PERFORMANCE OF BRUCE NATURAL UO_2 FUEL IRRADIATED TO EXTENDED BURNUPS

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ABSTRACT

Bruce-type bundles XY, AAH and GF were successfully irradiated in the NRU reactor at Chalk River Laboratories to outer-element burnups of 570-900 MWh/kgU. These bundles were of the Bruce Nuclear Generating Station (NGS)-A "first-charge" design that contained gas plenums in the outer elements. The maximum outer-element linear powers were 33-37 kW/m.

Post-irradiation examination of these bundles confirmed that all the elements were intact. Bundles XY and AAH, irradiated to outer-element burnups of 570-700 MWh/kgU, experienced low fission-gas release (FGR) (< 3%); bundle GF, irradiated to an outer-element burnup of 900 MWh/kgU, experienced high FGR (17%). Gas plenums and lower internal gas pressures appear to have contributed to the relatively low sheath strain observed in bundle GF (0.1% at midpellet). The analysis in this paper illustrates a dependence of FGR on power, burnup and power-history type.

Prior experience with Bruce NGS-A fuel experiencing declining power histories has shown that high FGR and fuel defects may occur at burnups > 500 MWh/kgU (equivalent to bundle-average 450 MWh/kgU) when maximum outer-element linear powers are > 50 kW/m. The analysis in this paper suggests that CANDU 37-element fuel can be successfully irradiated (low-FGR/defect-free) to burnups of at least 700 MWh/kgU, provided maximum powers do not exceed 40 kW/m.

1. INTRODUCTION

Normally, natural UO_2 fuel is discharged from CANDU* reactors at a bundle-average burnup of about 200 MWh/kgU. The performance of CANDU fuel at extended burnups (> 450 MWh/kgU) is of interest to fuel designers who desire a better understanding of parameters that influence performance. Such an understanding facilitates the optimization of bundle designs currently in use, and the development of advanced fuel designs for extended burnups. Extended-burnup fuel performance is also of interest to reactor operators who desire a better understanding of the limits of operation, particularly for fuel resident in fuel channels that cannot be refueled for an extended period of time.

In Ontario Hydro's Bruce Nuclear Generating Station (NGS)-A, 37-element fuel has achieved burnups > 450 MWh/kgU (equivalent to an outer-element burnup of 500 MWh/kgU) in channels experiencing refuelling restrictions [1, 2]. Some of the fuel that has achieved outer-element linear ratings > 50 kW/m has experienced high fission-gas release (FGR) and sheath failure due to stress-corrosion cracking (SCC). Elements whose ratings were < 50 kW/m have not experienced failure. This experience suggests that a power/burnup threshold exists, below which safe (defect-free/low FGR) operation can take place [1]. Further investigations and correlations are required to more clearly identify such a threshold.

Bundles XY, AAH and GF were successfully irradiated in the NRU reactor at Chalk River Laboratories (CRL) to outer-element burnups of 570-900 MWh/kgU. These bundles were of 37-element Bruce NGS-A "first-charge" design that contained gas plenums in the outer elements [3]. Post-irradiation examination (PIE) of these bundles was conducted to better understand the limits of extended-burnup performance. This paper summarizes the PIE results of the three bundles and discusses the correlation between parameters such as FGR and operating history. In addition, the results are compared with those previously reported for Bruce NGS-A fuel irradiated to extended burnups [1].

2. BACKGROUND

Bundles XY, AAH and GF were Bruce 37-element first charge production bundles manufactured in 1975 and 1976. These bundles were similar to the current Bruce bundles, except that they contained gas plenums in the outer elements to accommodate fission-gas release. These bundles were irradiated in the NRU reactor at CRL between 1975 and 1990 to outer-element burnups of 570-900 MWh/kgU (Table 1).

Figures 1-3 show the power histories for the three bundles; the powers indicate the average operating power for a given calculated burnup interval. In this paper, a maximum linear power

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

Table 1 Post-Irradiation Examination Data

Bundle	Power History Type	Element Type	Discharge Burnup (MWh/kgU)	Maximum Linear Power (kW/m)	Fission-Gas Release (%)	Final Grain Size at Pellet Centre (μm)	Average CANLUB Retention (%)[b]	Average Midpellet Strain (%)[c]
		Outer	902	37	17	10	20	0.1
GF[a]	constant	Intermediate	709	29	1	7	22	-0.2
		Inner			<1	7		-0.4
		Outer	689	37	2	7	7	-0.2
AAH[a]	declining	Intermediate	545	29	<1	5	5	-0.4
		Inner			<1	6		-0.5
		Outer	568	33	2	6	18	-0.2
XY[a]	constant	Intermediate	450	26	<1	6	44	-0.3
		Inner			<1	6		-0.6
	declining		400-773	36-58	0.1-25	6-44	9-63	-0.15 to 1
Database[d]	ramped		323-441	32-47	0.1-12	12-13	88	
	constant		458	24	0.1	7	73-78	

a - pellet density is about 10.6 g/cm^3 and initial grain size is about 5-6 μm
b - only outer and intermediate elements are CANLUB-coated
c - average diameter change
d - from Reference 1

during irradiation is defined as the highest operating power sustained for at least 12 hours. Bundle XY experienced a relatively steady power history with a sustained maximum outer-element linear power (OELP) of 33 kW/m (Table 1 and Figure 1). Bundle AAH experienced a declining power history, with a sustained maximum OELP of 37 kW/m (Figure 2 and Table 1). Bundle GF experienced a relatively high power (41 kW/m) in the very early stage of the irradiation (< 5 MWh/kgU) and then was maintained at a relatively steady power for the rest of its irradiation (Figure 3 and Table 1). The power history of bundle GF is classified as "constant" and a sustained maximum OELP of 37 kW/m is selected from the "constant" portion (> 5 MWh/kgU). Burnup values in Table 1 were chemically determined.

3. POST-IRRADIATION EXAMINATION-RESULTS AND DISCUSSION

Hot-cell examination of bundles XY, AAH and GF indicated that all the elements were intact.

3.1 Fission-Gas Release: Influence of Power History

The percent FGR experienced by the bundles is listed in Table 1. Release of gaseous and volatile fission-products to the free space within an operating fuel element is an important factor affecting the performance/integrity of a fuel element, especially when burnup is

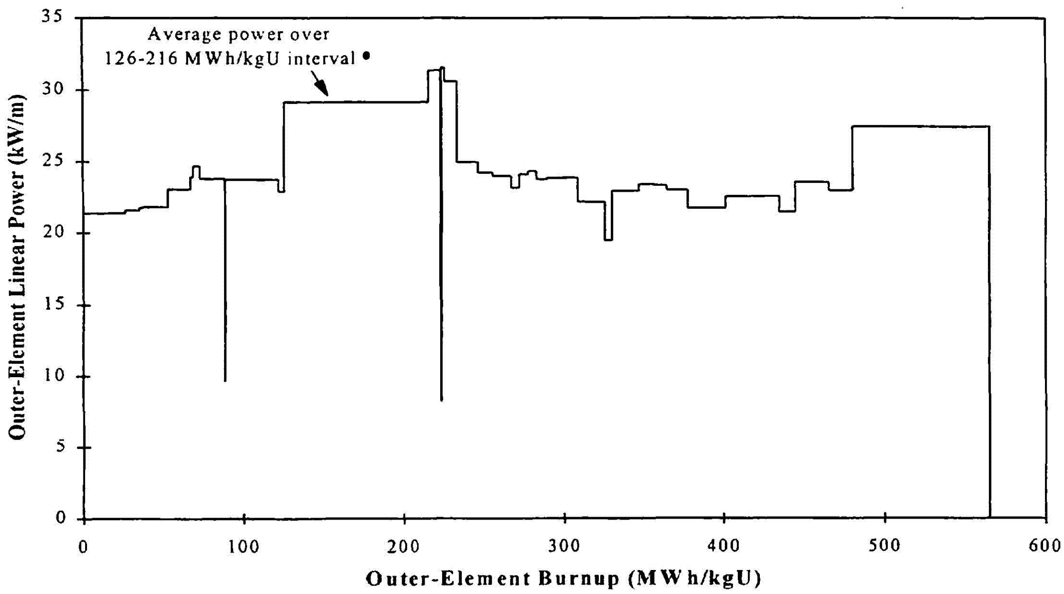

Figure 1 Bundle XY Power History: Outer-Element Average Linear Power versus Predicted Outer-Element Burnup. *Note: "Plateaus" Represent Average Power for a Given Burnup Interval.

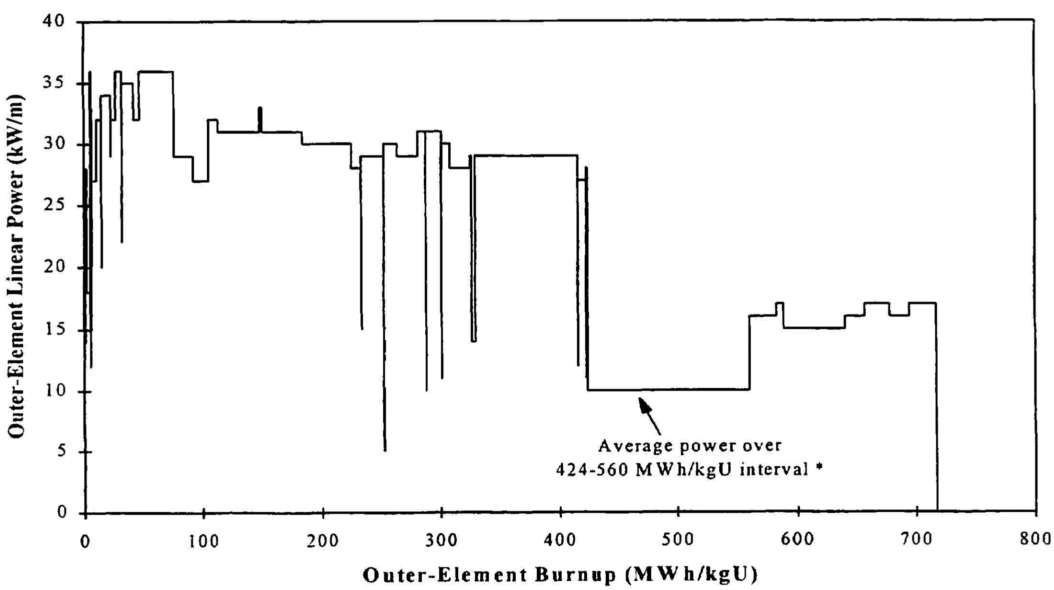

Figure 2 Bundle AAH Power History: Outer-Element Average Linear Power versus Predicted Outer-Element Burnup. *Note: "Plateaus" Represent Average Power for a Given Burnup Interval.

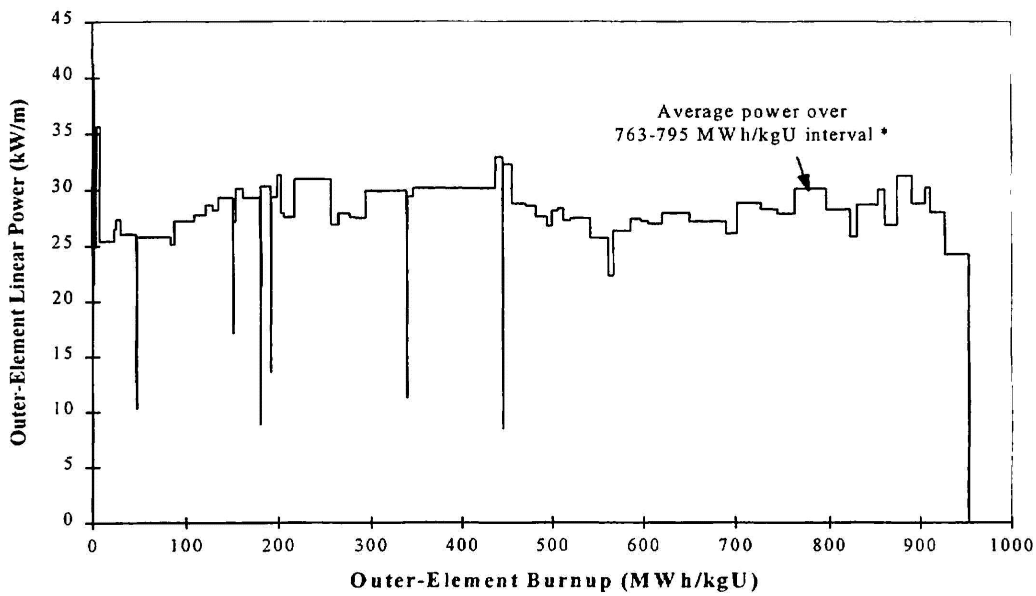

Figure 3 Bundle GF Power History: Outer-Element Average Linear Power versus Predicted Outer-Element Burnup. *Note: "Plateaus" Represent Average Power for a Given Burnup Interval.

high (> 450 MWh/kgU). The release of large quantities of gaseous species such as xenon and krypton can result in internal overpressurization of the element, leading to high sheath stress and possible failure. The release of volatile species such as iodine supplies the corrodants necessary for SCC of the sheath [4]. Thermal conductivity of the gas in the pellet-sheath gap is also degraded by FGR, leading to higher fuel temperatures.

It is generally considered that FGR is dependent on temperature (element power) and burnup (irradiation time), amongst other factors [5]. Floyd et al. [1] have summarized the FGR data from Bruce NGS-A extended-burnup fuel. Their results have shown that FGR exhibits an exponential dependence on fuel-element power, which largely obscures any burnup dependence. Their data is reproduced in Figures 4 and 5, along with that from bundles XY, AAH and GF.

The data from three different types of power history (i.e., declining, ramped and constant) were plotted in different groups in Figure 4, which shows the influence of maximum element linear power on FGR. Data from each different type of power history occupies a different region. It follows that fuel elements will have different FGR when they experience different types of power history, even when they have the same maximum power. Fuel that experiences a declining power history generally exhibits the lowest FGR for a given maximum element power. The "scatter" in Figure 4 may be accounted for (at least in part) by burnup variance. Figure 5 shows the influence of burnup on FGR for fuel elements with declining power histories. It is apparent

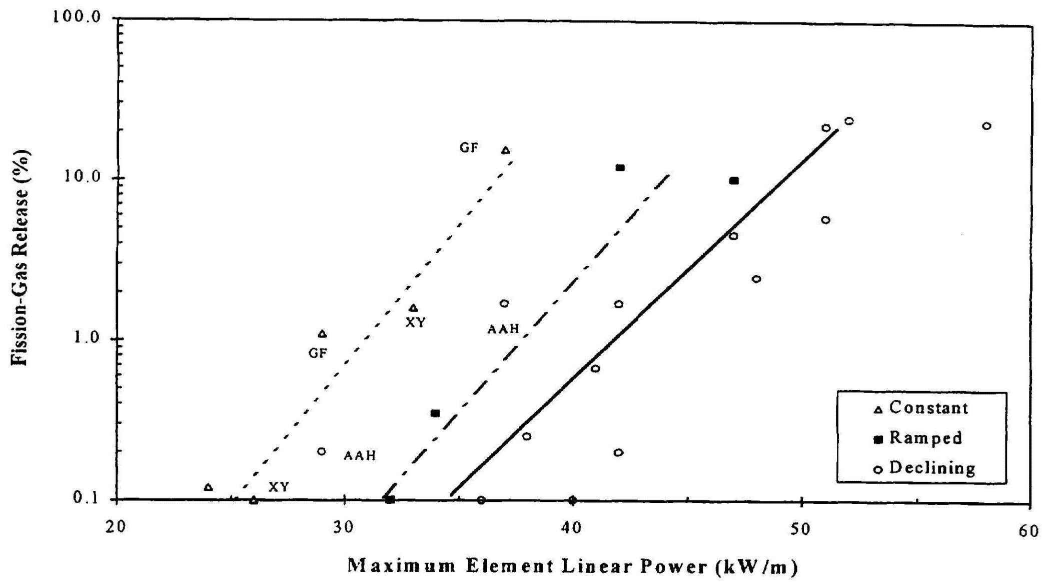

Figure 4 Fission-Gas Release versus Maximum Element Linear Power for Bundles with Different Types of Power Histories (Other Data from Reference 1)

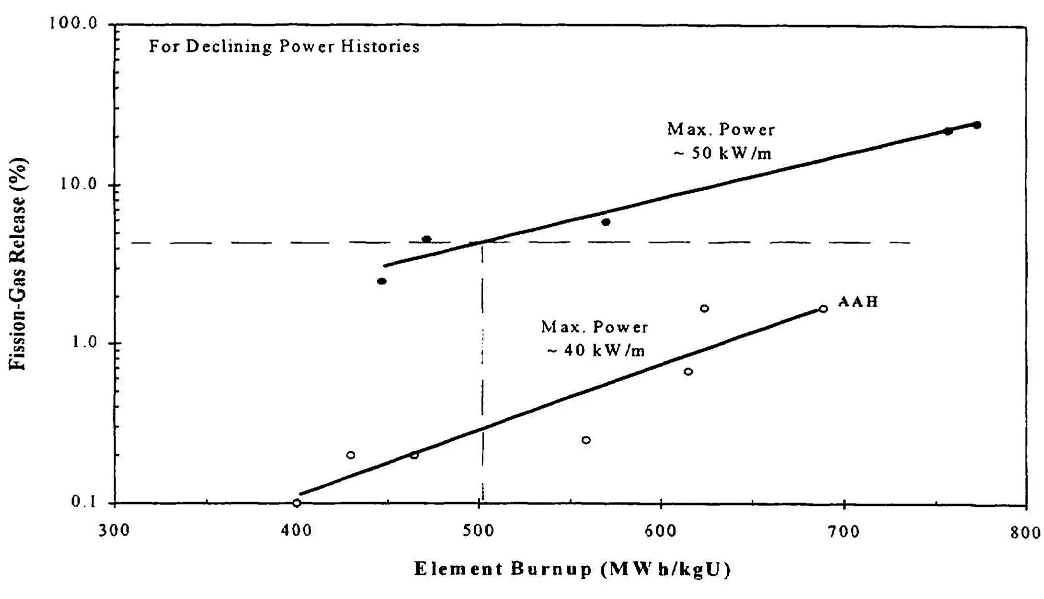

Figure 5 Fission-Gas Release versus Element Burnup for Bundles with "Declining" Power Histories (Other Data from Reference 1)

that FGR is burnup-dependent, although the effect is much less than that for element power. The effect of fuel density on FGR is not accounted for in this analysis [1, 4].

3.2 Grain Growth at Pellet Centre

Grain growth is observed in the outer elements of bundle GF, but not in bundles XY and AAH. Both FGR and grain growth are thermally-activated processes, and generally correlate with each other [1, 5]. Figures 6 and 7 show the correlation of grain growth to element maximum linear power, element burnup and FGR. Little grain growth is observed when the power is low (~ 40 kW/m). However, a factor of three can be attained in grain growth when powers are high (> 50 kW/m). Generally, significant grain growth (≥ a factor of two) is accompanied by significant FGR (Figure 7). Figure 8 shows typical grain morphology at the pellet centre of outer elements from bundle GF. Gas bubbles and tunnels are not as well developed as those observed in higher-powered bundles [1], but metallic fission-products (white dots in Figure 8) are clearly visible. The dark regions shown in Figure 8 are due to the grains pulled out during polishing.

3.3 CANLUB Coating Behaviour

Bundles AAH, XY and GF exhibited low CANLUB retention, consistent with that previously observed by Floyd et al. [1] in Bruce fuel irradiated to extended burnup (Table 1). Within the normal operating envelope, graphite CANLUB coatings significantly improve fuel performance

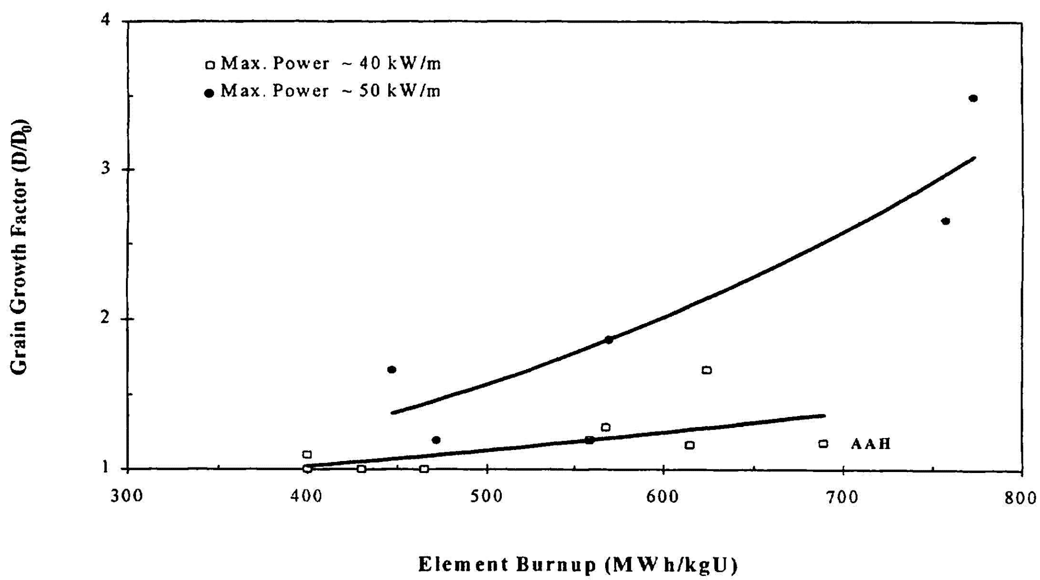

Figure 6 Final/Initial Grain Size at Pellet Centre versus Element Burnup for Bundles with "Declining" Power Histories (Other Data from Reference 1)

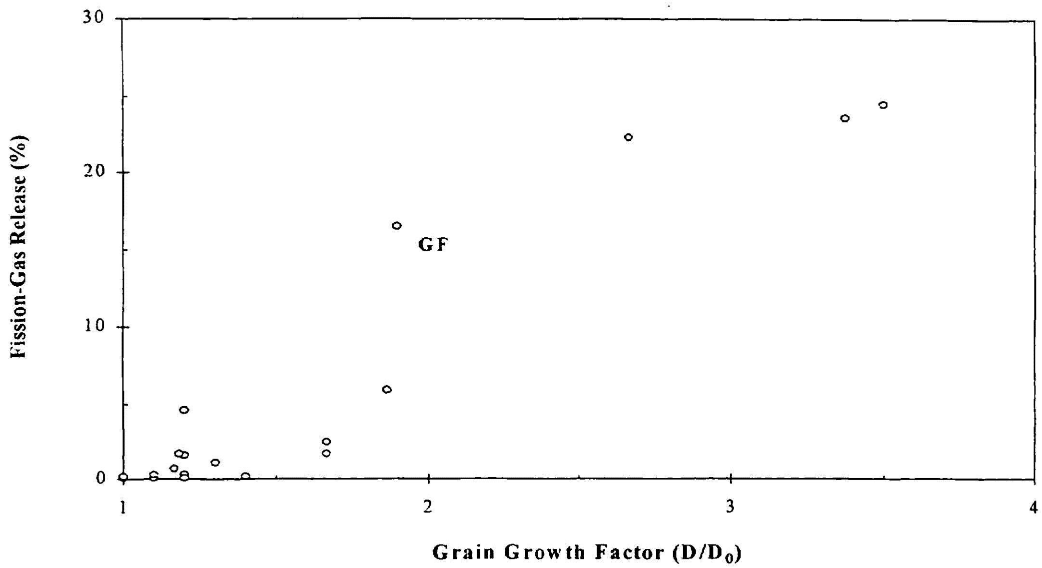

Figure 7 Final/Initial Grain Size at Pellet Centre versus Fission-Gas Release (Other Data from Reference 1)

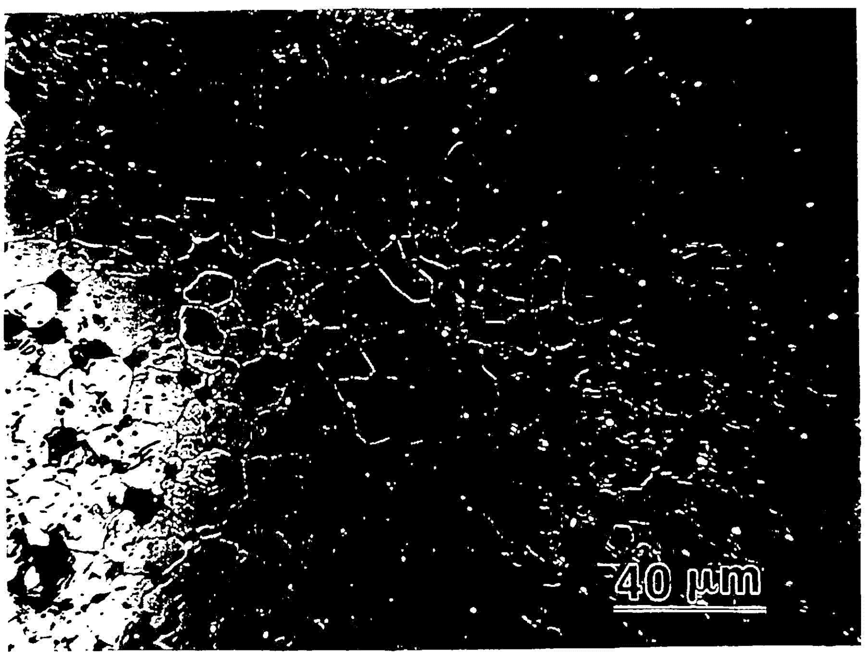

Figure 8 Grain Morphology at Pellet Centre at Midplane of Element 1 (Bundle GF). Average Grain Size is 10 μm (initial size = 5 μm). Note that White Dots are Solid Fission-Product Deposits and that Fission-Gas Bubbles and Tunnels are not Well Developed at Grain Boundaries as those Observed in High-Powered Bundles [1].

by increasing resistance to SCC-related power-ramp defects [4]. The "disappearance" of CANLUB at extended burnups is currently under investigation at AECL.

3.4 Sheath Strain

Midpellet sheath strain was generally observed to be compressive or slightly tensile in bundles AAH, XY and GF (Table 1). The largest average midpellet strain of 0.1% was observed in the highest burnup bundle GF. This strain is significantly lower than that observed in Bruce fuel irradiated to extended burnups; e.g., the average outer-element midpellet sheath strain of bundle J24533C is about 0.9% and the FGR is 25% [1]. This difference may be due to the presence of gas plenums in bundle GF.

3.5 Low FGR/Defect-Free Threshold

SCC-related defects have been observed in the sheath and endcaps of outer elements from Bruce NGS-A fuel bundles, which have experienced declining power histories to extended burnups when the maximum OELP is above 50 kW/m [1]. Therefore, a bundle-average limit of 450 MWh/kgU (equivalent to approximately 500 MWh/kgU outer-element burnup) has been recommended in Ontario Hydro CANDU reactors. This burnup limit corresponds to 4-5% FGR in Figure 5 for fuel having a power of ~ 50 kW/m. For fuel having powers of ~ 40 kW/m, Figure 5 illustrates that low FGR and defect-free operation can be extended to at least 700 MWh/kgU.

Bundle GF was successfully irradiated at maximum OELP of 37 kW/m to outer-element burnup of 900 MWh/kgU with a FGR of 17%. Gas plenums in the outer elements of bundle GF may have helped to decrease sheath strain by reducing internal gas pressure. Further work is needed to better define the low FGR/defect-free threshold for bundles at maximum OELP around 40 kW/m and investigate the performance of fuel at maximum OELP's of 40-50 kW/m to burnups > 600 MWh/kgU.

4. SUMMARY

Post-irradiation examination of bundles XY, AAH and GF confirmed that all the elements were intact. Bundles XY and AAH, irradiated to outer-element burnups of 570-700 MWh/kgU, experienced low fission-gas release (FGR) (< 3%); bundle GF, irradiated to an outer-element burnup of 900 MWh/kgU, experienced high FGR (17%). Gas plenums and lower internal gas pressures appear to have contributed to the relatively low sheath strain observed in bundle GF (0.1% at midpellet). The FGR of bundles XY, AAH and GF, and previously-examined Bruce fuel [1] exhibits a dependence of FGR on power, burnup and power-history type.

Past experience shows that Bruce-type elements irradiated at powers > 50 kW/m to > 500 MWh/kgU (equivalent to 450 MWh/kgU bundle-average burnup) may experience high FGR and SCC-related defects. The performance of bundle AAH suggests that low-FGR/defect-free operation can be extended to at least 700 MWh/kgU for bundles with declining power histories, provided powers do not exceed 40 kW/m. Additional investigations are recommended to better define the low FGR/defect-free threshold for fuel bundles experiencing powers of 40-50 kW/m.

5. ACKNOWLEDGMENTS

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