AECL CANDU OPERATIONS

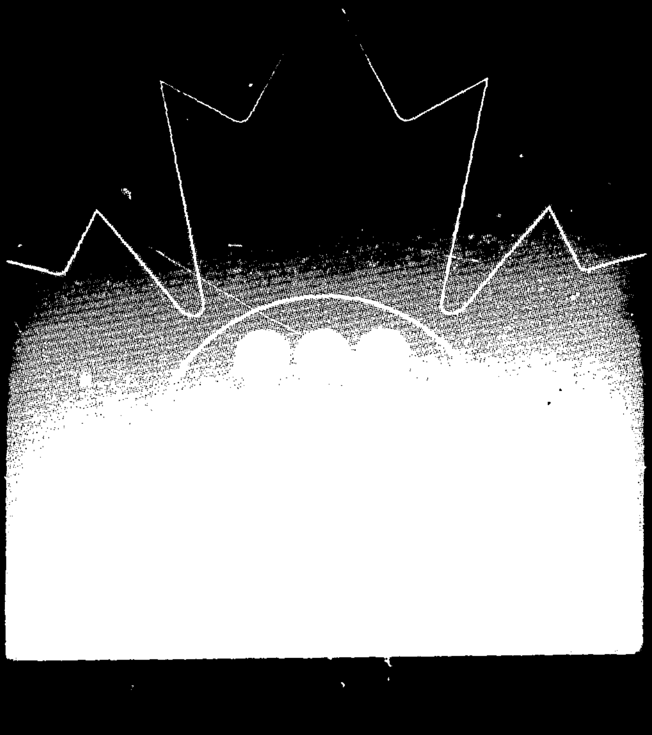
The Integrity of CANDU Fuel during Load Following

by M. Tayal*, A. M. Manzer*, R. Sejnoha*,
Y. Kinoshita**, A. J. Hains***

presented at:
The Tenth International Conference on
Structural Mechanics in Reactor Technology,
Anaheim, California, U. S. A.
Division C, August 14-18, 1989

AECL-9797

August 1989



Atomic Energy of Canada Limited
Énergie atomique du Canada limitée
CANDU Operations
Opérations CANDU

Sheridan Park Research Community
Mississauga, Ontario, Canada L5K 1B2

The Integrity of CANDU Fuel during Load Following

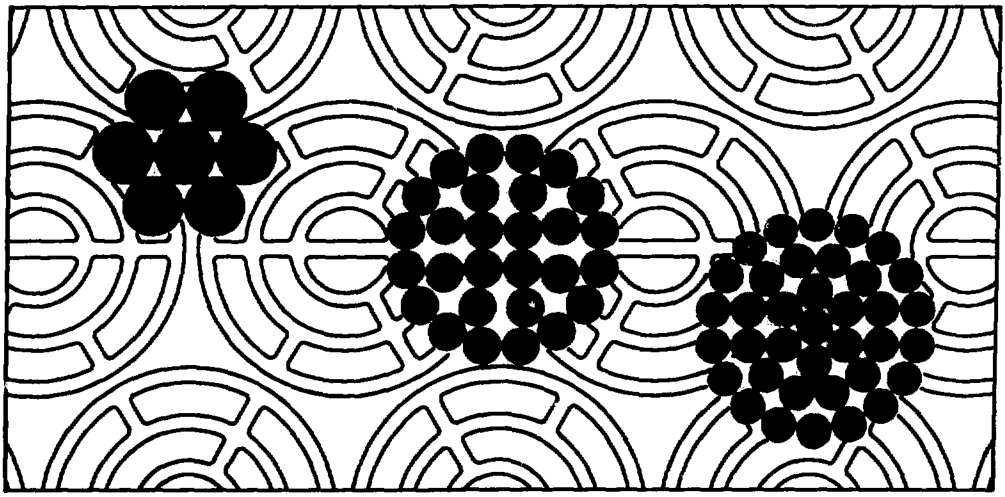
by M. Tayal*, A. M. Manzer*, R. Sejnoha*,
Y. Kinoshita**, A. J. Hains***

presented at:
The Tenth International Conference on
Structural Mechanics in Reactor Technology,
Anaheim, California, U. S. A.
Division C, August 14-18, 1989

AECL-9797

August 1989

FUEL BRANCH



SAFETY ENGINEERING DEPARTMENT

* Atomic Energy of Canada Ltd., Mississauga, Canada

** Electric Power Development Company, Ltd., Tokyo, Japan

*** Ontario Hydro, Toronto, Canada

Atomic Energy of Canada Limited
CANDU Operations

Énergie atomique du Canada limitée
Opérations CANDU

AECL-9797

Sheridan Park Research Community
Mississauga, Ontario, Canada L5K 1B2

The Integrity of CANDU Fuel during Load Following

by M. Tayal*, A. M. Manzer*, R. Sejnoha*,
Y. Kinoshita**, A. J. Hains***

presented at:
The Tenth International Conference on Structural Mechanics in Reactor Technology, Anaheim, California, U. S. A.
Division C, August 14-18, 1989

August 1989

Abstract

This paper summarizes data and analyses of integrity and of physics of CANDU fuel during load following. Measurements of irradiated fuel show that power cycles do not enhance release of fission gas. Data from research reactors show that the power cycles cause cyclic strains in the sheath. Finite element analyses show that the cyclic strains give highly multiaxial stresses in the sheath. The stresses and the strains are well into the plastic range. The cyclic loads 'use up' some fraction of the sheath's resistance to environmentally- assisted cracking (EAC), depending on the details of the fuel design and of the power cycles. The balance of the sheath's resistance to EAC continues to be available to counteract static loads.

Thousands of fuel bundles have experienced many power cycles in research and in commercial reactors. Overall integrity of fuel bundles is well over 99%. Thus, CANDU fuel continues to show good performance in both base-load and in load-following reactors.

Intégrité du combustible CANDU en suivi de charge

par M. Tayal*, A. M. Manzer*, R. Sejnoha*,
Y. Kinoshita**, A. J. Hains***

**Dixième conférence international sur la mécanique des structures dans la technologie des réacteurs
Anaheim, California, É.-U.**
DivisionC, 14 au 18 aout 1989

Août 1989

Résumé

La présente communication résume les données et les résultats d'analyse sur l'intégrité et la physique du combustible CANDU en suivi de charge. Les mesures effectuées sur le combustible irradié montrent que les cycles de puissance n'augmentent pas la libération de gaz de fission. Les données provenant des réacteurs de recherche montrent que le cyclage de puissance provoque des déformations sous l'effet de la fatigue dans la gaine.Les analyses par la méthode des éléments finis montrent que ces déformations créent des contraintes à forte multiaxialité dans la gaine. Les sollicitations et les contraintes sont bien à l'intérieur des limites du domaine plastique. Les charges cycliques "épuisent" une fraction de la résistance de la gaine à la fissuration accélérée par le milieu, selon la conception détaillée du combustible et le type de cyclage. Une certaine résistance de la gaine à la fissuration accélérée par le milieu est toujours présente pour neutraliser les charges statiques.

Des milliers de grappes de combustible ont subi de nombreux cycles de puissance dans les réacteurs de recherche et commerciaux. Plus de 99% des grappes de combustible ont maintenu leur intégrité. Le combustible CANDU, donc, continue de donner un bon rendement à la fois dans les réacteurs fournissant la charge de base et dans ceux fontionnant en suivi de charge.

---

* Atomic Energy of Canada Ltd., Mississauga, Canada

** Electric Power Development Company, Ltd., Tokyo, Japan

*** Ontario Hydro, Toronto, Canada

Table of Contents

Page

1. Introduction 1
2. Mechanistic Perspective 1
3. Parts at Risk 4
4. In-Reactor Experience 6
5. Conclusions 8
6. References 8

List of Figures

Page

Figure 1 Typical CANDU Fuel 1
Figure 2 Strain Cycles Measured in the Reactor 3
Figure 3 Impact of Power Cycling on Fuel Integrity 4
Figure 4 Distribution of Elastic-Plastic Stresses across the Sheath Thickness, near the Weld Line 5
Figure 5 Defect Thresholds for EAC applied to KANUPP Data 7

1. INTRODUCTION

The performance of CANDU* fuel, which uses natural uranium, is excellent: The historical bundle defect rate, about 0.1% in 700,000 bundles irradiated, is very low at core-average discharge burnups of 7-9 GWd/tU. Since the introduction of Canlub sheath coating, of new fuel management schemes, and of improved quality assurance, it has been less than 0.1%.

Though CANDU, and most other commercial nuclear reactors, are generally operated at steady high power (base-load) to take advantage of low fuel cost, there is a trend towards periodic variations in reactor power (load-following), to respond to grid requirements. This is particularly so as nuclear-generated electricity becomes a significant fraction of the capacity of the grid. This paper reviews the impact of load following on the integrity of CANDU fuel. It updates the previous assessments on this subject (Carter et al, 1983), which generally concluded that CANDU fuel could load follow successfully within the power and burnup ranges typical of natural-UO_2 fuel. Since that study, further data on the integrity of CANDU fuel during load following have been collected from research reactors, from power reactors (Embalse, Wolsung, Bruce), and from analyses. This article gives a summary.

During its residence in a CANDU-6 reactor, a natural UO_2 fuel bundle can experience 190-750 power cycles if the load following is done every day. Enriched fuel would have longer residence in the reactor, hence it would experience a proportionately higher number of cycles. Since data for that many cycles are sparse, there is a need for extrapolations. For this reason, the available data have been interpreted here from a mechanistic perspective.

2. MECHANISTIC PERSPECTIVE

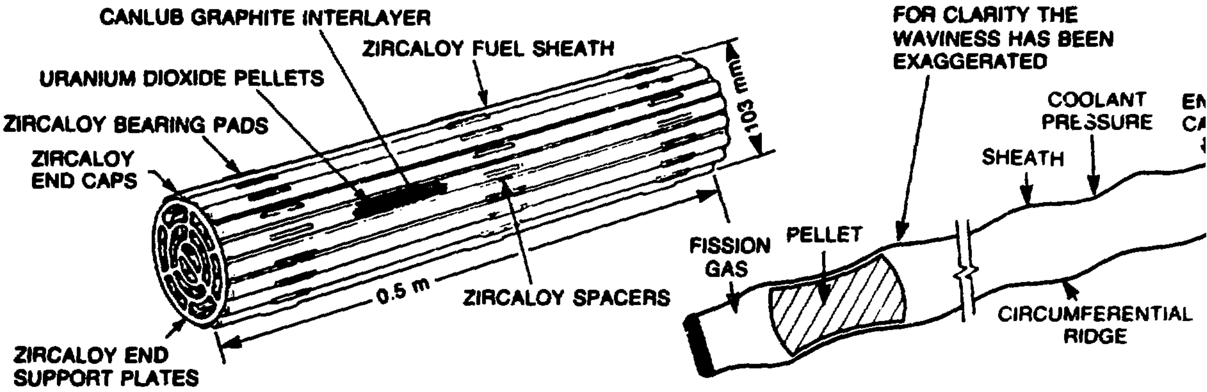
Figure 1 identifies the components of a fuel bundle. As noted earlier, fuel integrity is very high. The following mechanisms account for the few failures that have occurred:

- Environmentally-assisted cracking: ~35% of the defects.
- Fretting due to debris in the primary heat transport system: ~15% of the defects.
- Manufacturing, miscellaneous, and unknown: ~50%

Thus, from the perspective of fuel design, the major threat to fuel integrity comes from environmentally-assisted cracking (EAC). It occurs when a large stress is maintained for an extended time, simultaneously with high concentrations of corrodants. Initiation of environmentally- assisted cracks is easier in the presence of suitably oriented platelets of zirconium hydrides (or deuterides). Another way in which irradiation promotes EAC, is by embrittling the Zircaloy. The tensile stresses in the sheath are provided mainly by pellet expansion; the coolant pressure and fission gas pressure also play a role. The corrodants are provided by the fission products.

---

* CANDU: CANada Deuterium Uranium



(a) BUNDLE (b) ELEMENT

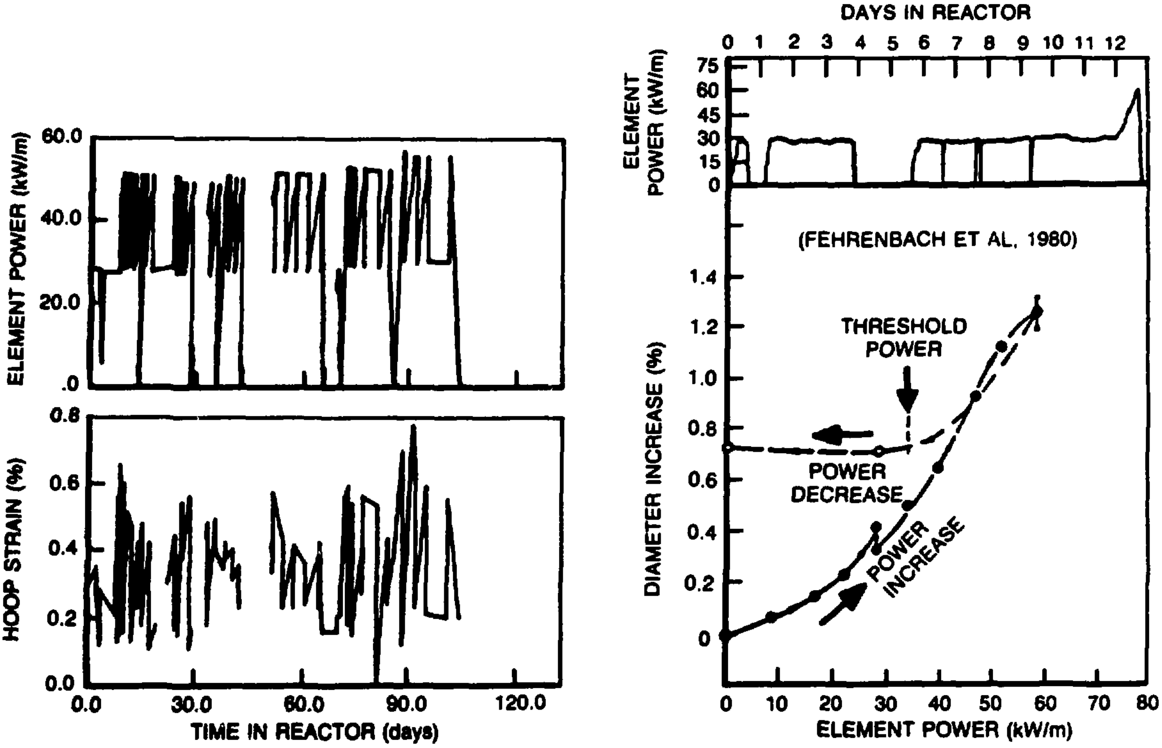
FIGURE 1 TYPICAL CANDU FUEL

2.1 FISSION GAS RELEASE

Power cycles are not expected to change the production of the gas, nor its diffusion to grain boundaries. Thus, the cycles do not change the inventory of gas at the grain boundaries. The cycles do, however, lead to more frequent cracking/healing of the pellets, causing more frequent releases of the stable gas to the pellet/sheath gap. Therefore, the same total volume of gas reaches the gap, but in a more continuous manner. Since the stable gases provide the bulk of total gas release, the total volume of fission gas release is not influenced by power cycling. This has now been confirmed via measurements of gas release in fuel irradiated in the Bruce-B reactors: Fuel that had experienced load-following showed no significant difference in gas release compared to similar fuel that had experienced similar power and burnups but had not undergone load-following (Truant et al, 1987).

2.2 STRESSES/STRAINS

Tests at Chalk River Nuclear Laboratories (CRNL), Canada, showed that repeated changes in power can apply cyclic strains on the sheath (Fehrenbach et al, 1980). They are caused by the thermal expansions and the contractions of the pellets in response to the changes in element power. Earlier experiments had suggested that only the first few cycles in power give significant cycles in sheath strains, and that successive cycles in power give substantially lower amplitudes of cyclic strains (Notley et al, 1972). However, more recent experiments show that the strain cycles can persist (Fehrenbach et al, 1980); see Figure 2a. Persistent cyclic hoop strains of up to 0.4% have been measured (Fehrenbach et al, 1980). The difference between the two experiments is attributed to their different operating conditions, suggesting that the details of the power histories play an important role in influencing sheath integrity.



(a) IRRADIATION ABH

(b) IRRADIATION ACK

FIGURE 2 STRAIN CYCLES MEASURED IN THE REACTOR

Figure 3 shows the impact of load following on fuel integrity. A central issue is environmentally-assisted cracking of the sheath, under the combined influences of static and of cyclic stresses. This means that the cyclic loads can potentially 'use-up' some fraction of the sheath's life. This can combine with the life used-up during a previous or during a subsequent power-ramp, increasing the likelihood of fuel defects.

The fission products provide a corrosive environment inside the sheath. Experiments confirm that corrosive environments can significantly reduce the fatigue life of Zircaloy: Specimen were subjected to repeated cycles of strains in air containing 30 g/m^3 of iodine and with a hold time of 1h. These specimens failed in 5 to 6 times fewer cycles than control specimens tested without iodine and with zero hold-time (Hosbons, 1973). Thus the sheath integrity also depends on the fission product concentration at the sheath inner surface, and on the magnitude, the duration, and the number of the stress/strain cycles. These in turn depend on reactor operation and on fuel design details like the shape, the size, the density and the enrichment of the pellet. Thus, the total additional risk from the power cycles depends on the following parameters:

a. the burnup (affects irradiation-embrittlement of Zircaloy; and affects the mass of fission products in the fuel element),

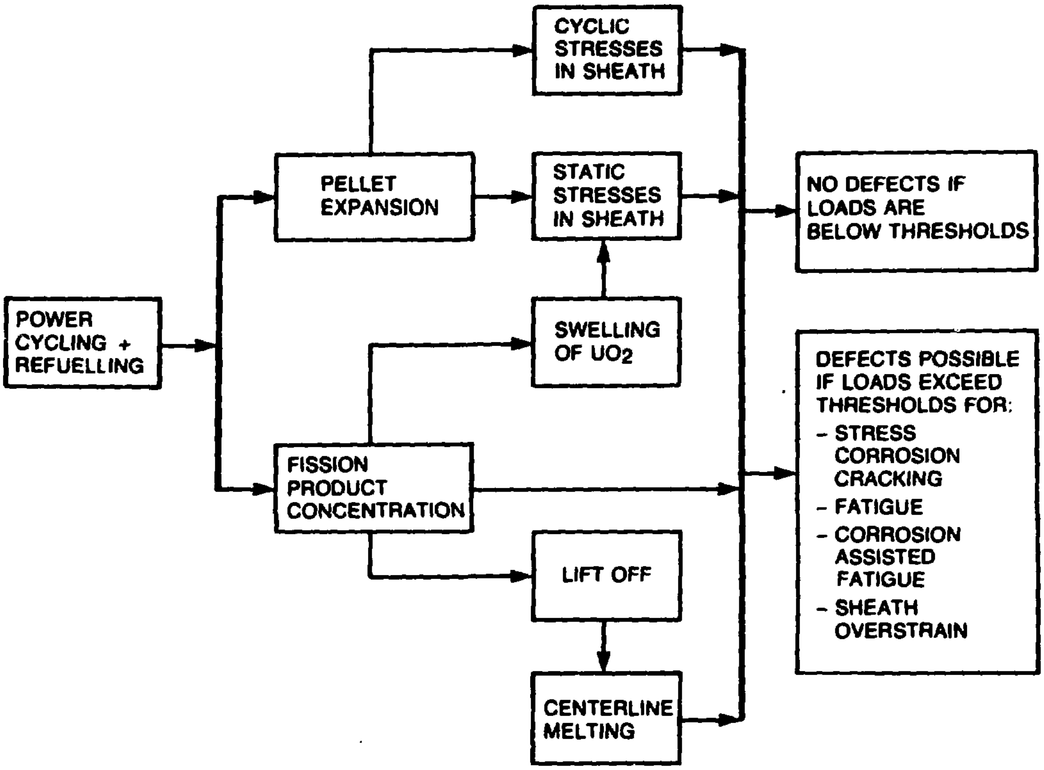


FIGURE 3 IMPACT OF POWER CYCLING ON FUEL INTEGRITY

b. the nominal power (affects the fission product concentration; overall level of stresses; and preconditioning),
c. the amplitude, frequency, and number of the power cycles (affect the stress cycles and the fraction of life 'used-up'), and
d. the internal design of the fuel element, such as UO$_2$ density and the pellet geometry (shape, size, etc.) (affects the stresses).

3. PARTS AT RISK

The stress/strain cycles in the sheath are highest at the following two locations, see Figure 1:

- circumferential ridge
- re-entrant corner near the sheath/end cap weld.

These two locations are therefore at the most risk. At these locations, the factors pertinent to corrosion-assisted fatigue compare as follows:

- Stresses: can be higher at the weld, due to the stress concentrations introduced by the re-entrant corner. Figure 4 shows the stress distribution near the weld, calculated by using the finite element code FEAST. The stresses are highly multiaxial, and well into the plastic range. The predictions for principal stresses match the observations for the location and the direction of potential cracks (Tayal et al, 1985). These stresses, caused by pellet expansion, relax rapidly due to thermal recovery.

- Strains: higher at the ridge, due to pellet hourglassing. Multiaxial strains, well into the plastic range, have previously been reported at the ridge (Tayal et al, 1985).

- Fission product concentration (FPC): The Canlub coating lowers fission product concentrations at the Zircaloy surfaces in proportion to the local thickness of the Canlub layer, which is likely thicker at the ridge than at the weld. Thus, the protection provided by the Canlub coating, to the sheath against the fission products, is greater at the ridge than at the weld. On the other hand, the Zircaloy end caps are expected to absorb, via 'gettering', some fraction of the fission gas released from the central regions of the pellets at the ends of the fuel stack. This effect would tend to lower the FPC at the weld.

Because of the above parallel effects, which of the two locations is more at risk depends on many details of the internal design of the fuel element.

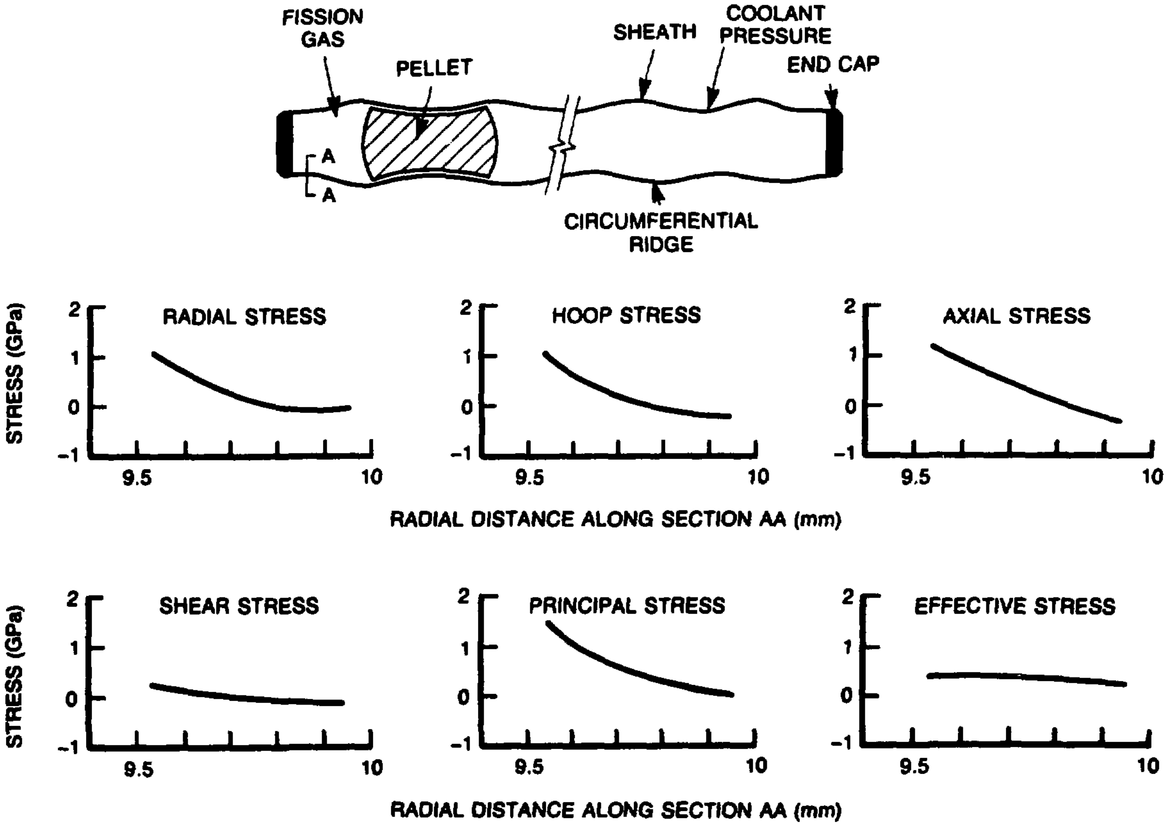


FIGURE 4 DISTRIBUTION OF ELASTIC-PLASTIC STRESSES ACROSS THE SHEATH THICKNESS, NEAR THE WELD LINE

4. IN-REACTOR EXPERIENCE

In the last few years, thousands of fuel bundles have experienced up to 40 large (≥20%) power cycles in commercial CANDU reactors. Overall fuel performance remains excellent: The fuel defect stayed near the target of 0.1% for all stations.

In the research reactor loops at Chalk River Nuclear Laboratories (CRNL), nine fuel elements have received 60 power cycles, mostly between 30 and 60 kW/m. The highest hoop strain was 1.8%. At the circumferential ridge, cyclic hoop strains of up to 0.4% have been measured. No fuel failures were attributed to power cycling.

Figure 2b illustrates how sheath strains respond to power cycles (Fehrenbach et al, 1980). The sheath strain increases as the power is increased. When the power is decreased, the sheath strain first decreases rapidly because of elastic recovery and because of elastic compression under coolant pressure. Beyond a certain decrease in power, however, further decreases in power are accompanied by a much slower rate of decrease in sheath strain; creep under coolant pressure is the mechanism for sheath strain in this range. This power is called the threshold power for elastic strain. Below this power, the power cycles have a negligible influence on sheath strains. The threshold power for elastic strain depends on the fuel design and on the power history prior to and during the power cycles. For the nine tests at CRNL, the threshold power for elastic strain ranged between 24 and 58 kW/m.

In the Embalse reactor in Argentina, individual fuel bundles have received a total of 30-40 power cycles during weekly load following. The defect rate in Canadian fuel is very low at Embalse: 0.11%. One Canadian bundle has defected during a power increase in a high-power channel after 2½ months of load following - Bundle #7, channel S14. The 'defect' may either be an 'opening up' of a fabrication flaw, or environmentally-assisted cracking, or a combination of the two. At the time of failure (95% reactor power) the bundle in channel S14 was below the defect threshold for failure by environmentally-assisted cracking under static stresses, hence failure was not expected.

Finite element calculations showed that the power cycles caused cycles of $\sim$40 MPa (average-to-peak) in the hoop stress at the ridge, superposed on a static component of hoop stress. The resulting fatigue is accelerated by radial, axial and shear components of stresses (Tayal et al, 1985). Due to stress-concentration, the stress-cycle is higher near the sheath/endcap weld. In comparison, the design-recommendation for the endurance limit of Zircaloy at 300°C is 55 MPa in inert environments (O'Donnel et al, 1964). As noted earlier, Hosbons' data show that corrosive environments can reduce the cycles-to-failure by a factor of 5-6. Since the magnitude of the stress cycle in S-14/7 is a significant fraction of the endurance limit, the cyclic stresses, and the resulting corrosion-assisted fatigue, may have contributed to the failure of S-14/7, in combination with environmentally-assisted cracking from static stresses due to the power-ramp. This mechanism may have opened-up an existing flaw in the weld between the sheath and the endcap, or may have produced a primary defect at the end of the fuel element. For this reason the role of cyclic stresses in assisting this failure cannot be ruled out at this time.

The Wolsung reactor in the Republic of Korea normally operates in the 'alternate mode', which shields the fuel from power fluctuations driven by minute-to-minute perturbations in grid demand. Fuel defect rate is again very low: 0.14%. During a test in 1984, fuel bundles experienced ∿1200 cycles in two days. The cycles were rapid (2 minutes apart on average), and of low amplitude (∿1 kW/m). No fuel failures occurred.

Thirty-four non-Canlub fuel bundles failed in the KANUPP reactor in Pakistan after about 90 cycles in power during 1973/74. Although the current reference fuel design contains Canlub coatings in all 37 elements, the failures of the non-CANLUB bundles provided an interesting insight. The defects occurred during power increases in the fuel elements at high-power positions, and were attributed to environmentally-assisted cracking. The existing correlations for EAC are based on single power-ramps (Penn et al, 1977), and do not consider the role of corrosion-assisted fatigue (CAF). In the 146 KANUPP fuel bundles for which detailed data are available, the existing correlations for EAC suggest that EAC should have produced five defects in the non-Canlub fuel. Hence, with 34 actual defects, the role of corrosion-assisted fatigue (CAF) is presently not ruled out in helping EAC.

In 1985-1986 the three commissioned 837 MWe reactors in the Bruce-B station in Canada performed 30-40 power cycles in the range 10 to 50% full power. No fuel defects were attributed to this mode of operation. Ontario Hydro expect to do much more generation maneouvering in the coming years.

Overall fuel performance continues to be excellent in the commercial CANDU reactors. A preliminary attempt has been made to empirically quantify the role of corrosion-assisted fatigue on defect thresholds. This involved modifying the curves for defect thresholds to reflect the KANUPP data while accounting for the effect of CANLUB. If the effect of CANLUB on CAF is similar to the effect of CANLUB on EAC under static stresses, then Figure 5 shows the role of CAF on defect thresholds, for the type of power cycles experienced by KANUPP fuel. Compared to single ramps, power cycles lower the power increases at which defects begin, by

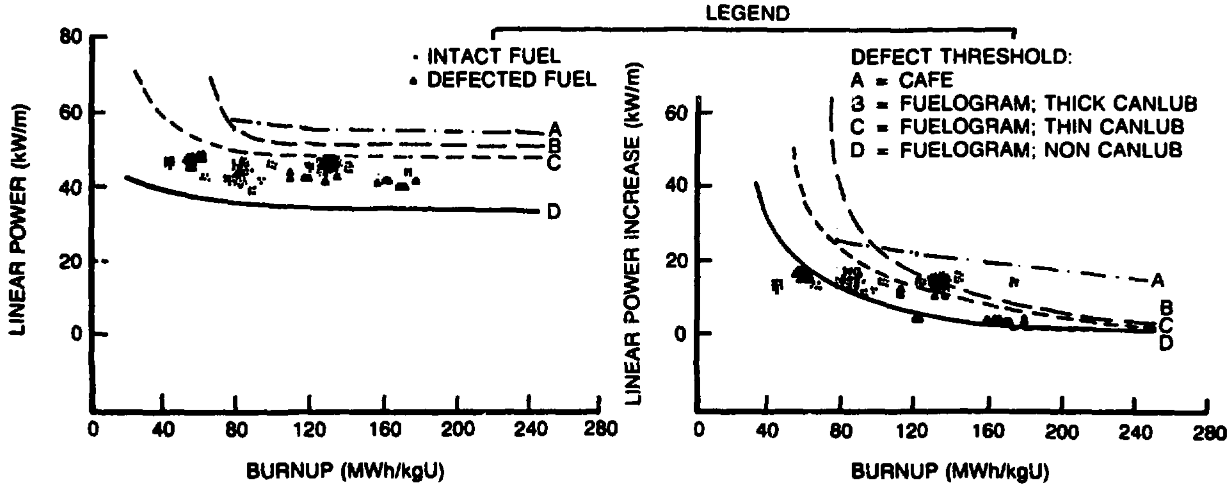


FIGURE 5 DEFECT THRESHOLDS FOR EAC APPLIED TO KANUPP DATA

0-10 kW/m, depending on burnup. A similar analysis for the Embalse fuel shows that the defect threshold for ramped power is lowered by ∿5 kW/m. The effect could be more pronounced for larger number of cycles.

Programs are in progress to improve the reliability of CANDU fuel even further, e.g. to more severe combinations of load following at higher burnups. This involves enhancements in the internal and in the external designs of the fuel element. The approach is to reduce the stresses and the fission product concentrations at locations most susceptible to EAC.

5. CONCLUSIONS

Power cycles do not appear to enhance fission gas release. Data from research reactors show that the power cycles cause cyclic hoop strains of 0-0.4% in the sheath. Threshold powers for elastic strains have been observed below which the power cycles have a negligible influence on sheath strain. They range beteween 24-58 kW/m, and are within the operating range of power reactors. The magnitudes of the strain cycles and of the threshold powers for elastic strains depend on the fuel internal design and on the power history prior to and during the power cycles. Finite element analyses show that the cyclic strains give highly multiaxial stresses in the sheath. The stresses and the strains are well into the plastic range. The predictions for principal stresses match the observations for the location and the direction of potential cracks. The cyclic stresses 'use up' some fraction of the sheath's resistance to environmentally-assisted cracking. Compared to single ramps, power cycles lower the power increase at which environmentally-assisted cracking begins, by 0-10 kW/m depending on the burnup, on the number and the magnitude of the cycles, and on the details of the internal fuel design. The corresponding threshold for ramped power is lowered by ∿5 kW/m.

In the research reactors, individual fuel elements have successfully experienced up to 60 cycles, mostly between 30 and 60 kW/m. In the Embalse reactor in Argentina, fuel has experienced about 35 weekly cycles, between 70 and 100% power. In the Wolsung reactor in the Republic of Korea, individual bundles have experienced ∿1200 cycles, but mostly of low amplitude: ∿1 kW/m. In some Bruce-B reactors in Canada, the fuel has experienced 30-40 daily/weekly cycles during spring when hydro power is abundant. Integrity of fuel bundles is well above 99%.

Thus, CANDU fuel continues to show good performance in both base load and in load following reactors.

6. REFERENCES

Carter, T.J., and Fehrenbach, P.J. (1983). The Load Following Capability of CANDU Fuel. Atomic Energy of Canada Limited, Report AECL-7096.

Fehrenbach, P.J. and Morel, P.A. (1980). In-reactor Measurement of Clad Strain: Effect of Power History. Atomic Energy of Canada Limited, Report AECL-6686.

Hosbons, R.R. (1973). Low-Cycle Fatigue Behaviour of Zircoloy at 573 K. Atomic Energy of Canada Limited, Report AECL-4547.

Notley, M.J.F., Pettigrew, M.J., and Vidal, H. (1972). Measurement of the Circumferential Strains of the Sheathing of UO_2 Fuel Elements During Reactor Operation. Atomic Energy of Canada Limited, Report AECL-4072.

O'Donnel, W.J., and Langer, B.F. (1964). Fatigue Design Basis for Zircaloy Components. Nuclear Science and Engineering, Vol. 20, pp 1-12.

Penn, W.J., Lo, R.K., and Wood, J.C. (1977). CANDU Fuel - Power Ramp Performance Criteria. Nuclear Technology, Vol. 34, pp 249-268.

Tayal, M., and Lim, D. (1985). Recent Uses of the Finite Element Method in Design/Analysis of CANDU Fuel. Atomic Energy of Canada Limited, Report AECL-8754.

Truant, P., Hains, A.J., and Lau, J.H. (1987). Generation Maneuvering at Bruce NGS-B: Fuel Fission Gas Release Results. Proc. IAEA Conf. on Power Ramping, Cycling and Load Following Behaviour of Water Reactor Fuel. IAEA-TC-624/11, pp 17-18.

The International Standard Serial Number

ISSN 0067-0367

has been assigned to this series of reports.

To identify individual documents in the series
we have assigned an AECL-number.

Please refer to the AECL-number when requesting additional
copies of this document from:

Scientific Document Distribution Office
Atomic Energy of Canada Limited
Chalk River, Ontario, Canada
K0J 1J0

Price Code A

Le numéro de série standard international

ISSN 0067-0367

a été attribué à cette série de rapports.

Pour identifier les rapports individuels faisant partie de cettessérie
nous leur avons attribué un numéro AECL-.

Veuillez faire mention du numéro AECL- si vous demandez
d'autres exemplaires de ce rapport au:

Service de Distribution des Documents Officiels
L'Energie Atomique du Canada, Limitée
Chalk River, Ontario, Canada
K0J 1J0

Code de prix A