], which is based on measurements of thermal conductivity in unirradiated UO_2. For CANDU fuel, the correlation gives thermal conductivities of 2-5 W/(m.K). At a 95% confidence level, this correlation has an uncertainty of ±0.7 W/(m.K). This number is consistent with the scatter/uncertainties cited by Namekawa et. al [8] and by Beauvy et. al [20] in their data.

In the previous version of ELESTRES, the effect of irradiation on pellet thermal conductivity was partially incorporated via its effect on density and on grain boundary swelling. Irradiation damage at low temperature was simulated by assuming the thermal conductivity to be constant below 454°C [5].

At the higher temperatures too, irradiation can change the thermal conductivity of UO_2 [8, 9]. The possible reasons include the following influences:

- New isotopes and elements are produced during the irradiation;
- Fission gas bubbles are also produced within the grains of UO_2;
- Macro and micro-cracks are created in the pellet; and
- The stoichiometry of the pellet changes.

Kleykamp reports [9] that at 10% burnup the solid solutions formed during the irradiation decrease the thermal conductivity by 19-28% at 700-1700°C, i.e., by about 0.4-1 W/(m.K). He offers the following explanation: "The thermal conductivity of oxide fuels changes during irradiation. It deteriorates due to the formation of a solid solution of the fuel with oxides of zirconium, strontium, the rare earths and other fission products in lower concentrations and is not counterbalanced by the metallic and oxide fission product inclusions precipitated within the fuel and in the grain boundaries". The experiments of Namekawa et. al show similar trends: Irradiation to 700-800 MW.h/kg decreases the conductivity of $(U, Pu)O_2$ pellets by 0.3-0.5 W/(m.K) depending on temperature in the range 600-1400°C.

To account for the observed effects of irradiation noted above, the current version of ELESTRES decreases the thermal conductivity of the pellet by 0-0.7 W/(m.K) depending on the burnup and on the local temperature. This level of modification is consistent with the trends in the data of Kleykamp and of Namekawa et. al combined with the experimental uncertainties noted above.

6. COMPARISONS WITH DATA

Previous reports [4,21] have documented a number of validations of ELESTRES. Some new comparisons are reported here.

6.1 SHEATH STRAIN

The predictions of ELESTRES were checked against in-reactor measurements of ridge strains [22], obtained on-power during irradiation ACH. This fuel experienced many power cycles between 30 and 60 kW/m. The sheath diameter was 14.8 mm (close to Pickering-size fuel) and the initial UO_2 density was 10.82 g/cc. Figure 4 shows that the predictions are in good agreement with measurements.

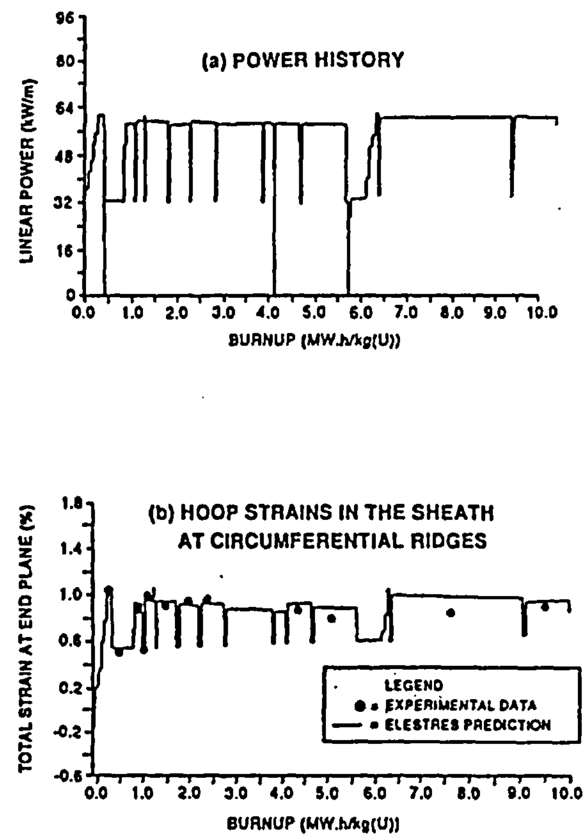


FIGURE 4 COMPARISON OF HOOP STRAINS : ELESTRES VS IRRADIATION ACH

6.2 FISSION GAS RELEASE

Figure 5 summarizes the predictions of the code against measurements of gas release from the 98 irradiations noted earlier. The predictions have a mean deviation of 1.3 percentage points from the measurements, with a standard deviation of 5.8 percentage points. Figure 6 shows the slope of the correlation between the measurements and the predictions. A perfect fit would yield a slope of 1. Compared to the original version of NOTPAT, the current version of ELESTRES exhibits significantly reduced bias with burnup, see Figure 6.

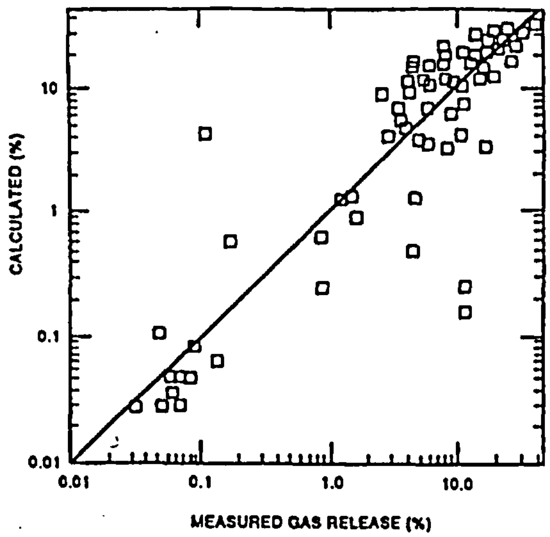


FIGURE 5 COMPARISON OF FISSION GAS RELEASE

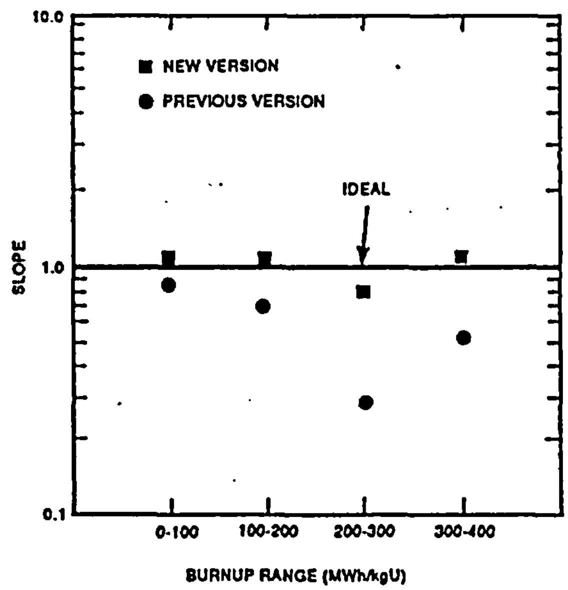


FIGURE 6 GAS RELEASE : SLOPE BASED ON BURNUP GROUP

7. ILLUSTRATIVE APPLICATION

Since its introduction in 1977, ELESTRES has been used in a large number of studies involving design and assessment of CANDU fuel. Some have been described previously [4]. Here we give a brief summary of a recent application related to extended burnups.

Reviews have identified that some CANDU fuel has failed at extended burnups [2,3]. The most likely reason is EAC; in some of the failures the assistance from gas overpressure is also not ruled out at this time [2,3]. ELESTRES was recently used to help identify an improved fuel design that would reduce/eliminate the likelihood of similar fuel failures in future. We simulated about 200 combinations of element design parameters and of power-histories. ELESTRES was among the computer codes used.

At this stage, it appears that the following internal design offers a large advantage in fuel performance compared to the current reference design: shorter pellets; larger land width; bigger chamfers; lower density of UO_2; and graphite discs. The internal design near the sheath/endcap weld has also been improved, including larger clearances. For example, Figure 7 shows the hoop stress in the sheath at the ridge, for a power ramp of 18→40 kW/m at 346 MW.h/kgU. This ramp was experienced by bundle J64703C which failed recently via EAC in the Bruce reactor [2]. Figure 7 shows that the new features reduce the stresses significantly.

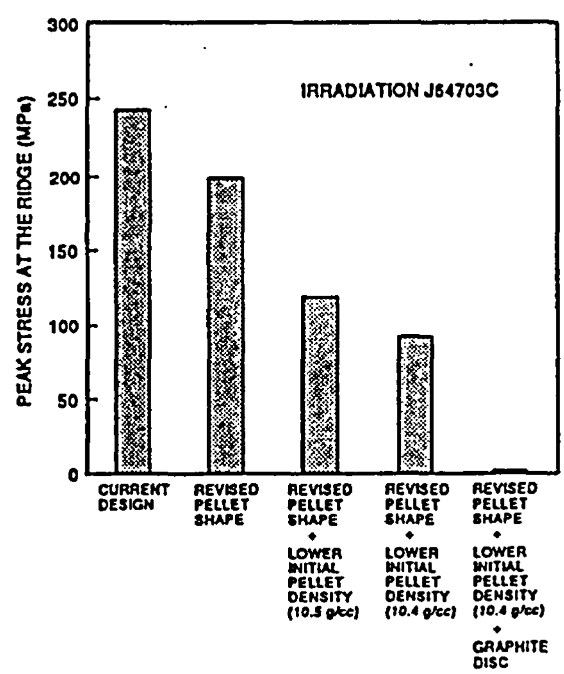


FIGURE 7 SHEATH HOOP STRESS AT THE RIDGE DURING A POWER-RAMP

Similarly, Figure 8 shows the predictions of gas pressure for an envelope power history with a peak rating of 58 kW/m and a discharge burnup of 720 MW.h/kgU. Under these conditions, the current reference design of the 37-element fuel would give internal gas pressure considerably higher than that of the coolant. Figure 8 shows that the revised design keeps the gas pressure below that of the coolant. This eliminates the risk of fuel failure via gas overpressure under normal operating conditions. A more detailed description is available from Reference [3].

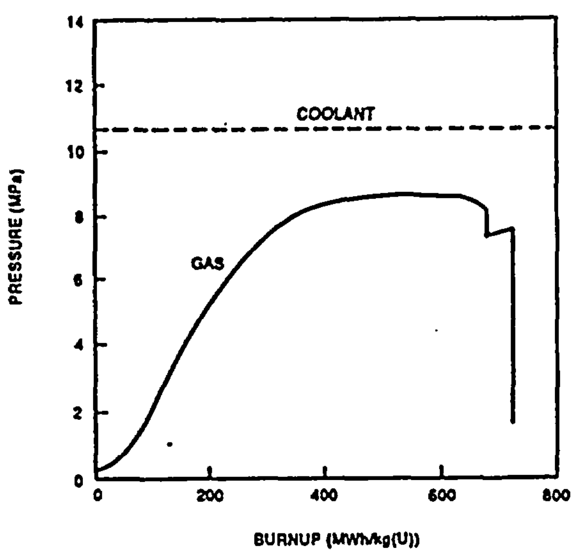


FIGURE 8 GAS PRESSURE IN AN ELEMENT CONTAINING SHORT PELLETS WITH BIG CHAMFERS

8. FURTHER EVOLUTION

Further evolution of ELESTRES is planned along the following lines:

8.1 IMPROVED CALCULATIONS OF TEMPERATURE

Experiments are in progress to further improve our understanding of the thermal conductivity of UO_2 as a function of irradiation, including the influence of fission products. The effect of pellet cracking has already been mentioned in several publications. Reviews of the pellet/sheath heat transfer coefficient are also planned. Under some conditions, the pellet temperatures can become multi-dimensional, for example: the large chamfers/tapers being considered for high-burnup fuel designs lead to multi-dimensional temperatures in the pellet. Ditto for graphite discs. Similarly, IRDMR data [22] show that low-power operation leads to a diametral gap between the pellet and the sheath. This leads to multi-dimensional pellet temperatures, which influence the sheath stresses/strains during a subsequent power-ramp. Multi-dimensional temperatures also occur temporarily during some accidents involving partial dryout, for example if the reactor runs for a short time at full nominal power with one pump tripped. We intend to review/assess the importance of the above and related subjects, and incorporate the results in future versions of the code.

8.2 MORE FUNDAMENTAL CALCULATIONS OF FISSION PRODUCT CONCENTRATION

Further data are being collected and verified in Canada and internationally, on fission product release and distribution at high-burnup, and on processes that influence them. As this data becomes available over the next few years, ELESTRES will be revised to reflect the new information.

8.3 IMPROVED CALCULATIONS OF SHEATH STRAINS AND STRESSES

We plan to account for some factors that are presently missing from the code, and refine others whose influences are considered in an approximate manner at present. The following are some of the important processes:

- Instantaneous and creep collapse of the sheath into the diametral and into the axial gaps among and between the pellets/sheath /endcaps;

- Relocation of the pellets; and
- Further refinements in the calculation of fission product swelling.

The above evolution is planned over the next few years and the results will be reported when available.

9. CONCLUSIONS

The ELESTRES code has recently been improved in the areas of pellet expansion and of fission gas release. The improvements in pellet expansion involve the influence of thermal stresses on the volume of gas bubble at grain boundaries. In the area of fission gas release, the modifications relate to calculations of the following parameters: bubble spacing; diffusivity; and thermal conductivity of UO_2. The predictions of the revised code show reasonable agreement with experimental data. Further evolution is planned to improve the confidence in the predictions of the code at extended burnups.

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