BOWING OF PELLETIZED FUEL ELEMENTS: THEORY AND IN-REACTOR EXPERIMENTS

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SUMMARY

Fuel element bowing is defined as the lateral deflection of an element during irradiation. It is important to understand and to be able to limit this type of deformation since the consequences of uncontrolled bowing could be, for example, element failure due to locally restricted coolant flow, or difficulty in removing fuel assemblies after irradiation due to element distortion. In this paper we analyse and discuss the phenomenon of bowing in pelletized fuel elements with special reference to observations and experiments made in WR-1, an organic-cooled, heavy-water moderated research reactor located at Pinawa, Manitoba. The elements are constituents of fuel bundles similar in size and shape to those used in CANDU (*CAN*ada *D*euterium *U*ranium) power reactors.

Bowing is attributed to the action of bending moments generated both within the sheath and between the fuel and sheath, by a temperature distribution which is not symmetric with respect to the element axis. This temperature asymmetry is caused by: (i) non-uniform coolant temperature due to imperfect coolant mixing; (ii) variable heat transfer coefficient between fuel and coolant and (iii) asymmetric heat generation due to neutron flux gradients across the element.

Explicit analytical formulae for the bending moments are derived, from which the relative importance of different parameters can be assessed. For the fuel and experimental conditions under discussion it is shown that neutron flux gradients and the interaction between fuel and sheath are the dominant factors in element bowing. Experimental evidence supports this analytical conclusion and suggests that progressive bowing is dependent upon such factors as, initial fuel-sheath diametral clearance, sheath strength, and pellet length.

In addition to describing experiments in which the effects of different parameters were investigated, a brief description is also given of the general experience and problems associated with bowing in the "driver" fuel of the reactor, together with advances in experimental techniques for studying in-reactor bowing. This experience coupled with a fundamental understanding of bowing mechanisms suggests that minor fuel bundle design changes can mitigate the undesirable consequences of fuel rod bowing.

NOTATION

δ	=	magnitude of bow
ℓ	=	unrestrained length of fuel element
a, b	=	inner, outer sheath radii
t	=	b - a, sheath wall thickness
r, Θ	=	cylindrical co-ordinates of point P w.r.t. axis of element
R_i	=	distance of element axis to bundle axis
R	=	distance of point P from bundle axis
κ	=	inverse diffusion length for thermal neutrons in homogenized bundle (fuel, sheath and coolant)
α	=	coefficient of thermal expansion
λ	=	thermal conductivity
h_{sc}, h_{fs}	=	heat transfer coefficients, sheath/coolant, fuel/sheath
1/H	=	$1/h_{fs} + 1/h_{sc} + t/\lambda_s$, thermal impedance between fuel surface and coolant (valid for thin-wall sheaths)
q	=	power per unit fuel length
w	=	surface heat flux
D	=	neutron flux gradient factor, defined in text
T(r,Θ)	=	temperature at point P
ΔT_s	=	difference between maximum and minimum sheath surface temperatures
$\bar{T}_c$	=	average coolant temperature
β, γ	=	quantities defined in text relating to variation of coolant temperatures and heat transfer
Subscript s, c	=	symbol with subscript s, c refers to sheath, coolant; otherwise symbol refers to fuel

1. INTRODUCTION

Fuel element bowing is defined as the lateral deflection of an element during irradiation, and the magnitude of the bow is the maximum deflection be ween points of restraint. This deflection is generally small in the sense that the deformation occurs within the elastic limit of the cladding material. For example, in a 500 mm long element of radius 7.5 mm, the bending strain due to a bow of 1.3 mm is 0.03% (bending strain due to bow $\approx 8b\delta/\ell^2$). The fact that some residual bow is usually observed during post-irradiation examination implies that elastic recovery is incomplete and some degree of stress-relaxation within the elastic range has occurred during irradiation.

The elements under consideration are constituents of fuel bundles similar in size and shape to those used in CANDU (Canada Deuterium Uranium) power reactors [1]. Figure 1 shows a typical CANDU fuel bundle section. Although in this paper we are primarily concerned with understanding the main factors which cause bowing, we will briefly mention two observed consequences of bowing in the driver fuel of the organic-cooled research reactor, WR-1 [2]. The first concerns the phenomenon known as "sticking" in which the force required to lift an assembly of fuel bundles out of a channel increases more or less progressively with irradiation. To prevent excessive lift forces during removal operations, the fuel had to be discharged when it reached an average burnup of ~ 120 MWh/kgU, i.e., about half its reactivity lifetime. The "sticking" is a consequence both of bowing and of the detailed fuel design. Subsequent modifications to the fuel bundle design have alleviated this problem and extended the operational life of the fuel. The second consequence, which has occurred several times in WR-1, is the failure of the cladding in elements which have bowed to closely approach or contact the wall of the coolant channel thereby causing local overheating due to restricted coolant flow [3]. This type of failure can be avoided by proper location of bearing pads in the fuel design.

In developing our model of bowing we do not discuss the time-dependent behaviour of the element for two reasons: (i) the stress-relaxation properties of the cladding in a neutron flux over a wide range of temperatures are not well known, nor are the changes in fuel/sheath interaction due to irradiation and power cycling (ii) although a time-dependent analysis would provide information on the rate of development of residual bow it would not add significantly to our understanding the main factors which cause bowing.

2. THEORY OF BOWING

2.1 <u>Hypothesis and Preliminary Remarks</u>

The basic hypothesis of our analysis is that bowing of pelletized fuel elements, of the type under consideration, is a thermally induced phenomenon. One side of the element becomes hotter than the other and the element deflects (bows) in the direction of the hotter side to accommodate the differential axial strain. An equivalent statement, but one which is more useful for analytical purposes, is that temperature variations around the fuel and sheath set up bending moments, and the problem is to calculate these temperature variations and hence the bending moments. These peripheral temperature gradients are caused by:

(i) non-uniform coolant temperatures due to imperfect mixing,

(ii) non-uniform heat transfer between sheath and coolant due to variations in subchannel geometry and local flow conditions,

(iii) asymmetric heat production due to neutron flux gradients across an element, henceforth called the flux gradient effect.

The flux gradient effect produces a bending moment which bows the element towards the wall of the coolant tube. Bending moments resulting from factors (i) and (ii) will cause the element to deflect in a direction depending on the location of the maximum coolant temperature or the minimum heat transfer coefficient with respect to the element. Bowing is therefore not necessarily confined to one plane and a variety of bowed shapes is possible depending on the relative magnitudes and directions of the bending moments resulting from factors (i), (ii) and (iii). Which of these factors dominate will depend on the specific circumstance. For example, if there is a sudden and large deterioration in coolant heat transfer due to dry-out on one side of an element it is likely that the bending moment (ii) will dominate and cause the element to bow in the direction of minimum heat transfer. On the other hand, both analysis and experiment confirm that under steady operating conditions the differential axial strain between fuel pellets and sheath due to the flux gradient effect is the dominant factor in element bowing (see sections 3 and 4).

2.2 Model and Assumptions

A diagram of the model and co-ordinate system used in the analysis is shown in figure 2. The angle Θ is measured in the clockwise direction from the vector CO. From the geometry of the bundle we make the plausible assumption that the temperature distributions within the fuel and sheath are symmetrical about the vector CO. We also assume that the neutron flux gradient through the bundle can be approximately described by a function of the form $I_o(\kappa R)$,* where κ is the inverse diffusion length for thermal neutrons in the homogenized fuel channel (fuel, coolant and sheath). There are some well-known neutron physics arguments, which will not be elaborated on here, for using this type of distribution. In addition, the function has useful co-ordinate transformation properties which permit solutions of the problem by analytical rather than numerical methods, i.e.,

$$I_o(\kappa R) = I_o(\kappa R_1)I_o(\kappa r) + 2\sum_{m=1}^{\infty}(-1)^m I_m(\kappa R_1)I_m(\kappa r)\cos m\Theta \tag{1}$$

With these assumptions it follows that the most general solutions to the temperature distributions in the sheath and fuel respectively are given by:

$$T_s(r,\Theta) = B_o + B\ln r + \sum_{m=1}^{\infty}\left(B_m r^m + \frac{C_m}{r^m}\right)\cos m\Theta \tag{2}$$

$$T(r,\Theta) = A_o + AI_o(\kappa R) + \sum_{m=1}^{\infty} A_m r^m \cos m\Theta \tag{3}$$

Note that in equation (3) terms in $\ln r$ and r^{-m} are inadmissible because the temperature must remain finite as $r \to 0$. The coefficients in these equations are determined by the boundary conditions and are found by equating terms in $\cos m\Theta$.

2.3 Analysis

(a) Bending of an Empty Tube

If we neglect initially the mechanical interaction between the sheath and fuel pellets and treat the sheath as an empty tube, the bending moment due to temperature variation within the sheath is found by substituting equation (2) into the formula for bending in small deflection beam theory, viz,

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* A more accurate function is of the form $I_o(\kappa R)I_o(\xi z)$ but the subsequent analysis is intractable [4].

$$M_s = \alpha_s E_s \int_a^b \int_o^{2\pi} T_s(r,\Theta) r^2 \cos\Theta \, dr \, d\Theta \tag{4}$$

which gives

$$M_s = \frac{\pi\alpha_s E_s}{4} \{B_1(b^4 - a^4) + 2C_1 (b^2 - a^2)\}$$

Assuming hinged-end conditions, the deflection δ of the sheath at the mid-span due to this bending moment is given by

$$\delta = \frac{M_s \ell^2}{8E_s I_s} \approx \frac{\alpha_s \ell^2}{8b} \left\{B_1 b + \frac{C_1}{b}\right\} \tag{5}$$

where $I_s \approx \pi b^3 t$ is the moment-of-inertia of a thin-walled tube of thickness $t = b-a$. It should be noted that the hinged-end condition has been found experimentally to be a good approximation for elements in the type of fuel bundles under investigation [5]. The problem is thus reduced to finding the bracketed term in equation (5), and this may be shown to be approximately equal to half the difference between the maximum and minimum surface sheath temperatures, that is,

$$B_1 b + \frac{C_1}{b} \approx \frac{\Delta T_s}{2} \tag{6}$$

If we call $\Delta T_s(i)$ the difference in maximum and minimum heath temperature due to effect (i) etc., then,

$$\Delta T_s(i) \approx \frac{2\beta \bar{T}_c}{1 + \frac{h_{fs}}{h_{sc}} \left(\frac{\lambda}{\lambda + a h_{fs}}\right)} \tag{7}$$

where
$$\beta = \frac{T_c(\max) - T_c(\min)}{T_c(\max) + T_c(\min)}$$

and $\bar{T}_c$ = average coolant temperature around the element.

Similarly
$$\Delta T_s(ii) \approx \frac{2\gamma \bar{w} b \left(1 + \frac{\lambda}{a h_{fs}}\right)}{\lambda + \left(1 - \frac{\gamma^2}{2}\right) b \bar{h}_{sc} \left(1 + \frac{\lambda}{a h_{fs}}\right)} \tag{8}$$

where
$$\gamma = \frac{h_{sc}(\max) - h_{sc}(\min)}{h_{sc}(\max) + h_{sc}(\min)}$$

$\bar{h}_{sc}$ = average heat transfer coefficient around the element.

$\bar{w}$ = average heat flux.

and finally
$$\Delta T_s(iii) \approx \frac{2qD}{\pi a} \left\{ \frac{\frac{1}{h_{sc}} + \frac{t}{2\lambda_s}}{1 + \frac{\lambda}{aH}} \right\} \tag{9}$$

where q is the power per unit length of the element and $D = \frac{I_1(\kappa R_1) I_2(\kappa a)}{I_0(\kappa R_1) I_1(\kappa a)}$ is a factor determined by the flux depression through the fuel bundle and is shown graphically in figure 3 as a function of κR_1 and κa.

The magnitude of the bow for each of the factors (i) - (iii) is found by multiplying the appropriate ΔT_s by $\alpha_s \ell^2/16b$.

(b) Interaction Between Pellet Stack and Sheath

The fuel column within the sheath is a stack of ceramic pellets each of which cracks into many smaller pieces during irradiation; the column is therefore incapable of withstanding an applied bending moment. If, however, the fuel grips the sheath it can induce a bending moment in the sheath because the thermal expansion of the fuel at the interface is greater than that of the sheath. At the point (a,Θ) the difference in longitudinal thermal strain between the fuel and sheath is given by,

$$\Delta s(a,\Theta) = \alpha T(a,\Theta) - \alpha_s T_s(a,\Theta) \tag{10}$$

and $$T(a,\Theta) - T_s(a,\Theta) = w(\Theta)/h_{fs}$$

where $w(\Theta)$ is the heat flux at the interface. If there is no slip between the fuel and sheath, the sheath will be strained in the axial direction by an amount equal to the differential thermal strain; if there is some slip the mechanical strain will be less than the differential thermal strain. We express the relationship between the differential thermal strain and the induced mechanical strain by,

$$\Delta\varepsilon(a,\Theta) = G\Delta s(a,\Theta) \tag{12}$$

where G is a factor between 0 and 1.
In the ensuing analysis we shall set G = 1 (an upper limit for the interaction effect) and postpone discussion of G until section 3.

From equations (10), (11) and (12) we find

$$\Delta\varepsilon(a,\Theta) = (\alpha-\alpha_s)T(a,\Theta) + \frac{\alpha_s w(\Theta)}{h_{fs}} \tag{13}$$

and by substituting equations (2) and (3) into (13) and using the fact that

$$w(\Theta) = -\lambda\frac{\partial T}{\partial r}\bigg|_{r=a}, \text{ gives}$$

$$\Delta\varepsilon(a,\Theta) = \frac{q}{2\pi a}\left[\frac{\alpha-\alpha_s}{H} + \frac{\alpha_s}{h_{fs}}\right]\left\{1 + \frac{2}{I_1(\kappa a)\ I_0(\kappa R_1)}\sum_{m=1}^{\infty}\frac{(-1)^m I_m(\kappa R_1) I_m(\kappa a)\cos m\Theta}{1+\frac{m\lambda}{Ha}}\right\} \tag{14}$$

The derivation of equation (14) assumes constant coolant temperature and constant heat transfer around the periphery of the sheath. In the fuel, temperature variations are due primarily to asymmetric heat generation and the error in neglecting the effects of non-uniform coolant temperature and heat transfer will be small.

The induced bending moment in the sheath is given by

$$M = E_s a^2 t \int_0^{2\pi} \Delta\varepsilon(a,\Theta)\cos\Theta d\Theta \tag{15}$$

Terms in the integrand of equation (15) which are independent of Θ vanish when integrated between the limits, as do all terms in $\cos m\Theta$ except for m=1. Hence

$$\frac{M}{E_s I_s} = \frac{qD}{\pi a^2\left(1 + \frac{\lambda}{aH}\right)} \left\{\frac{\alpha-\alpha_s}{H} + \frac{\alpha_s}{h_{fs}}\right\} \tag{16}$$

where we have used $I_s \approx \pi a^3 t$ for thin-wall tubing. Consequently the deflection is given by

$$\delta = \frac{qD\ell^2}{8\pi a^2\left(1 + \frac{\lambda}{aH}\right)} \left\{\frac{\alpha-\alpha_s}{H} + \frac{\alpha_s}{h_{fs}}\right\} \tag{17}$$

By expressing equation (17) in the form

$$\delta = \frac{\alpha_s \ell^2}{16b} \left[\frac{2qDb}{\pi a^2\left(1 + \frac{\lambda}{aH}\right)} \left\{\frac{\alpha/\alpha_s - 1}{H} + \frac{1}{h_{fs}}\right\}\right]$$

the term in square brackets may be regarded as being equivalent to a temperature difference across the sheath which would produce a deflection equal to that caused by pellet/sheath interaction, thus

$$\Delta T_s(iv) \approx G \frac{2qD}{\pi a\left(1 + \frac{\lambda}{aH}\right)} \left\{\frac{\alpha/\alpha_s - 1}{H} + \frac{1}{h_{fs}}\right\} \tag{18}$$

It should be noted that in equation (18) the G factor has been reintroduced to emphasize that the bowing caused by pellet/sheath interaction depends on the ability of the fuel to grip the sheath.

3. DISCUSSION OF RESULTS OF THEORY

To illustrate the relative importance of the various parameters affecting fuel element bowing, the quantities ΔT_s in equations (7), (8), (9) and (18) are calculated for fuels in two kinds of heavy-water moderated reactors. First is the 200 MW(e) power reactor at Douglas Point, Ontario, which belongs to the family of natural uranium reactors cooled by pressurized heavy-water. The second is WR-1, an enriched, organic-cooled research reactor located at Pinawa, Manitoba. In both reactors the moderator is kept cool and the fuel bundles are contained in zirconium alloy pressure tubes. The fuel for the Douglas Point reactor is UO_2 sheathed in Zircaloy and for WR-1 the driver fuel is UO_2 sheathed in Zr-2½ wt% Nb. In each case the calculations refer to an element in the outer-ring of a bundle. It should also be noted that the pressure tube internal diameter and bundle dimensions are similar for the two reactors.

3.1 Douglas Point Fuel (Natural Uranium)

The numerical values of the pertinent parameters are given in Table I. The flux gradient effect in the element (neglecting pellet/sheath interaction) is given by equation (9),

$\Delta T_s(iii) \approx \frac{2qD}{\pi a}\left[\frac{1}{h_{sc}} + \frac{t}{2\lambda_s}\right]$, where for UO_2 fuel we have neglected λ/aH in comparison with unity. Hence $\Delta T_s(iii) \approx 5^oC$. That is, the difference between maximum and minimum sheath surface temperature due to the flux gradient effect is of the order of 5°C. This will produce a deflection of the order of ~0.07 mm at the mid-span position.

We now inquire as to the variation in coolant heat transfer coefficient which can produce a deflection of this magnitude, i.e. the condition which makes $\Delta T_s(ii) \approx \Delta T_s(iii)$. Equating equations (9) and (8) and substituting the appropriate numerical values gives $\gamma \sim 0.12$. Expressed alternatively,

$$\frac{h_{sc}(max)}{h_{sc}(min} = \frac{1+\gamma}{1-\gamma} = 1.27$$

Similarly we find from equation (7) that a coolant temperature variation of 5°C between diametrically opposite sides of the element will give a deflection equal to that produced by the flux gradient effect. Variations of 5°C in coolant temperature, and about 20 to 30 per cent in heat transfer coefficient around an element, are of the correct order in pressurized water at 280°C flowing through a multi-element bundle at a Reynolds' number of $\sim 10^5$. Thus it is reasonable to deduce that effects (i), (ii) and (iii) cause the element to bow by approximately equal amounts, though not necessarily in the same direction. If there were no fuel/sheath interaction the bow would be small for this reactor, of the order of 0.1 mm or less. It is known, however, that the fuel grips the sheath due to a combination of fuel thermal expansion, small diametral clearances (0.08 mm) and collapse of the sheath down onto the fuel under coolant pressure (10 MPa), consequently it is reasonable to suppose that $G \sim 1$. Hence from equation (17), $\Delta T_s(iv) \sim 29°C$ and $\delta = 0.4$ mm. Mechanical interaction between the pellet stack and the sheath therefore has, in this instance, about 6 times the effect on element bowing than either of the other three factors. Since pellet/sheath interaction dominates, there will be a tendency for the elements in the bundle to bow out towards the wall of the pressure tube. The bows as calculated are elastic deflections; post-irradiation measurements should be less than these unless the thermal and mechanical stresses in the sheath have fully relaxed and there is no further elastic recovery.

3.2 WR-1 Fuel (2.4 wt% ^{235}U in Total Uranium)

The numerical values of the pertinent parameters are given in Table I. Carrying out the calculations as before we find $\Delta T_s(iii) \approx 30°C$ and the corresponding deflection $\delta \sim 0.4$ mm. This is a factor of 6 greater than the previous examples and is attributed to a doubling of the flux gradient factor D (due to fuel enrichment) and to a reduction in the coolant heat transfer coefficient, viz, 13.0 as against 50.0 $kW/m^2{}^\circ C$ for pressurized water. The pellet sheath interaction term gives $\Delta T_s(iv) \sim 74°C$ corresponding to a deflection of 0.96 mm. Thus the combined effect of (iii) and (iv) is to produce a bow of 1.36 mm corresponding to an effective $\Delta T_s \sim 104°C$. For a bow of this magnitude to be produced by a coolant effect alone, a temperature differential of ~104°C would have to exist in the coolant across an element diameter. This is much greater than the coolant temperature differentials measured in WR-1 fuel bundles. Similarly by means of equation (8), it is possible to show that the minimum and maximum heat transfer coefficients would have to differ by a factor of at least 4 in order that a bow of this magnitude could be produced by effect (ii). Thus, given strong pellet/sheath interaction, effects (iii) and (iv) will dominate the bowing pattern of the bundle.

From the previous numerical examples and from an inspection of the formuae for bowing given by equations (7), (8), (9) and (18) we can deduce the important parameters controlling the bow of pelletized fuel elements.

(a) If $G \sim 1$, the mechanical interaction between pellet stack and sheath will dominate the magnitude and the direction of the bow. The deflection will be in the direction of maximum neutron flux and this direction will generally be towards the wall of the pressure tube. Any factor in the design or operation of the element which increases the mechanical interaction between fuel and sheath will tend to increase the amount of bowing and vice versa.

(b) Bowing increases with increasing element power (q) and with increasing "blackness" to thermal neutrons (increasing κ) within the channel. If there is appreciable variation in neutron flux along the length of the element, the bowed shaped will be skewed towards the high flux end of the element.

(c) Fuel elements bow more when cooled by poor heat transfer media. Other factors equal, one would expect bowing to increase in the order of the following coolants: boiling water, pressurized water, organic, steam, gas. Boiling water channels in a power reactor may have heat transfer coefficients as high as 100 kW/m^2°C, but if the liquid cooling film becomes unstable and the whole element goes into dry-out then the heat transfer coefficient can drop to ~2.0 kW/m^2°C and the bow will increase by a factor of about 3 in the direction of the pressure tube. If dry-out occurs along one side of the element the bow will increase by about the same factor, but will be in the direction of the dry-out surface.

4. EXPERIMENTAL RESULTS

Some experimental results are presented to support the theoretical conclusions arrived at in sections 2 and 3. The nature of the problem makes it difficult to model the phenomenon exactly and does not permit a quantitative comparison to be made between theory and experiment. We have therefore restricted ourselves to comparing trends predicted by the theory with those observed in several experimental irradiations made in the WR-1 reactor.

Continuous traces of element bow as a function of length were obtained using a LVTD which measured the deflection of an element from its central axis. Deflections in several orientations can be obtained, but all the results shown here are for bending in the 0-π plane i.e., the direction which coincides with the vector CO. Since all measurements were made during out-of-core examinations they reflect only the amount of permanent or plastic deflection which occurred during irradiation. This does not obscure the effects on bowing of the several variables studied as will become evident during the discussion.

4.1 Effect of Diametral Clearance on Fuel-Sheath Mechanical Interaction

We have seen that under normal operating conditions theory suggests that the dominant factor governing bowing is the amount of mechanical interaction between the fuel pellets and sheath. To demonstrate the effect of fuel/sheath interaction on bowing we irradiated a number of UO_2 and UC elements having a range of diametral clearance. In assessing the results of the irradiations, which are shown in figures 4 to 7, the following two factors are relevant; (a) the cladding in these tests is stable under the low organic pressure (1.5 MPa), consequently any interaction between fuel and sheath must be the result of differential thermal expansion and, for longer exposures, swelling of the fuel due to irradiation effects, (b) the thermal conductivity of UC is a factor of 6 greater than UO_2, and for otherwise similar conditions the UC will expand less than UO_2.

The results of the irradiations clearly demonstrate the effect of diametral clearance on the development of bow, and are consistent with factors (a) and (b). In figure 5 it should be noted that the low clearance elements have bowed into contact with the channel wall at the location of the mid-span bearing pad. This location has now become a point of restraint, and the element continues to bow outward between this point and the end of the element (uppermost dashed curve). A second examination of the UC fuel at a higher burnup, figure 7, suggests that increased mechanical interaction is occurring in the high diametral clearance elements since they too are beginning to bow in the direction of maximum neutron flux, i.e. toward the coolant channel wall.

4.2 Effect of Neutron Flux Gradients

A stainless-steel sheathed element from an experiment intended to test the performance of UC fuel at high rating and to long burnups was rotated about its longitudinal axis through an angle of 180° after being irradiated for 2408 hours to a burnup of 100 MWh/kgU. The first period of irradiation resulted in a bow directed towards the coolant tube wall, i.e. in the direction of maximum neutron flux as shown in figure 2. The element was then rotated about its longitudinal axis through an angle of 180° so that the bow was directed towards the center of the coolant channel and away from the wall. If non-uniform heat transfer between sheath and coolant or non-uniform coolant temperature are to control thermal bowing then the element should now bow further toward the center of the coolant channel. As seen in figure 8, the measured deflections indicate that the element bowed in the direction of the channel wall during succeeding periods of the irradiation. This is a vivid demonstration that asymmetric heat generation in the fuel due to a neutron flux gradient across the element is controlling the magnitude and direction of element bow.

An example of the temperature distribution due to asymmetric heat generation in UO_2 can be obtained by observing the grain growth patterns on cross-sections of irradiated fuel as shown in figure 9. The displacement of the peak fuel temperature, defined by the position of the axial void which formed during irradiation, is ~1 mm. This is 13 - 14 per cent of the element radius and lies in the direction of maximum neutron flux as defined by the arrow.

4.3 Effect of Sheath Creep Strength

A comparison of the effect of sheath creep strength on bow has been made using several UC fuelled elements sheathed in either Zr-2½ wt% Nb or 304 stainless steel tubing. The increase in permanent bow with irradiation time for two of these elements is shown in figure 10. The element sheathed in stainless steel clearly exhibits less bow than the one sheathed in the zirconium alloy. The explanation for this is thought to be the difference in creep strength of the two materials. The effect on bow of a larger coefficient of thermal expansion for stainless steel compared to the zirconium alloy is small and can be neglected in considering the differences shown in figure 10. Sheath temperatures during this irradiation were in the range of 450 - 485°C and for the same stress it is estimated that the stainless steel sheathing would have a creep rate 3 or 4 orders of magnitude lower than Zr-2½ wt% Nb.

4.4 Effect of Pellet Length

A few remarks can be made about the effect of pellet length on element bowing. A reduction of pellet length/diameter ratio tends to reduce the amount of bowing in the initial stages of irradiation and this effect has been observed in UO_2 fuels cooled either with organic or with pressurized water [6]. This reduction, though measurable, was relatively small compared to the effect of increasing fuel/sheath clearance. The conclusion arrived at in reference [6] is that the fuel design giving lowest axial strain will cause the least bowing. Decreases in axial strain with reduction in pellet length have been reported previously [7] and lend some support to this conclusion.

5. CONCLUSIONS

It has been demonstrated both theoretically and experimentally that reducing the mechanical interaction between pellet stack and sheath reduces element bowing. One way of achieving this in a fuel design which uses free standing sheath in which there is a certain amount of interaction at power is to increase the initial clearance between fuel and sheath. This delays the onset of appreciable bowing, and increases the burnup at which permanent element distortions caused by bowing may lead to element failure or to difficulties in removing fuel assemblies after irradiation. Increasing initial fuel-sheath clearance also reduces element diametral expansion in this type of fuel design. It is now known that diametral expansion of the elements in a typical close packed, multi-element bundle makes a considerable contribution to the generation of the large sticking forces associated with removing bowed fuel assemblies from the WR-1 reactor. Thus, increasing initial fuel-sheath clearance can serve a dual purpose in improving the performance of WR-1 fuel.

Our conclusion, that given a strong pellet/sheath interaction the deflection of the element will be in the direction of the coolant tube, is given further support by recent measurements of in-reactor bowing using strain-guage bowmeters. The bowmeters consist of beams with strain guages which are loaded by the fuel elements during initial assembly. A lateral deflection of the fuel element during irradiation is detected as a change in the bending strain in the beam. Preliminary results indicate that bowing is directly proportional to changes in reactor power, as expected, and is in the direction of the coolant tube.

A device for measuring the forces required to move fuel assemblies with the reactor at power has been developed at WNRE and is now being used to monitor fuel moving forces as a function of operating history. These experimental techniques coupled with a fundamental understanding of bowing mechanisms will allow fuel designers to better assess the role of element bowing in the performance of various fuel designs.

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TABLE I

NUMERICAL VALUES OF PARAMETERS USED FOR CALCULATIONS IN SECTIONS 3.1 AND 3.2

	Douglas Point	WR-1
a	7.2 mm	7.2 mm
t	0.4 mm	0.68 mm
ℓ	500 mm	500 mm
κa	0.26	0.40
κR_i	1.20	1.90
D	0.032	0.07
$\bar{w}$	1.04 MW/m^2	0.94 MW/m^2
q	50.0 kW/m	46.5 kW/m
α_s	6.5 µm/m.°C	6.5 µm/m.°C
α	11.0 µm/m.°C	11.0 µm/m.°C
λ_s	0.013 kW/m.°C	0.013 kW/m.°C
λ	0.003 kW/m.°C	0.003 kW/m.°C
h_{sc}	50.0 kW/m^2.°C	13.0 kW/m^2.°C
h_{fs}	10.0 kW/m^2.°C	10.0 kW/m^2.°C
$\bar{T}_c$	280°C	350°C

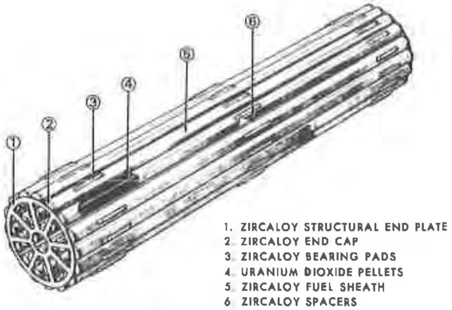

Figure 1: 28-Element CANDU Fuel Bundle

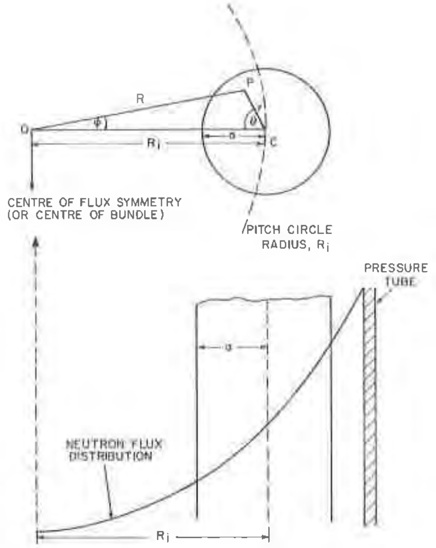

Figure 2: Co-ordinate System Used in the Analysis

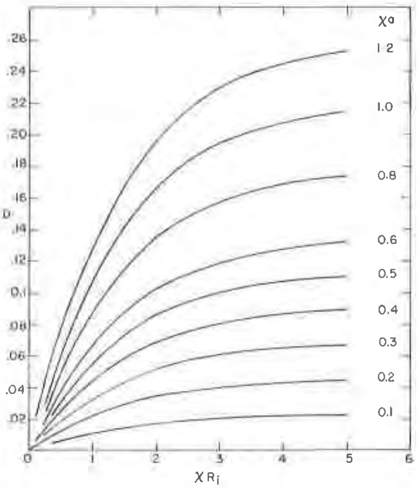

Figure 3: Flux Gradient Factor D Versus κR_i and κa

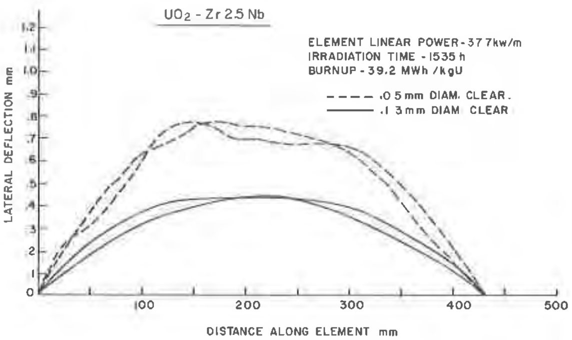

Figure 4: Bowing of Fuel Elements with Different Diametral Clearances

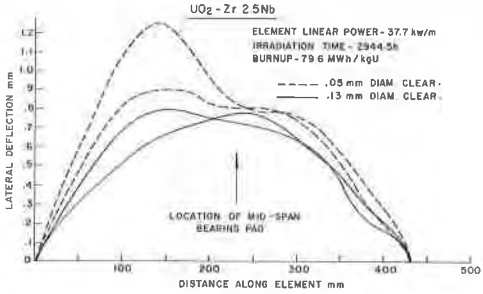

Figure 5: Same Elements as in Figure 4 after 2944 hours

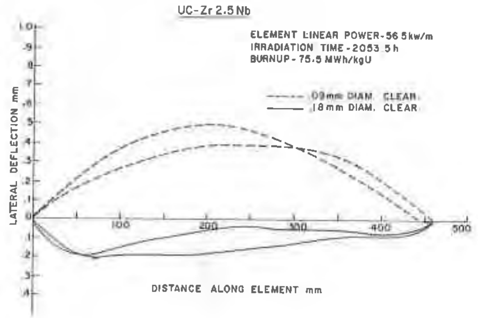

Figure 6: Bowing of Fuel Elements with Different Diametral Clearances

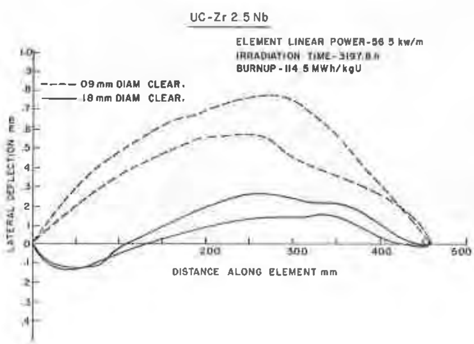

Figure 7: Same Elements as in Figure 6 after 3198 hours

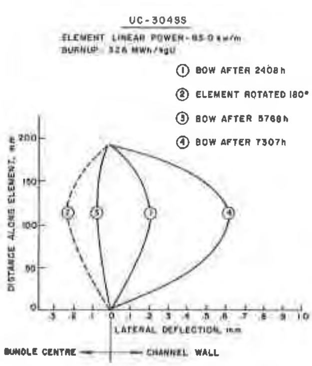

Figure 8: Results of Experiment to Demonstrate the Effect of Neutron Flux Gradient Across an Element

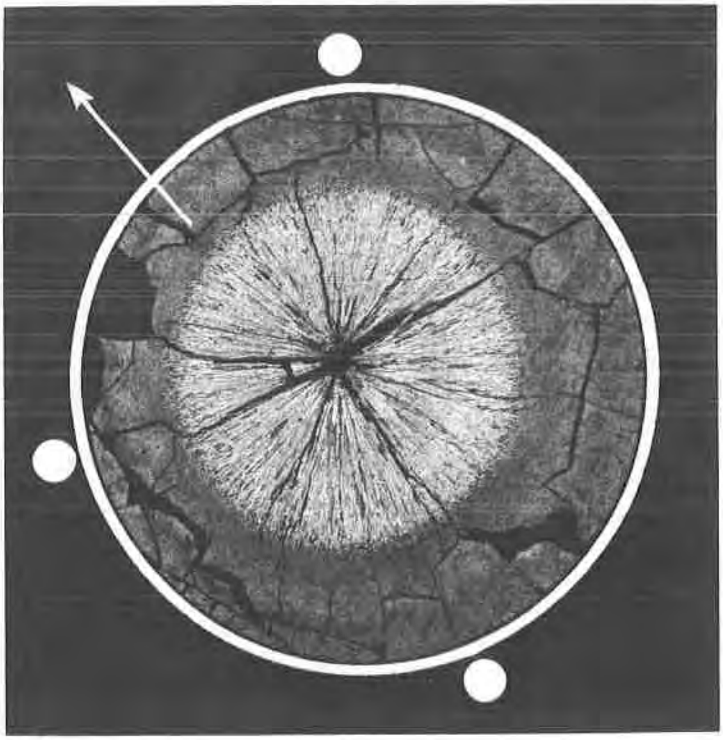

Figure 9: Displacement of Grain-growth Pattern in UO_2 in the Direction of Maximum Neutron Flux (see section 4.2)

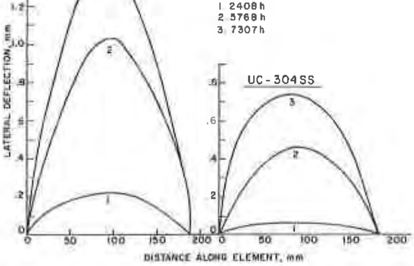

Figure 10: Illustrating the Effect of Cladding Creep Strength on Residual Bow