Recent Uses of the Finite Element Method in Design/Analysis of CANDU Fuel

Utilisations récentes de la méthode des éléments finis pour la conception et l'analyse du combustible CANDU

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Abstract

Finite element codes FEAST and ELESTRES have been used to show: that initial pellet density can have a significant effect on the probability of fuel defect near end cap welds; that sheath stresses/strains are highly multiaxial near circumferential ridges; and that the multiaxiality affects sheath integrity significantly. The finite element thermal code FEAT was used to redesign bearing pads to obtain lower temperature; this eliminated crevice corrosion. FEAT was also used to assess the influences of braze voids and of end flux peaking. These analyses involved complex geometries. By using finite elements, we could obtain accurate assessments economically and rapidly. Finite element codes are also being developed for bowing, diffusion, flow patterns, and stress corrosion cracking.

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Résumé

On a utilisé les codes d'éléments finis FEAST et ELESTRES pour démontrer: que la densité initiale des pastilles peut avoir une influence importante sur la probabilité de combustible défectueux près des soudures des chapeaux d'extrémité; que les contraintes des gaines sont de nature très multiaxiale près des saillies circonférentielles; et que cette nature multiaxiale influence l'intégrité de la gaine d'une façon importante. Le code d'éléments finis FEAT a servi à la nouvelle conception des patins pour obtenir une température plus basse. Cela a éliminé la corrosion de crevasses. FEAT a également servi à évaluer l'influence des vides de brasage et des pointes de flux finales. Ces analyses ont comporté des géométries complexes. En utilisant la méthode des éléments finis nous avons été capables d'obtenir des évaluations précises d'une façon économique et rapide. Des codes d'éléments finis sont également mis au point pour le courbement, la diffusion, les configurations d'écoulement et la fissuration de corrosion due aux contraintes.

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RECENT USES OF THE FINITE ELEMENT METHOD IN DESIGN/ANALYSIS OF CANDU FUEL

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ABSTRACT

Finite element codes FEAST and ELESTRES have been used to show: that initial pellet density can have a significant effect on the probability of fuel defect near end cap welds; that sheath stresses/strains are highly multiaxial near circumferential ridges; and that the multiaxiality affects sheath integrity significantly. The finite element thermal code FEAT was used to redesign bearing pads to obtain lower temperature; this eliminated crevice corrosion. FEAT was also used to assess the influences of braze voids and of end flux peaking. These analyses involved complex geometries. By using finite elements, we could obtain accurate assessments economically and rapidly. Finite element codes are also being developed for bowing, diffusion, flow patterns, and stress corrosion cracking.

INTRODUCTION

The finite element method is a numeric technique for solving differential equations. It is commonly used for a wide variety of engineering analyses in a number of industries like aircraft/aerospace, oil, electronics, shipbuilding, piping, and nuclear power. Many engineers consider it a proven and mature method, and have been using it as a standard design tool for a decade. The use of finite elements in the CANDU* fuel industry, although not extensive, is increasing rapidly.

Why use finite elements? Several numeric methods have evolved over the years for solving differential equations. The most familiar is the finite difference method. This method forms difference equations for an array of grid points, hence provides a pointwise approximation to the governing equations. This is adequate for many applications, but sometimes poses problems for irregular geometries and for unusual boundary conditions.

The finite element method divides the analyzed region not into grid points, but into smaller subregions called finite elements. Thus it provides a piecewise approximation to the governing equations. The individual finite elements can have a variety of shapes, and they can be assembled in many different combinations. Hence exceedingly complex shapes can be represented accurately. Also, since the solution is first formulated for individual elements, which are simple, complex boundary conditions can be accommodated. Further details are available from Ref. 1.

As an example of how the two preceding techniques differ, consider Figure 1. It represents, schematically, a hypothetical profile

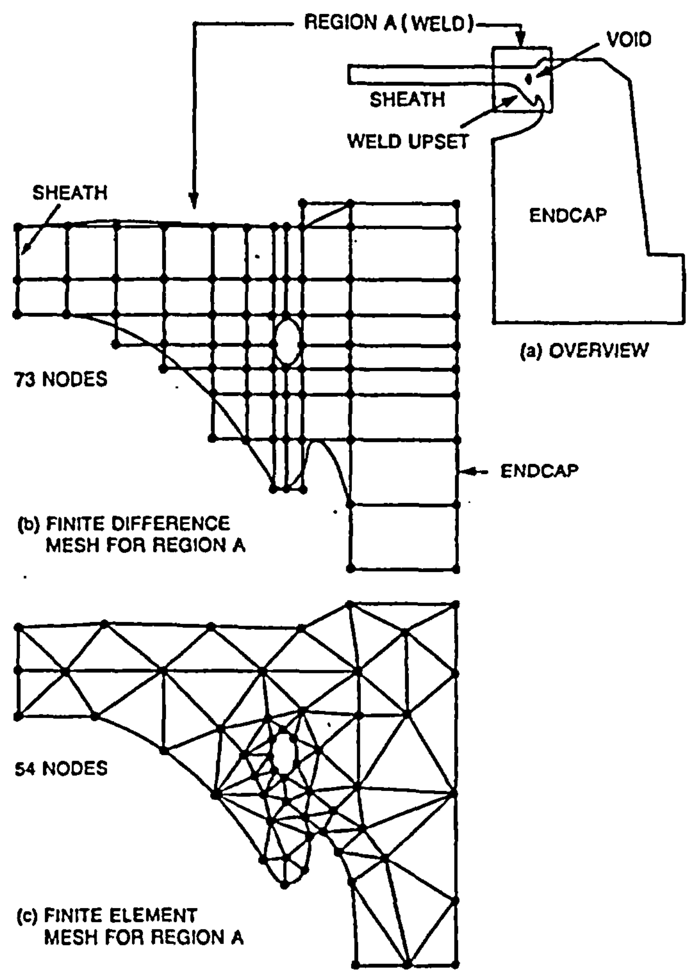

Figure 1 Finite difference and finite element idealizations of a hypothetical joint between the sheath and the endcap

* CANDU - CANada Deuterium Uranium - is a registered trademark of Atomic Energy of Canada Limited.

near an end cap weld. The figure shows finite difference and finite element idealizations near the end cap weld. A uniform finite difference mesh would reasonably cover the analysis region. But the curved boundaries must be approximated by a series of perpendicular grid lines. However, even simple, triangular, finite elements give a better approximation, and require fewer nodes.

As with many other numerical methods, finite element solutions are available in one, two or three dimensions. Setup costs can be reduced greatly by using pre-processors, including digitizers.

The purpose of this paper is to highlight some recent uses of the finite element method in design analyses of CANDU fuel. We do not present here the theory or description of the method because it is available from many textbooks, see for example Ref. 1. The following sections first discuss some recent uses of the finite element method for estimating stresses and temperatures in CANDU fuel. Then some potential new applications are discussed. For reasons of space, only selected details are given for each case.

Figure 2 shows a CANDU fuel bundle and identifies its components.

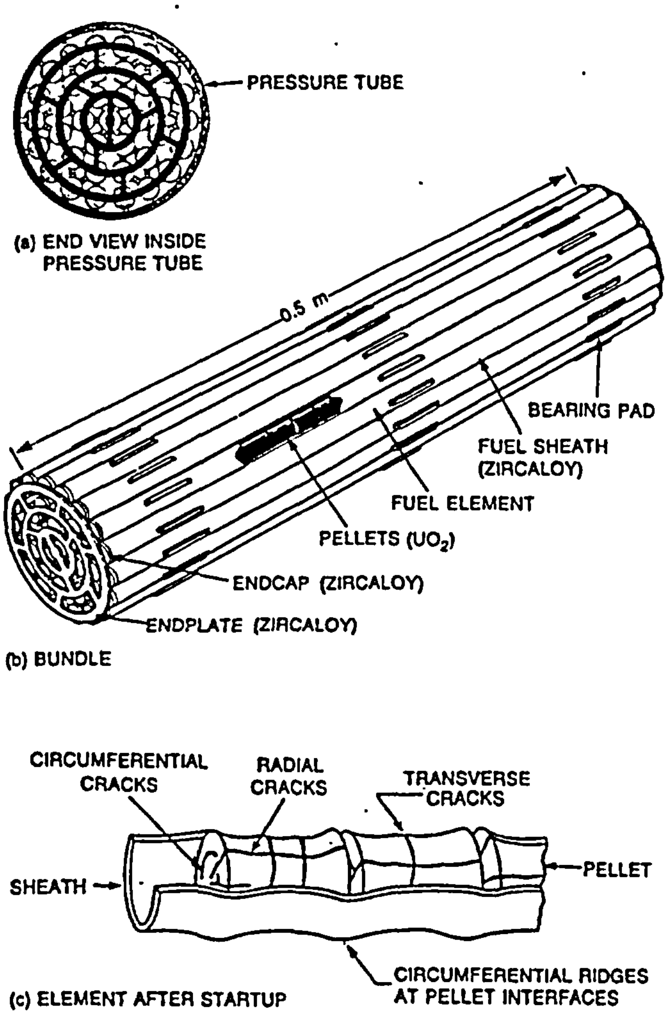

Figure 2 CANDU 37-element fuel bundle assembly

STRESSES

The FEAST Code

A computer program called FEAST has been developed to calculate stresses, strains, and displacements in CANDU fuel. The FEAST code is two-dimensional. That is, either plane or axisymmetric calculations can be done. The model includes the effects of elastic, plastic, creep and thermal strains. Triangular finite elements are used. The plastic strains are calculated from the incremental theory (Ref. 2) and from the Hencky-von Mises yield function (Ref. 2). The formulation for creep is similar to that for plasticity.

The user can specify arbitrary conditions of forces, pressures, and temperatures. As well, zero, non-zero, or limiting values of displacements can be imposed on parts of the body. These can all be specified as a function of time.

The predictions of FEAST have been compared to many analytical solutions. Figure 3 shows a typical comparison. It shows stationary stresses during creep in a thick, closed, internally pressurized cylinder. The agreement is usually

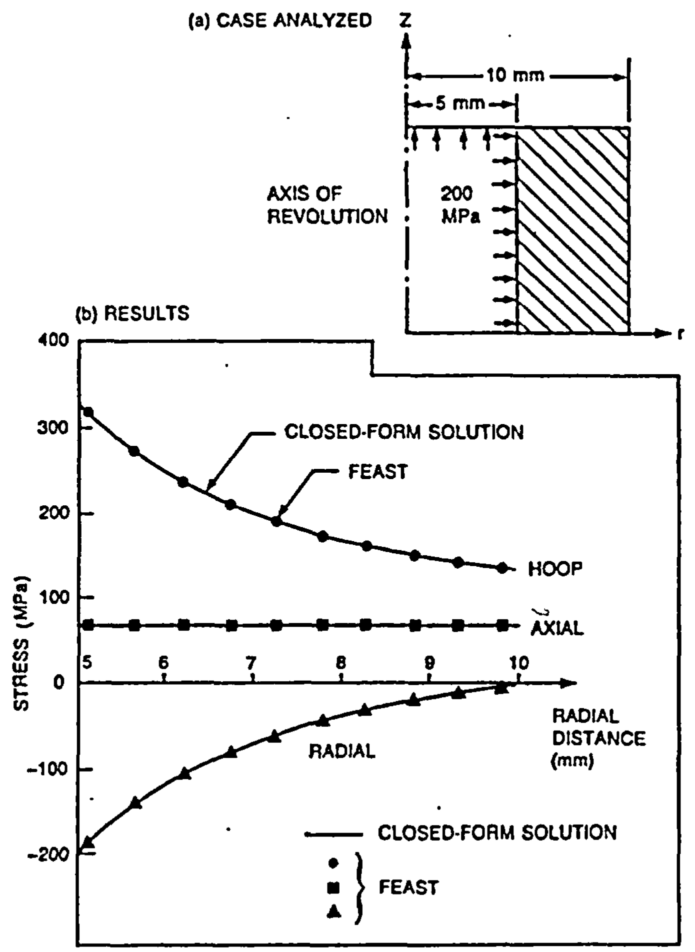

Figure 3 Creep stresses: FEAST vs closed-form solution

better than 5% for the comparisons made. In addition, a comparison is available against strain-gauge measurements for compression tests on end caps. Figure 4 shows that the predictions of the finite element code are in good agreement with measurements for axial strains.

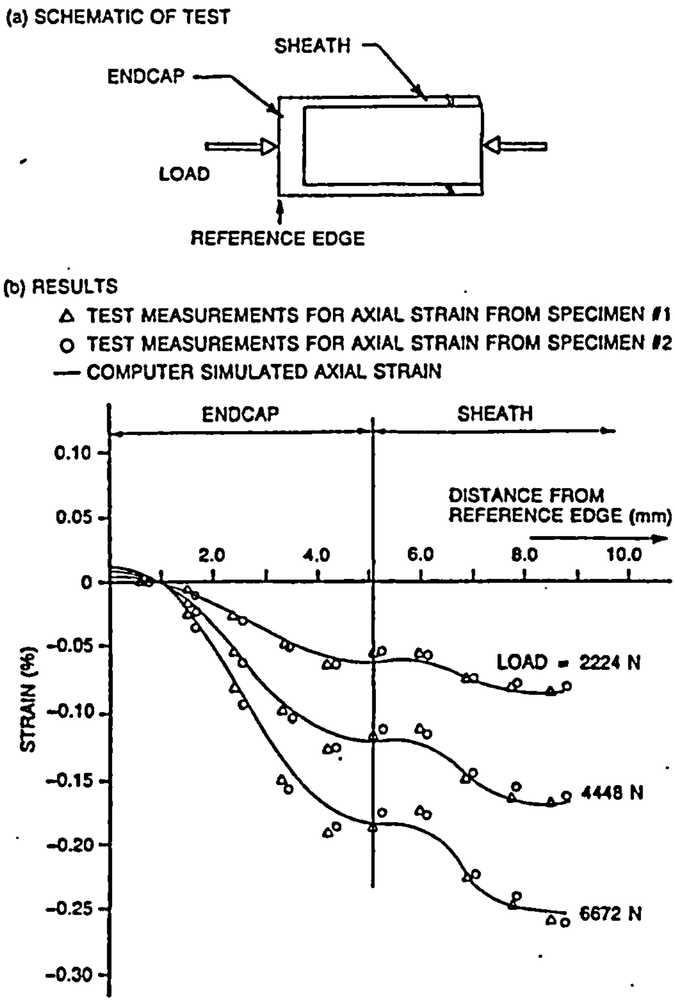

Figure 4 End cap strain: finite element vs measurements

FEAST is a "general purpose" code for stress analyses, in that it can also be used to analyze components other than nuclear fuel.

The ELESTRES Code

A "fuel-specific" version of FEAST is included as a subroutine in the fuel performance code ELESTRES (Ref. 3). "Fuel-specific" features include, for example, cracking of UO_2, and a special formulation for rapid creep of high temperature UO_2.

How does ELESTRES differ from the more familiar fuel performance code ELESIM (Ref. 4)? ELESIM and ELESTRES both model the behaviour of CANDU fuel elements during normal operation. The constituent models are physically (rather than empirically) based, and include such phenomena as: fuel to sheath heat transfer; temperature and porosity dependence of fuel thermal conductivity; burnup-dependent neutron flux depression; burnup- and microstructure-dependent fission gas release; and stress-, dose-, and temperature-dependent constitutive equations for the sheath.

ELESIM contains a semi-empirical one-dimensional calculation of pellet stresses. Instead, ELESTRES uses FEAST, which is a more fundamental and detailed calculation of pellet stresses, strains, and displacements. This is expected to improve the accuracy of stress calculations. Also, since FEAST is a two-dimensional code, ELESTRES is able to estimate hoop strain in the sheath near circumferential ridges. Ridges form (Ref. 5) in the sheath at pellet ends due to axially non-uniform thermomechanical expansion of the pellets, see Figure 2c.

Ref. 3 shows that predictions of ELESTRES for ridge strains compare well with post-irradiation measurements covering a wide range of operating conditions. The remaining calculations of ELESTRES (e.g. grain growth, fission gas release, flux depression, pellet densification) use the same constituent sub-models as ELESIM.

The calculations of ELESTRES include two-dimensional deformations of the curved surfaces of the pellet, see Figure 5a. Elasticity, plasticity, creep, and cracking are included. Yet for typical irradiation histories, it requires less than 40 seconds of computing time on a CDC/CYBER 175 computer!

Below, we give some examples of recent uses of FEAST and of ELESTRES.

Stresses Near End Caps: Effect of Pellet Density

Stress profiles are needed to assess the influence of initial (as-fabricated) pellet density on cracking near end caps. Since the geometry of the end cap differs for different fuel fabricators and for different reactors, we studied an "idealized" geometry. The dimensions were consistent with a typical fuel element of a 37-element bundle. The fuel element was assumed to generate 25 kW/m until a burnup of 80 MW.h/kg(U). Then, it was assumed shifted to a high-power position in the channel, producing 55 kW/m.

Power increases (fuel start-up, power boosts) result in higher fuel temperatures, and in pellet thermal expansion. Fuel densification (in-reactor) counteracts such increases. With standard density pellets, a large part of the thermal expansion can be compensated by pellet densification. High initial density of pellets reduces the extent of densification. Thus higher stresses are expected in fuel of higher density.

We first used ELESTRES to simulate pellet behaviour. The finite element calculations for pellet displacements were then used as boundary conditions for the sheath and for the end cap, see Figure 5. FEAST was used to model the sheath and the end cap using 300-350 finite elements. In addition to stresses due to pellet expansion, the calculations also accounted for: coolant pressure, internal gas pressure, and hydraulic drag. To reflect changes in Zircaloy microstructure during end cap welding, different plastic moduli were assigned to the sheath, the end cap, and the weld. Elastic-plastic axisymmetric calculations were done.

FEAST results show that the stresses near the weld are highly multiaxial in that no single component dominates. This is also expected intuitively.

Figure 5 shows the predicted principal stress as a function of initial density of the pellet.

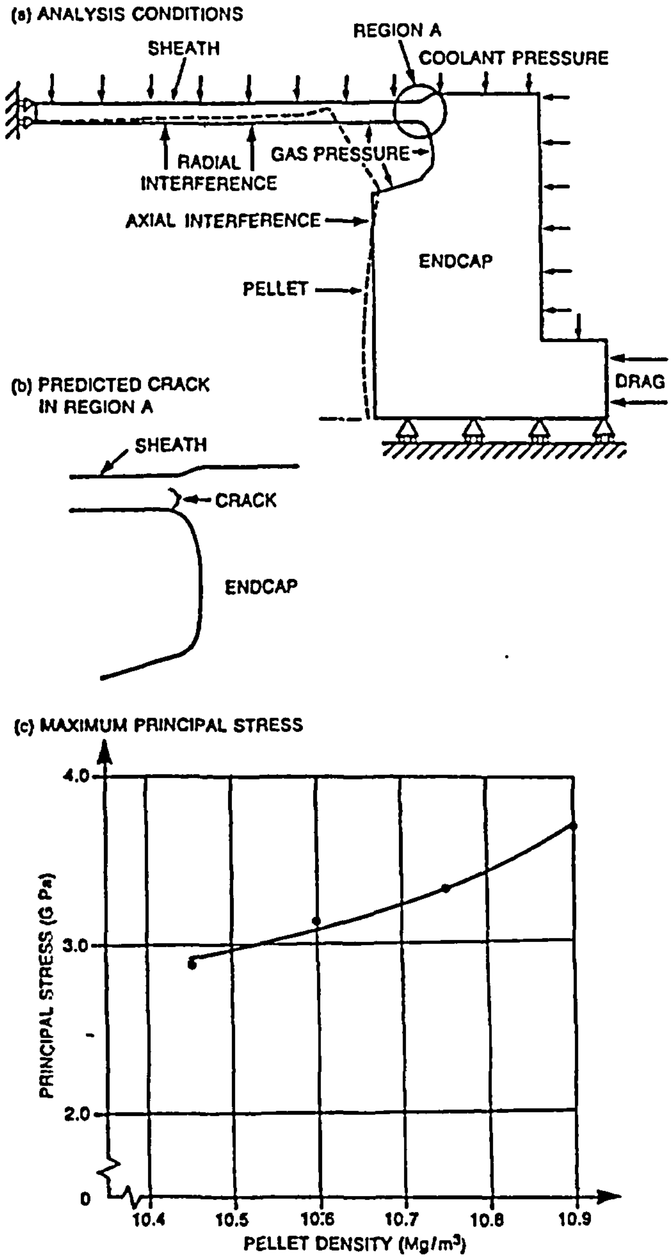

Figure 5 Higher pellet density gives larger weld stress

Due to the multiaxiality, the principal stresses can be significantly higher than the yield strength of Zircaloy. Increasing the initial density from 10.45 to 10.9 Mg/m^3 increases the principal stress from 2.9 to 3.7 GPa. Comparison with fuelograms (Ref. 6) indicates that the corresponding defect probabilities are 0 and ~30% respectively; the variation in-between is highly non-linear.

The preceding estimates are pertinent only to the conditions analyzed. Some assumptions have been mentioned earlier. Others include the assumed values of diametral and axial gaps between the pellets and the sheath; stress relaxation during hold at low power; and idealized shapes of the pellet, end cap, and weld.

Figure 5 also shows our prediction for the location and direction of initial growth of a crack, if the stresses and the chemical environment are too severe.

Finite elements were ideally suited for this study because of the complex geometry near the weld.

Stresses Near End Caps: Effect of Unbonded Length

FEAST was used to examine the influence of the location of discontinuity in a sheath/end cap weld, on the load carrying capacity of CANDU fuel elements. The length of sound joint in the radial direction is called the bonded length. Four different arrangements of the bonded length were considered, see Fig. 6. All four had the same total bonded length, but the locations of the discontinuity were different. In the first two geometries, the entire bonded length was within the projected area of the sheath thickness. In geometries 3 and 4, 80% of the bonded length was assumed within the projected area of the sheath thickness, and the remaining 20% outside the projected area. In the FEAST simulations, all four geometries were subjected to the same loads. The loads represented our judgement of the worst conditions that can possibly exist in the reactor. An elastic-plastic axisymmetric analysis was done.

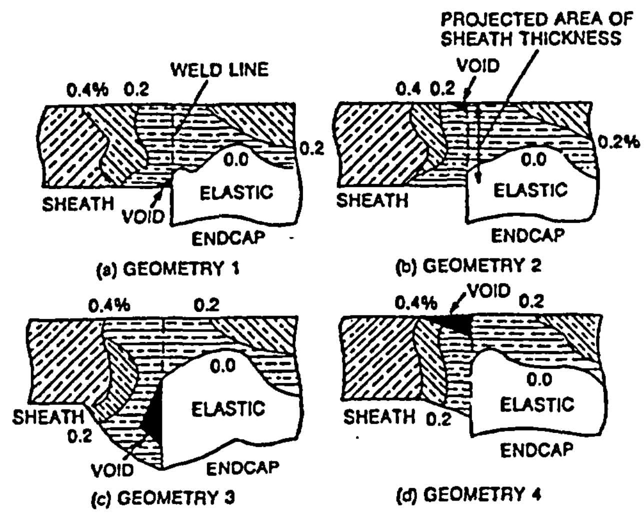

Figure 6 Plastic strains: Effect of discontinuity in the sheath/endcap weld

Finite elements enabled an accurate yet economical representation of the irregular geometries near the voids.

Figure 6 shows the strain contours in the weld region (region A of Figure 5a) of the four simulated geometries. The four different locations of the bonded area result in similar levels of strains and stresses near the weld. Hence, we conclude that the resistance of the sheath/end cap weld against ductile failure is not likely to be adversely affected if up to 20% of the bonded length falls outside the projected area of sheath thickness.

This conclusion applies only when all the assumptions of the analysis are satisfied.

This information was used to modify the weld specification, reducing the cost of fuel fabrication.

Sheath Strains Near Circumferential Ridges

We assessed sheath fatigue during power cycles. As a first step, we determined the patterns of stresses and strains in the sheath near circumferential ridges, see Figure 7. The pellet dimensions used in this study differ somewhat from those normally used in CANDUs. The calculations assumed that fresh fuel is taken rapidly from 0 to 56.3 kW/m.

First, ELESTRES was used to estimate thermomechanical expansion of the pellet. Then, the sheath was modelled with FEAST. The expanded profile of the pellet was used to drive the circumferential expansion of the sheath.

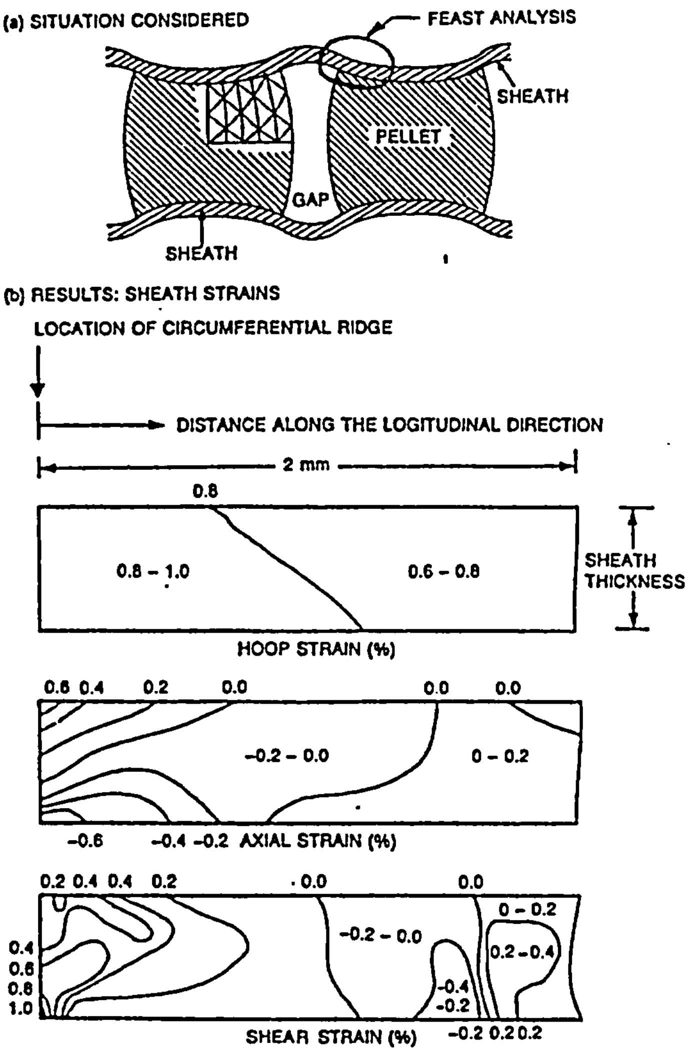

Figure 7 Multiaxial sheath strains near the circumferential ridge

Figure 7 shows FEAST predictions for hoop, axial, and shear strains in the sheath near the circumferential ridge. The peak values of these three components of strain have comparable magnitudes. Since no single component dominates, the stresses and strains are "highly" multiaxial.

To estimate fatigue life, one needs to first convert the multiaxial strains into an equivalent uniaxial strain. For stresses in the elastic-plastic region, Sines Law (Ref. 7) is often recommended (Ref. 8) for estimating the equivalent strain. For the strain pattern shown in Figure 7, the peak value of equivalent strain is 30% higher than that of hoop strain. Hosbons data (Ref. 9) show that a 30% increase in the magnitude of the strain cycle decreases the fatigue life of Zircaloy by a factor of two!

We conclude that reliable predictions of fatigue integrity of the sheath require a multiaxial calculation of sheath stresses and strains.

Pellets of Small Diameter

Fuel stacks in elements may include pellets with small differences in diameters. This feature reduces the cost of fuel fabrication. The possibility of local overstrain at pellet junctions, due to coolant pressure, was studied using finite elements.

FEAST was used to simulate the instantaneous collapse and creep collapse of the sheath, see Fig. 8. Features included: axial load due to side stop loading, coolant pressure, and thermal expansion of the pellets. Elastic and creep analyses were done.

Assumed values were used for: diameter of the sheath, diameters of the standard and reduced pellets, pellet length, and sheath thickness.

Figure 8 shows that the deformed shape of the sheath is stable in the analyzed range. Coolant pressure does not force the sheath into the corner at the pellet step. Rather, the dominating sheath stresses are tensile from pellet expansion. The net creep of the sheath is small, but outward. It was therefore concluded that within the analyzed range, the small diameter of some pellets does not adversely affect creep collapse of the sheath.

TEMPERATURES

The FEAT Code

Our temperature calculations often use the finite element code FEAT. FEAT solves the classical equation for steady state conduction of heat. Gap elements are available to simulate interfaces between neighbouring surfaces. Two versions of FEAT are available: a simple version for one or two-dimensional calculations in plane or axisymmetric bodies, and a three-dimensional version (Ref. 10) for more complex situations. The code can model: conduction; internal generation of heat; prescribed convection to a heat sink; prescribed temperatures at boundaries; prescribed heat fluxes on some surfaces; and temperature-dependence of material properties like thermal conductivity. The user has an option of specifying the detailed variation of thermal conductivity with temperature. Or, for convenience, the program can be asked to use pre-coded values of thermal conductivity, which were obtained from the MATPRO data base (Ref. 11). Some convenience features are also available, such as: a) link to a digitizer, which permits rapid setup, and b) link to a plotter, which permits rapid display of results.

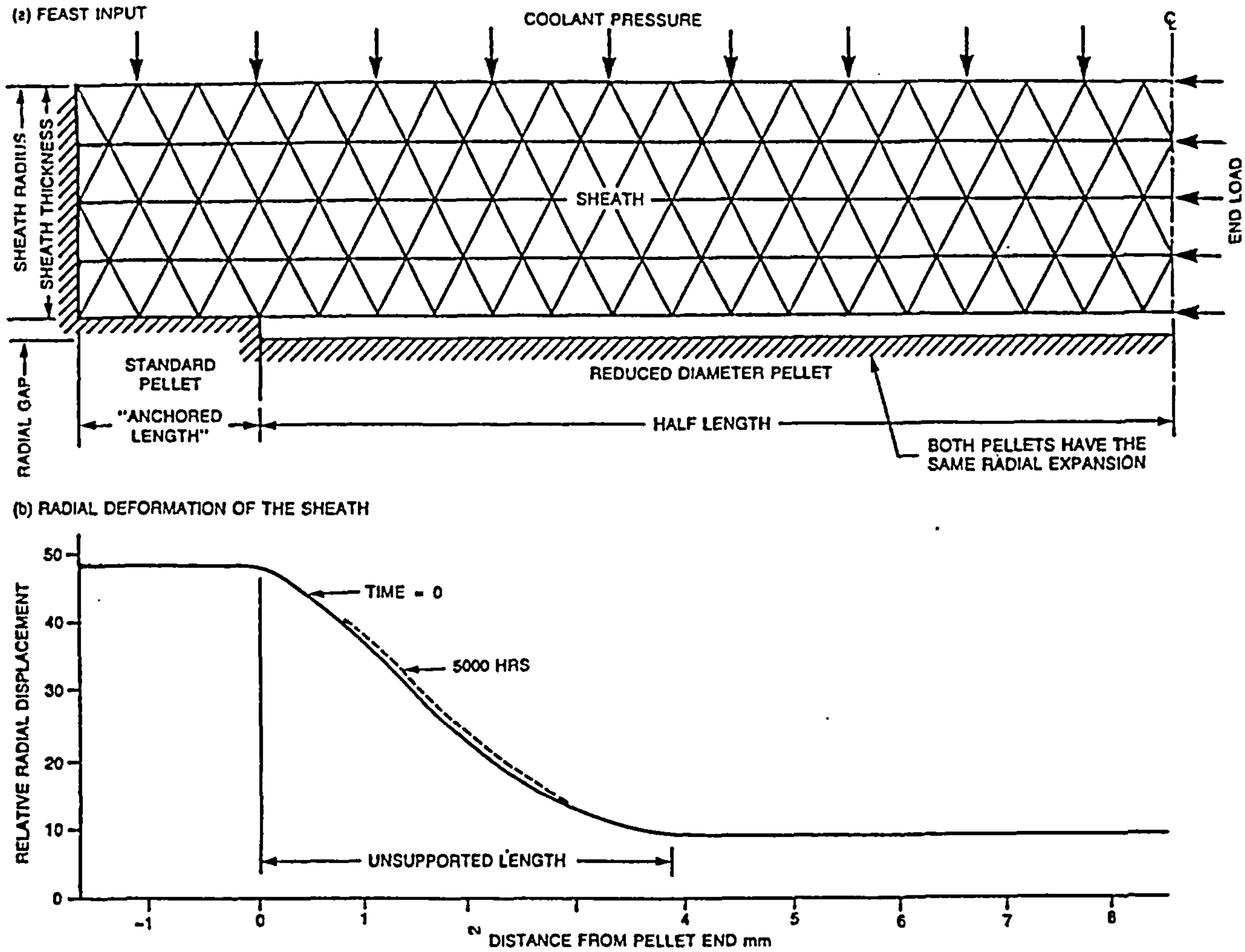

Figure 8 Creep of sheath on a pellet of reduced diameter

The predictions of FEAT show excellent agreement with many analytical solutions for simple geometries. Figure 9 shows typical results for isotherms in a rectangular slab whose four sides are kept at the indicated temperatures. The isotherms predicted by FEAT cannot be distinguished from those obtained by a Fourier series solution.

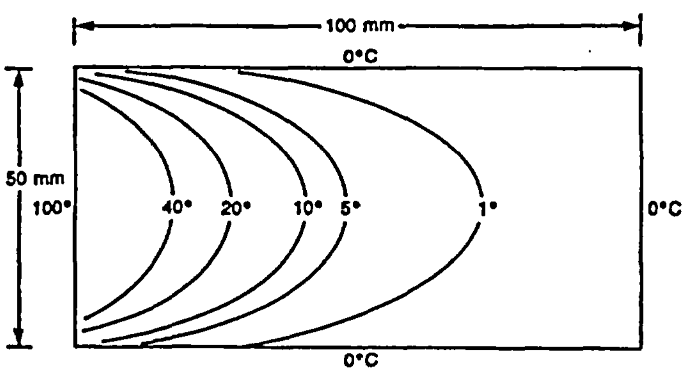

Figure 9 Isotherms (°C): FEAT predictions

A check against thermocouple measurements is also available, see Figure 10. It shows a section of a sheath and bearing pad in contact with the pressure tube. The heat flux at the inner surface of the sheath was 110 W/cm^2; the coolant temperature outside the pressure tube was ~302°C. Thermocouple measurements at two locations in the pressure tube are shown in Figure 10, and compared with temperature contours predicted by FEAT. The FEAT simulations assume a heat transfer coefficient of 0.4 W/cm^2K at the interface between the bearing pad and the pressure tube. From Figure 10, we conclude that the prediction of FEAT for the temperature drop between the two thermocouples is consistent with measurements.

Crevice Corrosion

Shallow corrosion marks have been observed (Ref. 12) in CANDU pressure tubes in locations of contact with fuel bearing pads. The corrosion marks are not considered to be a determining factor in the service life of the pressure tubes or of the fuel. However, it is good engineering practice to seek ways to eliminate the cause of such marks.

Such localized corrosion is avoided if we reduce the heat flux towards the bearing surface of the pad to less than approximately 10% of the current value. Changes in bearing pad geometry can achieve such a reduction.

FEAT simulations assisted in designing the changed geometry of the bearing pads. A large number of modified geometries were first simulated on FEAT, to obtain isotherms similar to Figure 10. It was found (Ref. 12) that the calculated difference between the highest temperature in the bearing surface (T_B) and the coolant temperature (T_C), $\Delta T = T_B - T_C$ is proportional to the element heat flux.

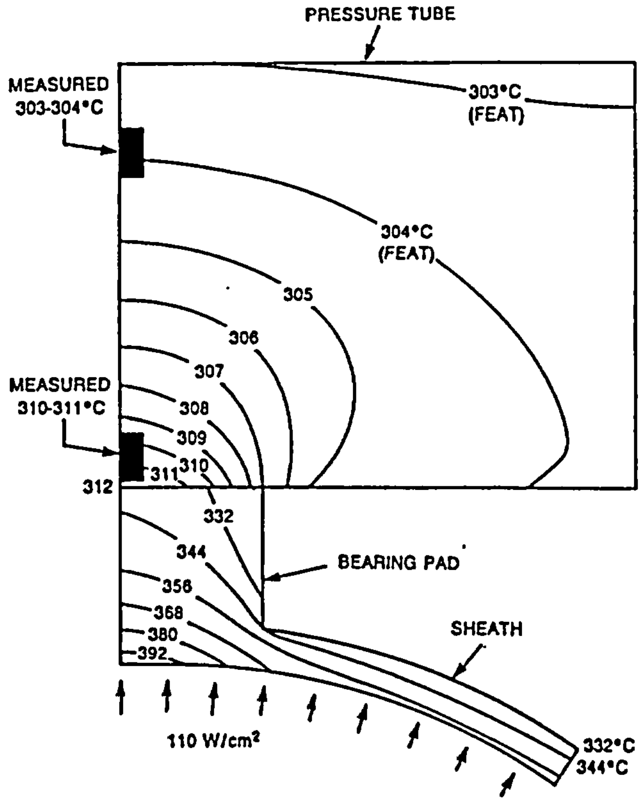

Figure 10 Isotherms (°C) near a bearing pad: Thermocouple measurements vs FEAT predictions

From a review of these simulations and of other information, several promising designs were selected for testing. Figure 11 shows the measured

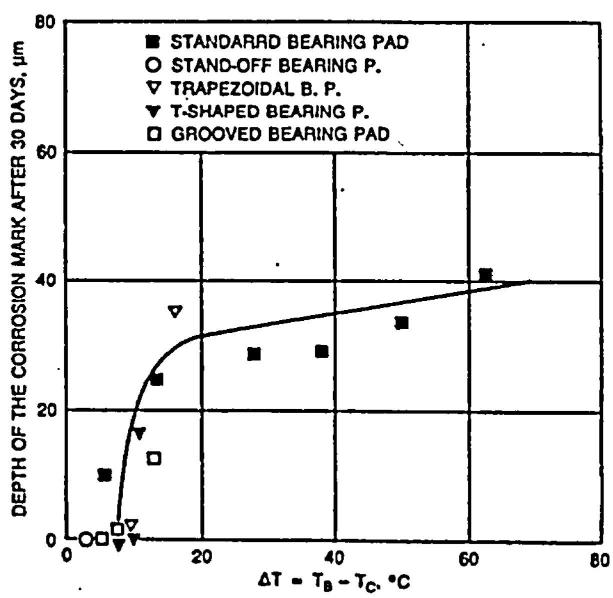

Figure 11 FEAT predictions for temperatures helped correlate corrosion rates in bearing pads of different designs

corrosion rates (Ref. 12) as a function of calculated ΔT. In this manner, FEAT assisted in interpreting and correlating test data.

This combination of FEAT analysis and testing enabled modification of the bearing pad design, giving reduced rate of crevice corrosion.

The importance of finite elements was in the accurate, economic, and rapid modelling of the curved and complex surfaces of the new pads.

Braze Voids

This study determined the size of voids that can be permitted in the braze between the sheath and the bearing pad. A large void can restrict heat conduction via the bearing pad, increasing the sheath temperature. As a first step, temperatures near the void were assessed by considering radial and circumferential conduction of heat, see Figure 12. The calculations considered a variety of lengths for the braze void. The heat flux was 130 W/cm^2 at the inner surface of the sheath.

Figure 12 shows the influence of void length, on the temperature at the inside surface of the

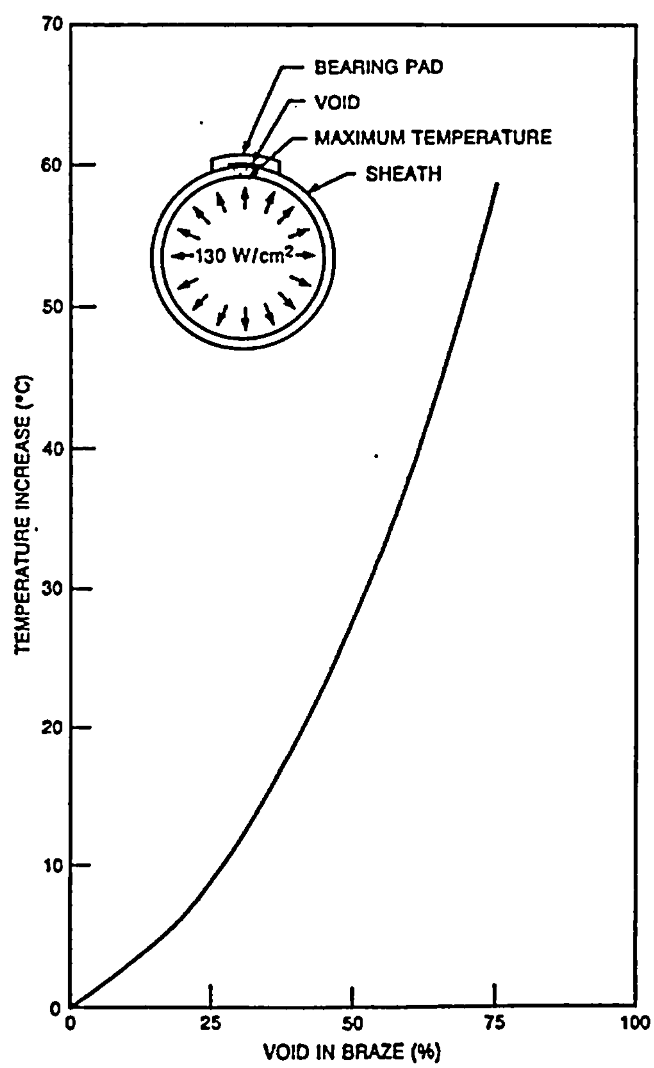

Figure 12 Increase in maximum sheath temperature due to void in braze

sheath. When the braze void exceeds ~20-50% of the braze width, the sheath temperature increases rapidly.

Voids create irregular geometries; finite elements reduced the effort to assess them.

End Flux Peaking

It is well-known (Ref. 13) that the neutron flux is higher near the two ends of a fuel element than at the center of the element. This is called end flux peaking. It causes higher temperatures in the pellets near the ends of the fuel stack. This is partly compensated by axial conduction of heat via the end cap.

Figure 13 shows the section of a fuel element we simulated in an axisymmetric calculation using FEAT. The analysis assumed a nominal heat rating of ~57 kW/m, endflux peaking of ~10%, and element burnup of 50 MW.h/kgU which is approximately the plutonium peak in natural UO_2 fuel.

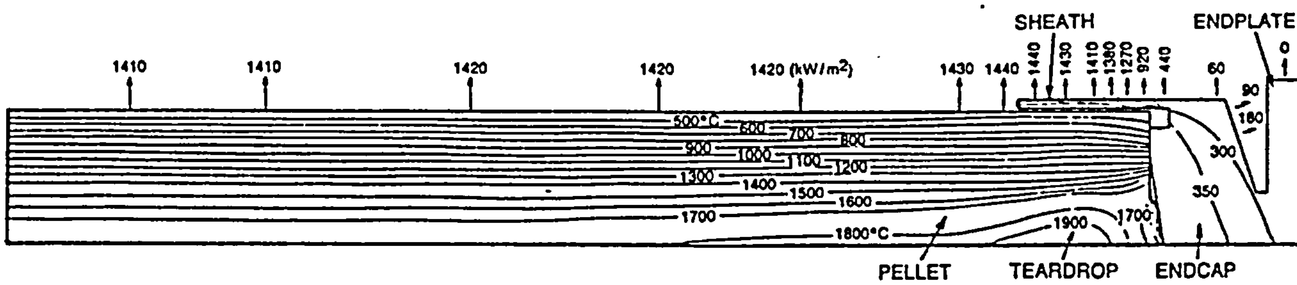

Figure 13 Isotherms (°C), heat flux (kW/m^2), and tear drop near the end of a fuel stack

Figure 13 shows that although the neutron flux peaking is ~10%, the peaking in surface heat flux is ~2% (=(1440/1410-1)*100). Thus cooling through the end cap is significant. Figure 13 also shows the "tear-drop" shape of isotherms near the end of the stack. Central voids of this shape have been observed at Chalk River Nuclear Laboratories, during neutron radiography of elements irradiated at high powers (~60-80 kW/m).

As in other example, the curved surfaces of the pellets, end cap, and endplate were easily accommodated by finite elements.

NEW APPLICATIONS

Bowing

A finite element program, BOW, is under active development. Its objective is to predict fuel element bowing during conditions of post-dryout, when drypatches exist on the sheath. Features include: ability to accommodate arbitrary variations of temperatures around the sheath circumference and along the element length; hydraulic drag load; gravity; resistances from the sheath, pellet, and endplate; pellet cracking; lateral restraints from the pressure tube and/or from neighbouring fuel elements; and material properties from the MATPRO data base.

Extend Correlation for Defect Probability

We also plan to use our existing finite element codes to extend defect probability correlations such as FULOMO and fuelograms (Ref. 6). The objective is to extend these correlations inexpensively, and cover conditions not included in the data base of the correlations. Examples include: fuel with high density, with low pellet/Zircaloy clearance, or of large sheath diameter; multiple ramps in power; power cycling; and/or extended burnups.

Diffusion

We have developed a preliminary version of a finite element code FEED, which solves the equation for diffusion in solids (Ref. 14). The equation is solved in two dimensions, i.e., for either plane or axisymmetric conditions. Diffusion due to the following effects is considered: concentration gradient; temperature gradient; and pickup at exposed surfaces. The predictions of the code show good agreement with a number of analytical solutions. Figure 14 shows that FEED predictions also agree well with Sawatzky's measurements (Ref. 14) for diffusion of hydrogen in Zircaloy-2 after a 41-day anneal under a temperature difference of 157-454°C. The original development of FEED was focussed towards estimating diffusion of hydrogen towards the cool regions of new bearing pads (Ref. 12) being considered to reduce crevice corrosion. But with further development, FEED could be applied to the following situations: diffusion of hydrogen during post-defect deterioration of fuel; diffusion of hydrogen in pressure tubes; diffusion of neutrons; and diffusion of oxygen. The first new application above would enhance our ability to determine the rate at which the region of hydrogen-embrittled zircaloy grows near secondary defects. This in turn would improve our ability to determine timely removal of defected fuel.

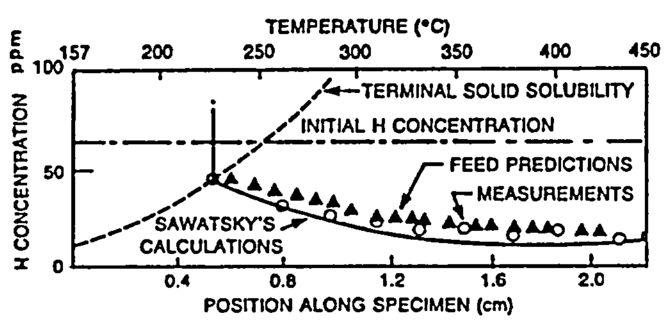

Figure 14 Diffusion of hydrogen: FEED vs measurements

Flow Patterns

Finite element codes are being developed in and outside Canada for predicting flow patterns.

Figure 15 compares predictions vs. measurements of subchannel axial velocities around circular cylinders between parallel plates (Ref. 15). The coordinates are the same in Figures 15a and 15b; W is the primary axial velocity. By providing a detailed estimate of flow patterns within subchannels and around endplates, these codes may enable better estimates of pressure drop and of critical heat flux in fuel bundles containing novel arrangements of fuel elements, and/or containing new designs of endplates and end caps.

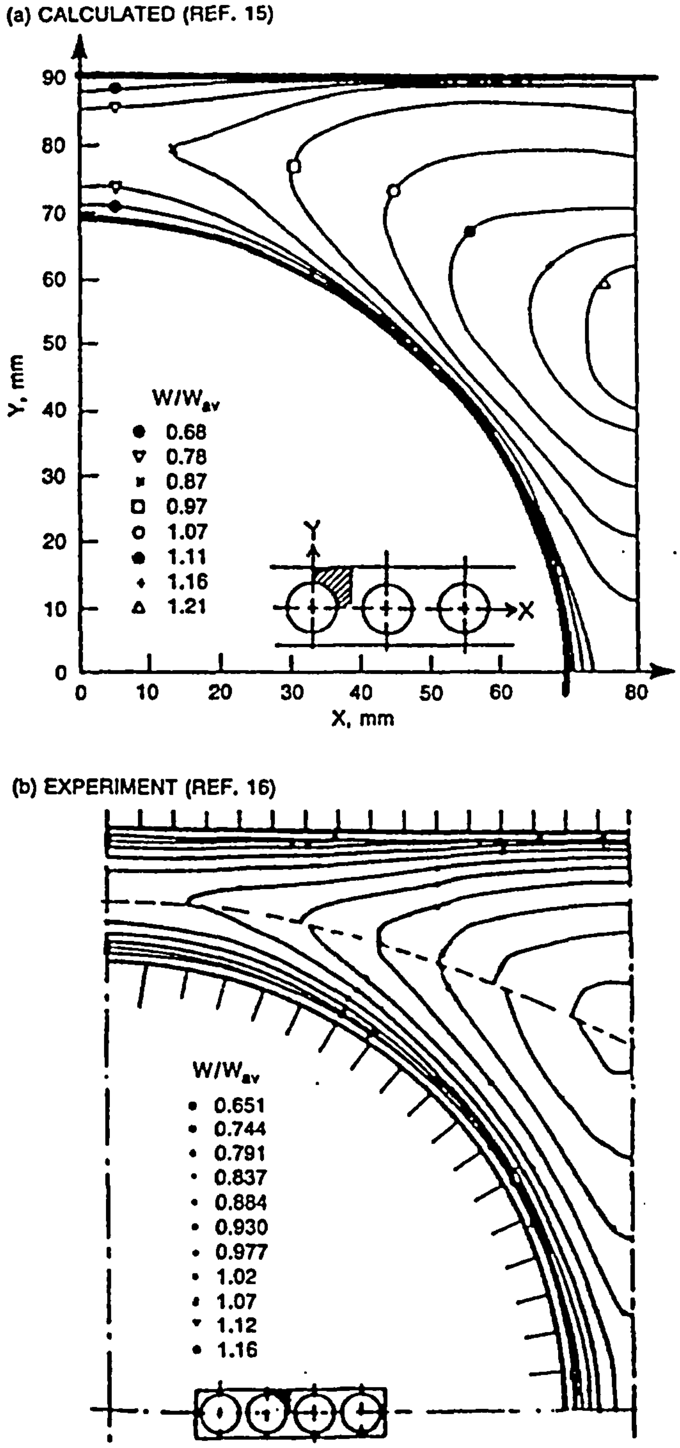

Figure 15 Comparison of the axial velocity distribution in a subchannel

DISCUSSION

The preceding examples show that the finite element method is especially suited for a variety of applications in CANDU fuel. This is because CANDU fuel has many curved, inclined, and irregular surfaces. The finite element method can represent them accurately using few nodes. This leads to economic and stable computer codes.

With judicious use, the finite element method can also provide early warnings of potential problems, especially when experiments require either a long lead time (e.g., high burnup), or when they are expensive (e.g., post-dryout operation). Finite element predictions can also be used to guide the design of such experiments, to determine appropriate test conditions, and to interpret results. Thus one can also use finite element calculations to establish the parameters that, in their plausible ranges, have the most influence on the final result.

SUMMARY AND CONCLUSIONS

1) Strains predicted by the finite element stress code FEAST compare well with out-reactor strain gauge measurements on end caps.

2) Ridge strains in the sheath, predicted by the finite element fuel performance code ELESTRES, compare well with post-irradiation measurements covering a wide range of operating conditions.

3) Finite element studies enabled us to assess the influence of pellet density on defect probability. We assumed a power boost of 30 kW/m at 80 MW.h/kg(U). When the density changes from 10.45 to 10.9 Mg/m^3, the defect probability changes from negligible to ~30%. This result is valid only for an idealized geometry of the end cap, and for the assumed clearances between UO_2 and Zircaloy.

4) Finite element studies show that the stresses and strains in the sheath are highly multiaxial near a circumferential ridge. The multiaxiality can have a significant effect on the fatigue integrity of the sheath during power cycling.

5) FEAST has also been used successfully to show that for the analyzed conditions, the location of the unbonded length between the end cap and the sheath has a negligible effect on elastic-plastic stresses; and to show that within certain limits, the creep collapse of sheath on suitably chosen pellets of small diameter gives acceptable stresses and strains.

6) Temperatures predicted by the finite element thermal code FEAT compare well with thermocouple measurements near the interface between the bearing pad and the pressure tube.

7) FEAT has been used successfully to help select a new bearing pad design that eliminates crevice corrosion; to select a specification for the length of braze voids; and to demonstrate that endpeaking in heat flux is significantly less than the endpeaking in neutron flux.

8) Finite element codes for the following phenomena are under various stages of development: fuel element bowing; stress corrosion cracking; diffusion; and flow patterns.

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REFERENCES

(1) HUEBNER, K.H., "The Finite Element method for Engineers", John Wiley & Sons, New York, 1975.

(2) HILL, R, "The Mathematical Theory of Plasticity", Oxford Clarendon Press, U.K., 1950.

(3) WONG, H.H., ALP, E., CLENDENING, W.R., TAYAL, M., JONES, L.R., "ELESTRES: A Finite Element Fuel Model for Normal Operating conditions", Nuclear Technology, Vol. 57, 1982, pp 203-212.

(4) NOTLEY, M.J.F., "ELESIM: A Computer Code for Predicting the Performance of Nuclear Fuel Elements", Nuclear Technology, Vol. 44, August 1979, pp 445-450.

(5) CARTER, T.J., "Experimental Investigation of Various Pellet Geometries to Reduce Strains in Zirconium Alloy Cladding", Nuclear Technology, Vol. 45, September 1979, pp 166-176.

(6) PENN, W.J., LO, P.K., WOOD, J.C., "CANDU Fuel Power Ramp Performance Criteria", Nuclear Technology, Vol. 34, July 1977, pp 249-268.

(7) SINES, G., "Failure of Metals Under Combined Repeated Stresses with Superimposed Static Stresses", NACA Technical Note 3495, 1955.

(8) FUCHS, H.V., STEPHENS, R.J., "Metal Fatigue in Engineering", John Wiley and Sons, 1980.

(9) HOSBONS, R.R., "Low-Cycle Fatigue Behaviour of Zirconium Alloys at 300°C", International conference on Creep and Fatigue in Elevated Temperature Applications, Philadelphia, September 1973, pp 176.1-176.6

(10) BANAS, A., WILLIAMS, V.L., "FEAT3D: Aid in Bearing Pad Design for CANDU Fuel Elements", CNS Conference on Numerical Methods in Nuclear Engineering, Montreal, 1983.

(11) McDONALD, P.E., THOMPSON, L.B., "MATPRO - Version 09; A Handbook of Materials Properties for Use in the Analysis of Light Water Reactor Fuel Rod Behaviour", TREE-NUREG-1005, E.G. & G., Idaho, December 1976.

(12) SEJNOHA, R., OLDAKER, I.E., LIM, D., ARCHINOFF, G.H., GACESA, M., HU, R., "Elimination of Crevice Corrosion of Pressure Tubes in CANDU Reactors: Effect of Bearing Pad Geometry", Fifth Annual Conference of the Canadian Nuclear Society, Saskatoon, June 1984.

(13) ROSHD, M.H.M., CHOW, H.C., "The Analysis of Flux Peaking at Nuclear Fuel bundle Ends Using PEAKAN", Atomic Energy of Canada Limited, Report AECL-6174, 1978.

(14) SAWATZKY, A., "Hydrogen in Zircaloy-2: Its Distribution and Heat of Transport", Journal of Nuclear Materials, Vol. 2, 1960, pp 321.

(15) ABDELGHANY, M., ROCO, M.C., EICHHORN, R., "A Simplified Finite Element Model for Fully Developed Axial Turbulent Flow in Rod Bundles", Nuclear Science and Engineering, Vol. 85, 1983, pp 1-16.

(16) REHME, K., "The Structure of Turbulent Flow Through Subchannels of Rod Bundles", Proc. Symp. Fluid Flow and Heat Transfer over Rod or Tube Bundles, December 2-7, 1979, page 67, American Society of Mechanical Engineers, New York.

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