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EXTENDED-BURNUP CANDU FUEL PERFORMANCE

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ABSTRACT

Significant experience exists with CANDU® fuel performance up to a burnup of 1200 MWh/kgHE. Several performance parameters are germane to extended burnup, including fission-gas release (FGR), pellet microstructural changes, CANLUB retention, sheath corrosion, hydriding/deuteriding and strain, and power-ramp defect thresholds. This paper reviews extended-burnup post-irradiation examination data with a view to trending performance parameters. Fuel that operates at powers > 50 kW/m to burnups > 500 MWh/kgHE may experience high FGR, resulting in high internal gas pressure and related stress-corrosion cracking (SCC) failure. It is observed that such failures may occur when the internal gas volume measured following irradiation exceeds about 100 mL, in fuel with standard internal void volumes. Microstructural changes in the fuel pellets are generally found to trend with operating history, similar to that for FGR (both being primarily temperature dependent). CANLUB retention is observed to be diminished above 350 MWh/kgHE. Sheath waterside corrosion increases with burnup, but is benign. Sheath hydriding/deuteriding does not correlate well with burnup, apparently being more dependent on other parameters such as coolant chemistry and neutron fluence. Sheath strain is dependent on both power and burnup; high internal gas volumes can lead to strains in excess of 1.0%. The understanding of power ramp defect thresholds at > 150 MWh/kgHE is being further investigated. Parameters that influence SCC failure are discussed. MOX and thoria fuel performance at extended burnup is compared to UO_2, and is generally found to be similar.

In summary, AECL has significant experience with CANDU fuel behaviour at extended burnup. By understanding the parameters that affect fuel behaviour at extended burnup, confidence exists in designing fuel that will achieve the same excellent performance experienced with natural uranium fuel presently operating in CANDU reactors. AECL has a number of fuel irradiation tests underway that will further elucidate extended-burnup fuel behaviour, and confirm both individual and integrated design features for extended-burnup application.

1. INTRODUCTION

Natural UO_2 (NU) fuel presently utilized in operating CANDU® reactors typically achieves a burnup of approximately 200 MWh/kgHE. Excellent fuel performance

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continues to be demonstrated for CANDU fuel operating to this level of burnup.[1] AECL has developed technologies to extend burnups in order to increase fissile material utilization and reduce spent fuel quantities. These advanced fuels include slightly-enriched uranium (SEU, 400-600 MWh/kgHE), MOX and thoria (up to 1000 MWh/kgHE). The reference design for extended-burnup fuel cycles is the 43-element CANFLEX® bundle, which provides increased operating margins over the 37-element design. In addition, changes to fuel element internals are being investigated to improve fuel performance at extended burnup.

Over the past twenty years, a significant number of CANDU fuel bundles have operated at various powers to burnups in the range of 400-1200 MWh/kgHE. These include bundles that have operated in power reactors, including Bruce Nuclear Generating Station-A (BNGS-A; 37-element geometry) and the Nuclear Power Demonstration Reactor (NPD; 19-element geometry). In addition, a number of extended-burnup tests have taken place in the NRU reactor at CRL, including UO_2, MOX and thoria fuels. Several tests have been recently completed, are in progress, or are being initiated/planned.

This paper reviews the behaviour of key performance parameters (measured during post-irradiation examination) as a function of operating history, for CANDU fuel that has operated to burnups > 400 MWh/kgHE. On-going and future tests are also discussed, including tests to demonstrate power-ramp performance at extended burnup.

2. EXTENDED-BURNUP PERFORMANCE - BACKGROUND

Several summaries have been published since 1985 that include various aspects of extended-burnup CANDU fuel behaviour.[2-11] Extending the burnup of CANDU fuel to > 400 MWh/kgHE requires assessment of a number of performance issues. High fission-gas release (FGR) may be observed, particularly in fuel achieving powers > 50 kW/m and burnups > 500 MWh/kgHE; this can result in high internal gas pressures that cause stress-corrosion cracking (SCC) in the sheath. Other performance parameters such as sheath strain, hydriding/deuteriding and corrosion, power-ramp defect thresholds, CANLUB retention and pellet microstructural changes are also important to consider at extended burnup. Experience with extended-burnup CANDU fuel is updated and reviewed in view of these issues.

3. FISSION-GAS RELEASE

Inert gases are produced in the fuel matrix as a result of fissioning; most of the gas produced is xenon, in addition to krypton and helium. Helium, used as a filling gas during fabrication, is produced during irradiation as a result of ternary fissioning and alpha decay of transuranic elements. These inert gases diffuse from the fuel matrix to the internal element free void space, primarily as a function of fuel temperature; as a result, FGR occurs primarily from the centre of fuel pellets where the highest fuel temperatures

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are achieved, coinciding with grain growth, grain-boundary bubble formation and swelling. Without adequate amelioration through fuel design, the release of large quantities of fission gases to the free void space may result in high internal gas pressures that lead to high sheath stresses and strains, and possible failure due to sheath SCC.

Operating internal gas pressure is a calculated parameter that is related to internal gas volume by the ideal gas law; however, the temperature distribution of the gas within the element is complex, requiring sophisticated modelling tools for its calculation. Such calculations are beyond the scope of this paper, which is focused on trending performance parameters that are measured during post-irradiation examination (PIE). Figure 1 shows measured internal gas volumes as a function of burnup for the 37-element extended-burnup database. A large amount of scatter exists in the data, primarily due to variations in fuel power. Two observations are made for 37-element fuel with a standard as-fabricated internal void volume of ~ 2 mL:

1. Failures due to high FGR (and associated high internal gas pressures, significantly exceeeding coolant pressure) are observed when internal gas volumes exceed 100 mL. These failures are referred to as "overpressure" failures throughout this paper.

2. No overpressure failures have occurred below 500 MWh/kgHE.

Overpressure failures have been observed in four bundles irradiated in Bruce NGS-A.[3,5,6,8] In addition, overpressure failures have been confirmed or suspected in 37-element geometry bundles AAW, AAX, AAY and ADP from experiments BDL-416, BDL-417 and BDL-419, irradiated in the NRU reactor. Elements from the BDL-406, BDL-416 and BDL-421 experiments that contained large as-fabricated internal void volumes have successfully operated with gas release in excess of 100 mL. It is apparent that a small increase in internal void volume (typically from ~ 2 mL to > 3 mL, accomplished by the use of plena or modified pellet geometry), significantly reduces internal gas pressure. The DME-217 experiment, currently under irradiation in NRU, has the objective of demonstrating the effect of varied pellet geometry and internal void volume on UO_2 fuel performance at incremented burnups in the range of 200-700 MWh/kgHE.

Fuel temperature depends primarily on fuel power; as a result, FGR shows a strong dependence on the maximum fuel power sustained during irradiation (Figure 2). This creates a strong incentive for reducing maximum element powers in extended burnup fuel that can be achieved through greater subdivision of the fuel bundle. The reference design for extended-burnup fuel cycles is the 43-element CANFLEX bundle, which operates at up to 20% lower element linear powers than a 37-element bundle operating at the same bundle power. At a given burnup, FGR is generally larger when the maximum power is achieved at or near the end-of-life (EOL), as opposed to near the beginning-of-life (BOL). FGR also exhibits a dependence on fuel burnup (Figure 3). For UO_2 fuels operating at ~ 40 kW/m, FGR may increase from 1% at 400-500 MWh/kgHE to 20% at 900 MWh/kgHE; at ~ 50 kW/m, FGR may increase from 5% at 400-500 MW/kgHE to

25% at 750 MWh/kgHE. FGR of 25% has been observed at burnups of 500 MWh/kgHE in fuels that have operated at BOL powers of 59 kW/m.[8]

Other parameters such as pellet microstructure and density may also influence FGR at extended burnup. The BDL-416 test incorporated both high-density (HD – 10.6 Mg/m^3) and low-density (LD – 10.4 Mg/m^3) UO_2 pellets. This fuel achieved a maximum outer element power of 70 kW/m and a burnup of 643 MWh/kgHE. The HD pellets had a microstructure that is typical of standard production UO_2 fuel, including an average grain size of 8 μm and relatively small, inter- and intragranular pores. The LD pellets were characterized by large grains (typically 17 μm in diameter) and large intergranular pores. The FGR from the LD pellets was 25% lower than that from the HD pellets (Figure 4). This difference may be attributed to the presence of larger grains and large, stable pores that act as "traps" for fission gas.[12] The objective of the recently-completed DME-216 irradiation is to demonstrate the effect of introducing irradiation-stable pores on parameters including FGR. Investigations at burnups up to 250 MWh/kgHE have shown that the presence of large stable pores has no effect on FGR for fuel irradiated at maximum powers of 38 kW/m and 66 kW/m. The effect of irradiation-stable pores at intermediate ratings has yet to be tested. The irradiation of DME-216 elements to extended burnups (450 MWh/kgHE) is complete; destructive PIE is pending. Recent irradiations carried out with HD and LD pellets operating at maximum powers of ~ 50 kW/m to burnups of 175 MWh/kgHE, showed that the LD fuel fabricated with large, irradiation-stable porosity had slightly higher (yet benign) FGR than identically-operated HD fuel.[13] The above result suggests that although microstructural parameters such as pore size and density may have benign or negligible effects at burnups < 200 MWh/kgHE, the effect may be stronger at extended burnups and power dependent. This requires further investigation.

Experience with MOX CANDU fuel in the BDL-419 test indicates that at powers up to 60 kW/m and burnups of 550 MWh/kgHE, FGR is similar to that observed in UO_2.[11] The BDL-419 experiment is continuing with the objective of achieving burnups of 750-1000 MWh/kgHE. Further experiments, including BDL-446, are in progress to investigate the effect of Pu homogeneity on performance at extended burnup.[14]

In spite of its higher thermal conductivity, AECL experience with thoria fuel has shown that FGR can be highly variable, depending on the as-fabricated microstructure of the pellets. The DME-221 experiment is in progress, with the intent of demonstrating the effect of optimized microstructure on thoria fuel performance. The BDL-422 experiment involves 37-element bundles containing $(Th, Pu)O_2$ pellets irradiated to 440-1070 MWh/kgHE at maximum powers of 50-69 kW/m. To date, three bundles have completed PIE, having achieved burnups of 440-815 MWh/kgHE and maximum powers of 50-66 kW/m. These bundles experienced lower FGR than would be expected for similarly-operated UO_2 or $(U, Pu)O_2$ bundles.

4. PELLET MICROSTRUCTURAL BEHAVIOUR

Like FGR, UO_2 grain growth is primarily a temperature-dependent phenomenon, and is most strongly affected by operating power. Previously published investigations have demonstrated that grain growth has a similar burnup dependence to that exhibited for FGR, as shown in Figure 5.[6,9] At ~ 40 kW/m, grain-growth factors (the ratio of the observed pellet-centre grain size to that at the pellet periphery, assumed to represent the as-fabricated, pellet-centre grain size) progress marginally from 1.0 (i.e., no grain growth) to 1.5 at burnups of 600-700 MWh/kgHE and 2.0 at 900 MWh/kgHE. At ~ 50 kW/m, grain-growth progresses more rapidly from 1.5 at 450 MWh/kgHE to as high as 3.5 at 750 MWh/kgHE. At 59 kW/m and 540 MWh/kgHE grain-growth factors of 3.5 have been observed.[6] This burnup-enhanced grain growth is also accompanied by an evolution of bubbles along the grain boundaries and tunnels at the grain-boundary triple points that facilitate gas release (Figure 6). The grain boundaries can also be decorated with solid fission-product deposits. The enhanced microstructural evolution (grain-growth and bubble/tunnel formation) observed at extended burnup coincides with a degradation in fuel pellet thermal conductivity that is a result of the presence of dissolved and precipitated solid fission products, fission-gas bubbles, hyperstoichiometry (oxidation) and radiation damage.[15]

Several UO_2 fuels irradiated to burnups > 500 MWh/kgHE have exhibited evidence of grain boundary oxidation at the periphery of the fuel pellets. The grain boundaries in this region of the fuel preferentially etch, resulting in grain pull-out during polishing (Figure 7).[6,8] Microcracks have also been observed along radial pellet cracks indicating the presence of a higher-oxide phase (Figure 8).[8]

The outer elements of BDL-406 UO_2 bundle GF that achieved a burnup of 900 MWh/kgHE exhibited a "rim structure" similar to that observed in high-burnup LWR fuels (Figure 9). Rim structure has been extensively studied in LWR fuel.[16-20] The structure forms a band at the pellet periphery that is characterized by a porous microstructure that contains subdivided grains less than 1 μm in size. The width of the rim structure varies with fuel burnup; in the case of bundle GF, the width of the rim was approximately 40-50 μm. Neodymium and plutonium measurements indicate that the local burnup in the rim region was at least a factor of two greater than the burnup remote from the pellet edge. The precise mechanism for the formation of rim structure is not understood, although it appears to be related to the local buildup up of fission-gas pressure within the fuel matrix. In its incipient stage, rim structure appears to manifest itself as needle-shaped microchannels within each grain. Preliminary evidence suggests that this incipient form of rim structure is present in UO_2 fuels irradiated to burnups of 500-600 MWh/kgHE, respectively. The extent of rim structure formation observed in CANDU fuel appears to have little or no effect on overall fuel performance.

The BDL-419 $(U, Pu)O_2$ fuel experienced pellet-centre Pu homogenization and columnar grain growth.[11] These effects appeared to occur at BOL at sustained maximum powers > 55 kW/m. As such, these observed microstructural changes are not extended-burnup effects, per se. Columnar grain growth is not normally observed in CANDU UO_2 fuel below powers of 65 kW/m. The lower threshold for columnar grain growth observed in BDL-419 MOX fuel may be indicative of higher operating temperatures and/or different grain growth kinetics, although the FGR was comparable to similarly operated UO_2 fuels. Further extended-burnup investigations into MOX fuel behaviour, including the effect of as-fabricated microstructure, are on-going in the BDL-419 and BDL-446 tests.

Unlike $(U, Pu)O_2$ and UO_2 fuel, thoria does not exhibit columnar grain growth at high powers. BDL-417 bundles AAX and AAY achieved BOL powers of ~ 75 kW/m and burnups of 500-600 MWh/kgHE and did not exhibit columnar grain growth; however, large equiaxed grains ranging from 35-60 μm in size were observed, approximately ten times larger than the as-fabricated grain size of 5 μm. Similar pellet-centre grain growth was observed in BDL-421 thoria bundle ACT (irradiated at powers up to 68 kW/m to a burnup of 846 MWh/kgHE), and was accompanied by the extensive interlinkage of gas bubbles along the grain boundaries giving rise to FGR in excess of 20%. BDL-422 bundles ADC, ADE and ADF that contained $(Th, Pu)O_2$ pellets were irradiated at powers of 50-66 kW/m to burnups of 440-820 MWh/kgHE. Little or no grain growth was observed in these bundles, and was accompanied by benign FGR and sheath strain. In general, thoria exhibits less microstructural change than UO_2 owing to its higher thermal conductivity (lower operating temperatures) and the fact that it is a more refractory material than UO_2. $(Th, Pu)O_2$ appears to be very stable, exhibiting little or no grain growth at both high power and extended burnup, and accompanied by only modest quantities of FGR.

5. CANLUB BEHAVIOUR

During destructive PIE, the retention of the graphite CANLUB coating on the inner sheath surface is routinely surveyed using a high-power microscope and recorded. Various coatings have been developed, including DAG-154 (standard production; alcohol-based), ES-242 (water-based, experimental) and siloxane (experimental). In general, the three coatings behave similarly, providing protection against SCC. At burnups less than 350 MWh/kgHE, typically more than 70% of the coating can be accounted for between the sheath inner surface and the fuel pellet periphery.[6] Figure 10 shows the percent retention of the graphite CANLUB interlayer as a function of burnup for the extended-burnup database. At burnups of 350-500 MWh/kgHE, typical retentions are in the range of 40-70%. At burnups of 500-900 MWh/kgHE, approximately 50% of the retention values are below 40%.

CANLUB improves power-ramp performance, by increasing the SCC threshold. The mechanism for CANLUB degradation is currently under investigation; preliminary studies indicate that it is related to radiation damage.[21] The DME-215 test, currently under irradiation in NRU, has the objective of demonstrating the active ingredient in CANLUB and further characterizing its behaviour at extended burnup.

CANLUB behaviour in MOX and thoria fuels appears to be similar to that observed in similarly-operated UO_2 fuels.

6. SHEATH CORROSION BEHAVIOUR

Sheath corrosion behaviour for extended-burnup CANDU fuel has recently been compiled and studied. The correlation between waterside sheath oxide thickness and burnup is shown in Figure 11. The maximum thickness of waterside sheath oxide observed in fuel irradiated to burnups < 450 MWh/kgHE is < 10 μm. At burnups of 450-1000 MWh/kgHE, maximum thicknesses up to 20 μm are observed. At burnups of 1000-1200 MWd/kgHE, oxide thicknesses up to 30 μm are observed. This indicates that the corrosion rate above 450 MWh/kgHE is approximately twice that observed below 450 MWh/kgHE.

There is no evidence that waterside corrosion contributes to fuel failures at extended burnup. The apparently benign effect of waterside corrosion (up to 30 μm) is best illustrated by the NPD-40 and NPD-51 fuels which operated successfully to burnups > 1000 MWh/kgHE.

The presence of oxide on the inner surface of the sheath is greatly affected by the CANLUB interlayer and its retention.[6] Elements that are not CANLUB coated exhibit oxide patches on the inner surface of the sheath up to 11 μm in thickness. CANLUB-coated elements that experience high retention values (typically up to 350 MWh/kgU) exhibit no visibly detectable oxide on the sheath inner surface (i.e., < 1 μm). At higher burnups, where CANLUB retention is reduced, oxide films 1-2 μm in thickness appear on the sheath inner surface. This behaviour suggests that CANLUB inhibits the sheath from acting as a getter for liberated oxygen. Recent investigations have shown this effect to be benign at burnups of approximately 200 MWh/kgU.[22]

At burnups > 400 MWh/kgHE, MOX fuel exhibits significantly more oxidation on the inner surface of the sheath than similarly-operated UO_2.[11] This effect is related to the fact that fewer oxide-forming fission-product elements are produced by Pu-239, as compared to U-235. Notwithstanding, the effect appears to be benign up to a burnup of 550 MWh/kgHE.

Thoria fuels appear to experience less internal sheath oxidation at extended burnups than similarly-operated UO_2 fuels.

7. SHEATH HYDRIDING/DEUTERIDING BEHAVIOUR

Sheath hydrogen/deuterium (H/D) uptake behaviour for extended-burnup fuel has recently been compiled and studied. For comparison purposes, sheath D concentrations are expressed in equivalent H units (= D/2). With the exception of siloxane-coated fuels, equivalent H concentrations are generally observed up to 200 μg/g, with most of the data being bounded by 150 μg/g. Most of this is picked up from the waterside, the combined as-fabricated H and fuelside H pickup being bounded by 60 μg/g. A large variation in equivalent H exists over the range of 400-1200 MWh/kgHE suggesting that other parameters such as coolant chemistry, neutron fluence, coolant/sheath temperatures and sheath properties have a dominant effect on H/D pickup.

Fuel sheaths that have the inner bore coated with siloxane typically exhibit equivalent H pickup twice that of other coated or non-coated sheaths (up to 400 μg/g).

Sheath H/D behaviour in MOX and thoria fuels at extended burnup is similar to that in UO_2 fuels.

SCC failure thresholds can be influenced by the presence of sheath H/D;[23,24] however, since H/D levels are not primarily influenced by burnup extension, it is concluded that the H/D levels observed in extended burnup fuel are not, of themselves, detrimental to performance.

8. SHEATH STRAIN BEHAVIOUR

Fuel operated at burnups < 400 MWh/kgHE typically exhibits midpellet sheath strains up to 0.5%.[13,25] Sheath strain is dependent on pellet geometry/density, fuel power and as-fabricated diametral clearance (between pellets and sheath).[13,26] Figure 12 shows the midpellet strain observed in extended-burnup UO_2 fuels as a function of burnup. Much scatter exists in the data, owing to the variances in other aforementioned parameters such as power (Figure 13); however, the maximum strain observed at a given burnup generally increases gradually from 0.5% at 400 MWh/kgHE to 1.5% at 750 MWh/kgHE. This increase in strain appears to be related to two effects:

1. Swelling of the pellets due to the buildup of fission products in the ceramic matrix and associated PCI. Palleck has reported an empirical trend of 0.15% per 100 MWh/kgHE over the range of 100-500 MWh/kgHE.[27]

2. Internal gas pressure above the gas overpressurization threshold. The BDL-416 experiment (Figure 4) suggests that in 37-element fuel, the incremental strain is 0.25% per 10 mL of internal gas in excess of 100 mL.

Generally, strains in elements with < 100 mL of internal gas are bounded by 1.0%. These elements appear to have been primarily strained as a result of PCI; an increase from 0.5% to 1.0% over the range of 400-750 MWh/kgHE is predicted by extrapolating Palleck's trend. Standard 37-element-geometry elements that have internal gas volumes > 100 mL typically exhibit strains higher than that expected solely due to PCI. This is illustrated by the BDL-416 experiment (Figure 4) where strains in unplenumed elements increased proportionally with increasing internal gas volume over the range of 110-190 mL. Intact element 10 of bundle J24546C exhibited a gas volume of 110 mL at a burnup of 757 MWh/kgHE; several other elements in this bundle failed due to overpressure.[3,5,6] For this element, Palleck's correlation predicts PCI strain of approximately 1.0% due solely to PCI; the BDL-416 correlation predicts an additional gas overpressure strain increment of 0.25% (1.25% in total). This is close to the observed strain of 1.5%.

To date, tests on MOX fuel indicate that it has similar sheath strain behaviour to that expected of similarly-operated UO_2 fuel up to burnups of 550 MWh/kgHE.[11] Tests with CANDU MOX fuel to burnups up to 1000 MWh/kgHE are on-going (BDL-419).

Strain behaviour in thoria fuel may vary significantly depending on the initial microstructure of the fuel. The performance of thoria pellets with optimized microstructure is being demonstrated in the DME-221 experiment, currently under irradiation in the NRU reactor.

9. POWER-RAMP DEFECT THRESHOLDS

The majority of CANDU fuel power-ramp data has been generated by 4-bundle refueling operations resulting in power ramps for 28- and 37-element NU fuel to a burnup of 150 MWh/kgHE. Experiments are in progress at CRL to better understand and define the limits of power ramp operation at burnups > 150 MWh/kgU, including BDL-443 and BDL-445. The DME-217 declining-power test has demonstrated a pellet geometry that has superior ridging behaviour. This pellet geometry will be tested under power ramp conditions in BDL-445.

Recently, Tayal and Chassie have developed a new methodology for power-ramp defect criteria, with particular relevance to extended burnup applications.[28] This new methodology produces excellent agreement with observed power-ramp defects over a wide range of burnups. The BDL-445 test will provide additional data to further validate this new criteria.

The DME-215 power ramp test has completed its lower power soak to 150 MWh/kgHE, with the power ramp of 36 demountable elements scheduled for early 2002. The elements contain several CANLUB coating variants including DAG-154, baked at various temperatures, and a new coating (DAGZR). The experimental objectives include demonstrating the active ingredient in CANLUB and identifying its optimal baking temperature, and testing a potentially improved CANLUB formulation.

A limited number of tests have been conducted with CANDU fuel containing thoria pellets. The BDL-421 test incorporated short pellets, to which the excellent performance under repeated power ramp conditions is primarily attributed. Experience with the DME-166 and WR1-218 experiments indicate that thoria fuel experiences SCC defects that are similar to that experienced by UO_2 under similar power-ramp conditions.

To date, power ramp tests have not been conducted on CANDU MOX fuel. Based on its performance under declining power conditions, similar power ramp performance to that of UO_2 is expected.

10. DEFECT MECHANISMS

Extended-burnup-related failures have been observed in CANDU fuel, resulting from either internal gas overpressure (under declining power conditions at burnups > 500 MWh/kgHE) or PCI that result from power ramps at burnups > 150 MWh/kgHE. Both defect mechanisms are SCC-related. Overpressure-related SCC defects may appear anywhere in the sheath, but often occur at locations that are adjacent to bearing pads, where large axial splits may develop.[8] Overpressure-related SCC defects can be mitigated through fuel design (e.g., reduced element ratings and/or increased internal void space). Power-ramp-related sheath SCC defects generally are observed at or near pellet interface locations where ridge stresses/strains are largest. In addition, both overpressure and PCI defects may appear as circumferential endcap cracks, inboard of the closure weld.[3,8] This endcap defect mechanism is influenced by weld geometry, end-pellet geometry, axial/diametral clearance, sheath microstructure and the presence of hydrides/deuterides.[8,22,23] In particular, elements with "notch-free" endcap closure welds are not susceptible to failure, as are welds with sharp re-entrant notches.[8,22]

11. SUMMARY

Significant experience exists with CANDU fuel irradiated to extended burnups up to 1200 MWh/kgHE, including natural UO_2 power reactor fuel and experimental fuel containing UO_2, MOX and thoria pellets. Key extended-burnup performance parameters have been identified and trended. Several irradiation tests are underway to better characterize aspects of extended-burnup behaviour, and to confirm the effectiveness of advanced fuel designs for extended-burnup application.

Fission-gas release from the pellets to the free void of the fuel element is a key performance parameter at extended burnup. SCC-related defects may be observed due to overpressurization when FGR exceeds 100 mL in standard 37-element fuel. Other fuel parameters such as endcap closure-weld geometry may also influence defect thresholds. The means to avoid gas overpressurization at a given burnup include increasing element internal void space (e.g., plenums and/or modified pellet geometry), and lowering element linear powers (through greater subdivision of the bundle; i.e., CANFLEX).

UO_2 microstructural changes follow a similar trend to that of FGR. An apparently benign rim structure may begin to develop in CANDU fuels irradiated to > 500 MWh/kgHE.

CANLUB retention is typically high at < 350 MWh/kgHE, but typically declines above this burnup, especially at > 500 MWh/kgHE. As such, diminished CANLUB retention does not appear to be an issue for fuel that experiences power ramps up to 350 MWh/kgHE.

The waterside sheath corrosion rate above 450 MWh/kgHE is approximately twice that observed below 450 MWh/kgHE. Nevertheless, corrosion layers up to 30 μm appear to be benign. Internal sheath corrosion is inhibited by the presence of the CANLUB interlayer.

Large variations are observed in sheath H/D concentrations, suggesting that parameters in addition to burnup (irradiation time) have a dominant effect on H/D pickup. The H/D levels observed in extended-burnup fuel are not, of themselves, detrimental to fuel performance, although they may influence SCC thresholds.

Sheath strain is primarily influenced by fuel power, but also increases with increasing burnup due to pellet fission-product swelling. Midpellet residual sheath strains are typically limited to 1.0%, but may increase beyond this value when internal gas volumes exceed 100 mL (in standard 37-element fuel). Pellet geometry/density and as-fabricated pellet-sheath diametral clearance also influence sheath strain.

Extended-burnup fuel cycles will require power ramps at burnups > 150 MWh/kgHE, where failure margins are smaller than at < 150 MWh/kgHE. Tests are underway to better define power-ramp defect thresholds at burnups > 150 MWh/kgHE, and to confirm the effectiveness of advanced coatings and optimized fuel element designs.

In summary, AECL has significant experience with CANDU fuel behaviour at extended burnup. By understanding the parameters that affect fuel behaviour at extended burnup, confidence exists in designing fuel that will achieve the same excellent performance experienced with natural uranium fuel presently operating in CANDU reactors. AECL has a number of fuel irradiation tests underway that will further elucidate extended burnup fuel behaviour, and confirm both individual and integrated design features for extended burnup application.

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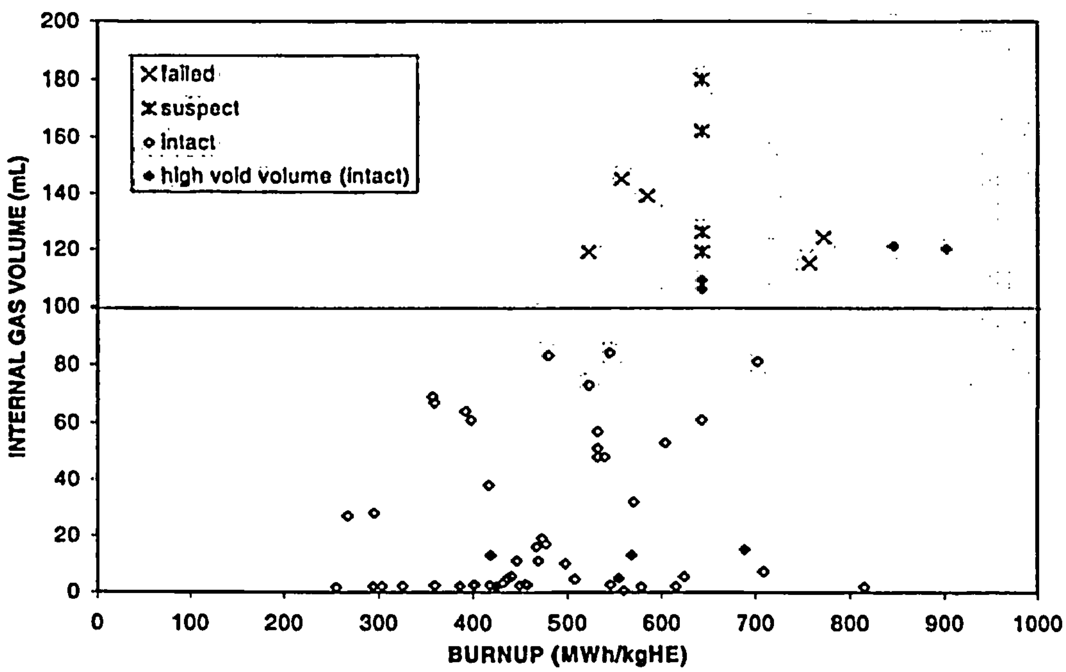

FIGURE 1. INTERNAL GAS VOLUMES FOR EXTENDED-BURNUP 37-ELEMENT FUEL. NO FAILURES ARE OBSERVED BELOW 100 mL.

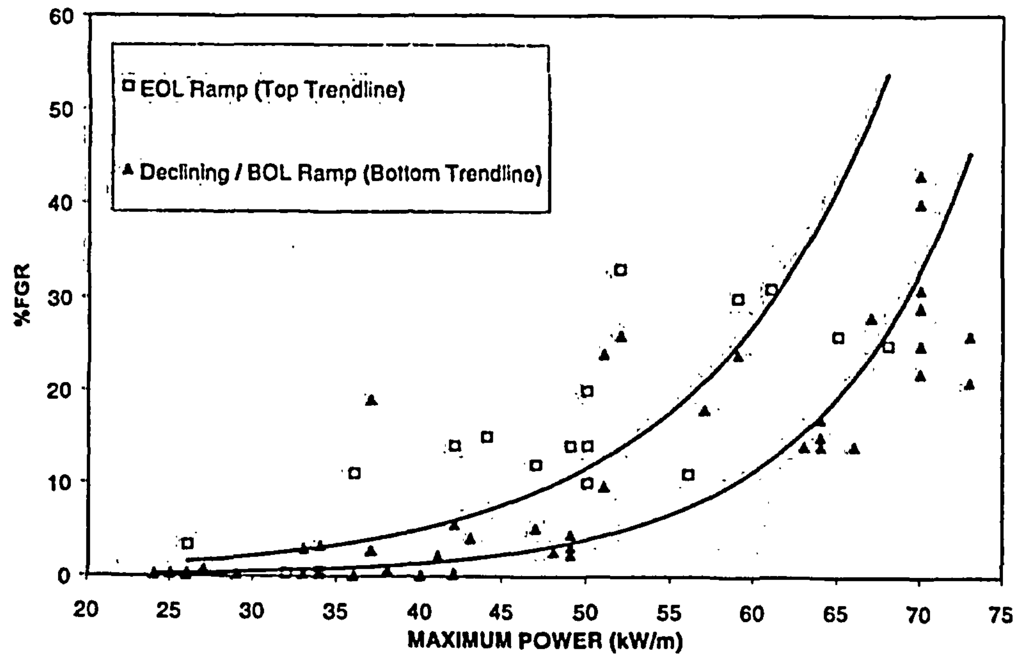

FIGURE 2. EFFECT OF POWER ON FISSION-GAS RELEASE FOR EXTENDED-BURNUP UO_2 FUEL.

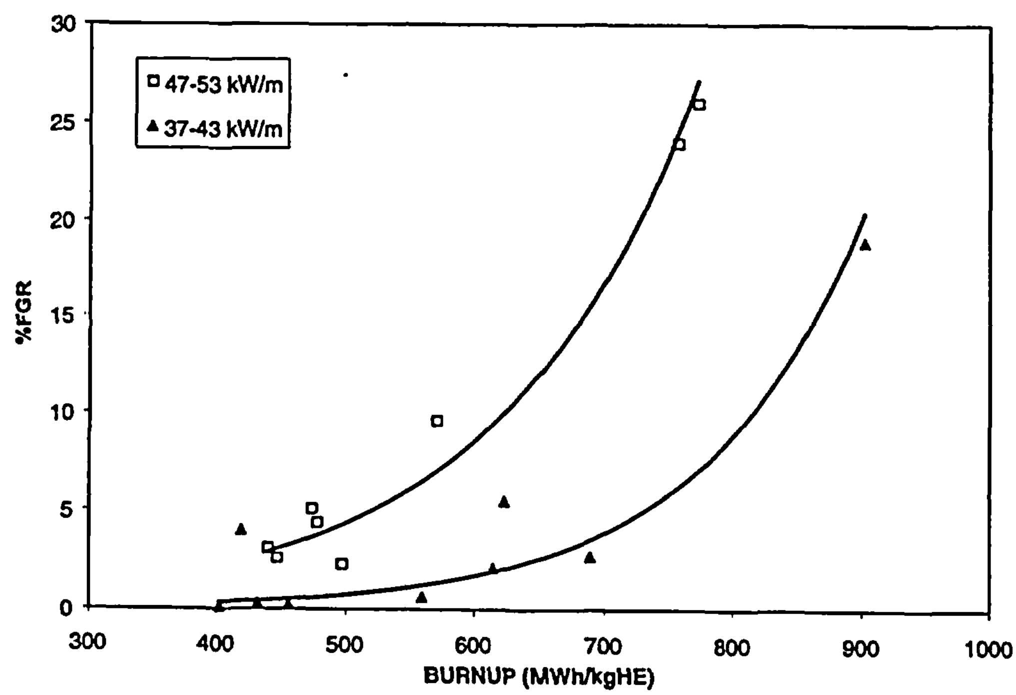

FIGURE 3. FISSION-GAS RELEASE VS. BURNUP FOR UO_2 FUELS WITH CONSTANT OR DECLINING POWER HISTORIES.

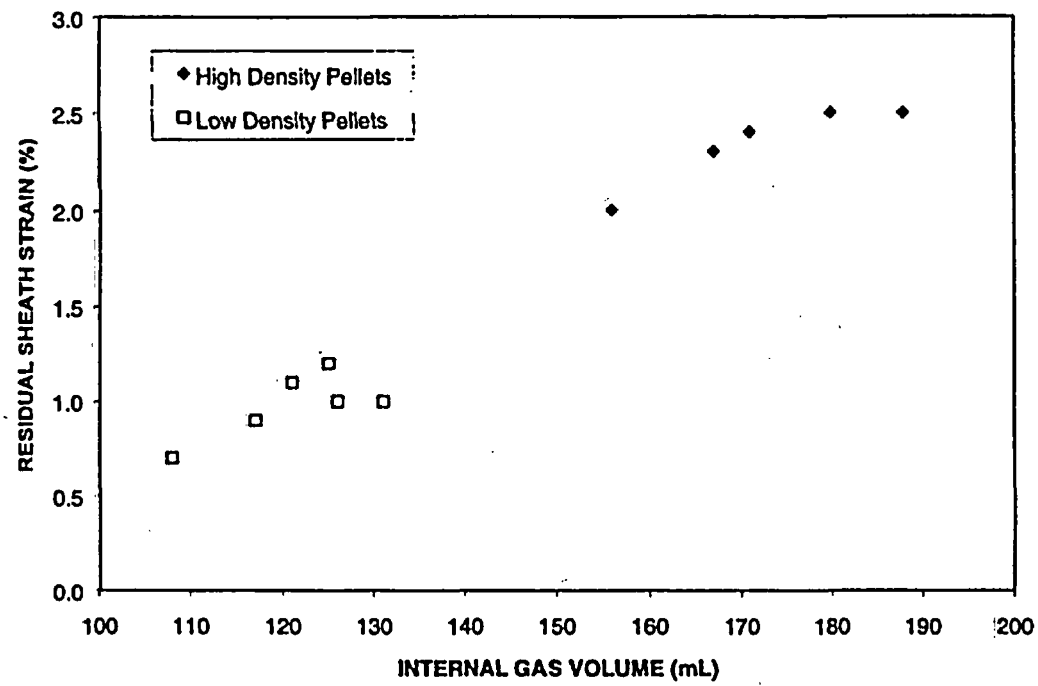

FIGURE 4. BDL-416 UNPLENUMED ELEMENT MIDPELLET STRAIN RESULTING FROM HIGH INTERNAL GAS VOLUMES.

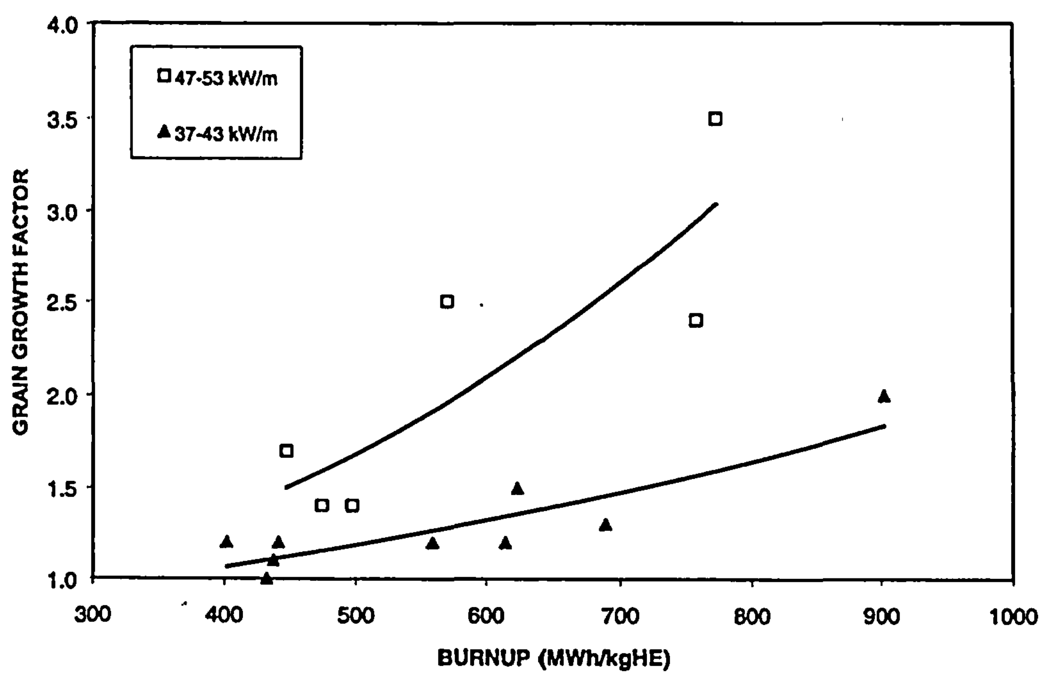

FIGURE 5. UO_2 PELLET-CENTRE GRAIN GROWTH: DEPENDENCE ON OPERATING HISTORY.

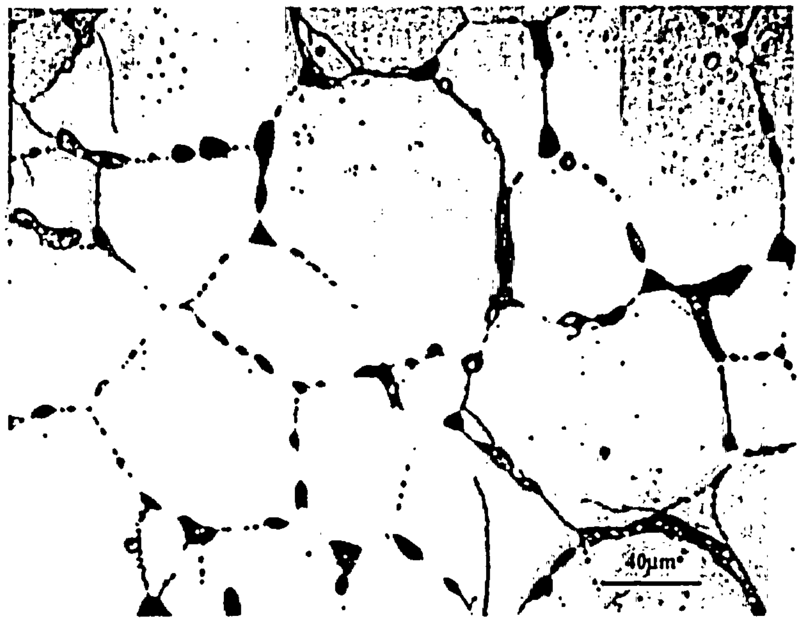

FIGURE 6. TYPICAL PELLET-CENTRE MICROSTRUCTURE OF UO_2 FUEL IRRADIATED AT MAXIMUM BOL POWERS > 50 kW/m TO > 500 MWh/kgHE.[7] NOTE LARGE GRAINS, GAS BUBBLES ALONG GRAIN BOUNDARIES, TUNNELS AT TRIPLE POINTS AND SOLID FISSION PRODUCT DEPOSITS (WHITE).

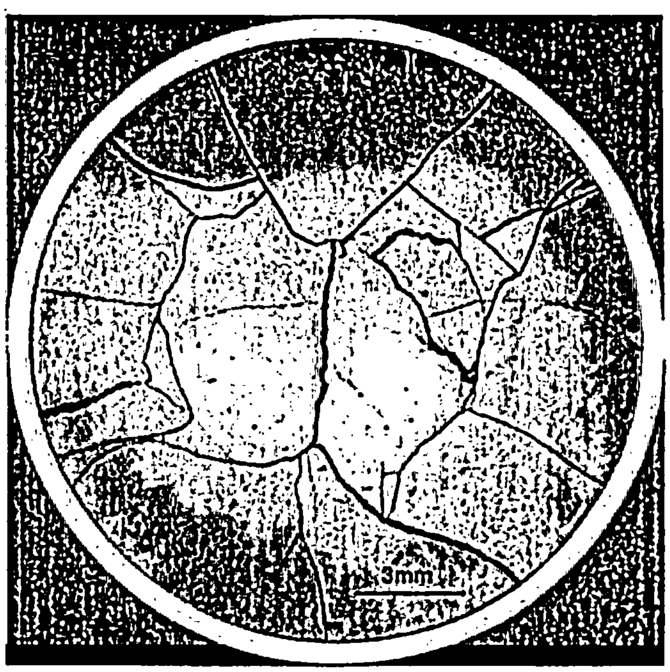

FIGURE 7. MACROSTRUCTURE OF UO_2 FUEL IRRADIATED AT MAXIMUM BOL POWERS OF > 50 kW/m TO 750 MWh/kgU.[5] NOTE DARK PERIPHERAL BAND AT TOP CAUSED BY ETCHING OUT OF OXIDIZED GRAIN BOUNDARIES.

FIGURE 8. MICROCRACKING ALONG RADIAL CRACK OF UO_2 FUEL IRRADIATED AT MAXIMUM BOL POWERS > 50 kW/m TO > 500 MWh/kgHE.[7]

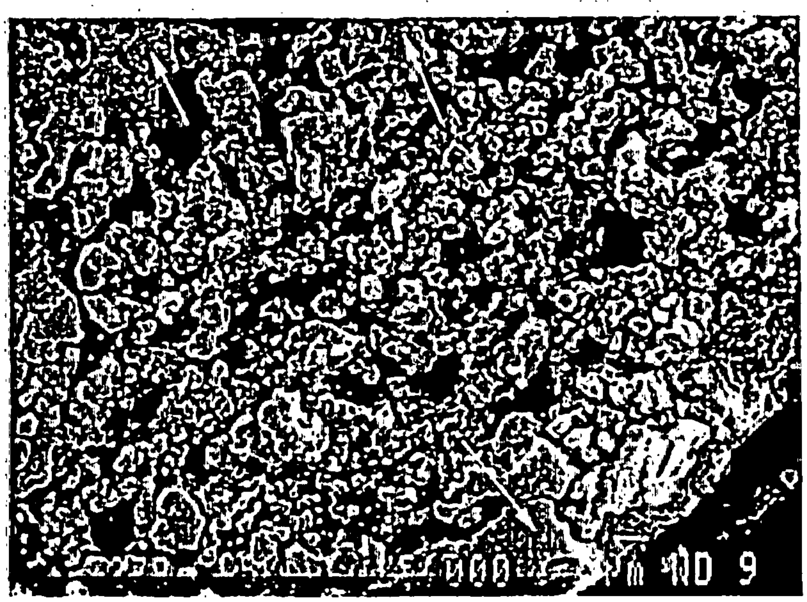

FIGURE 9. "RIM STRUCTURE" AT PERIPHERY OF UO_2 FUEL IRRADIATED AT ~ 40 kW/m to > 900 MWh/kgHE. NOTE SUBDIVISION OF GRAINS TO SIZE < 1 µm. ARROWED GRAINS REPRESENT ORIGINAL GRAINS APPROXIMATELY 10 µm IN SIZE.

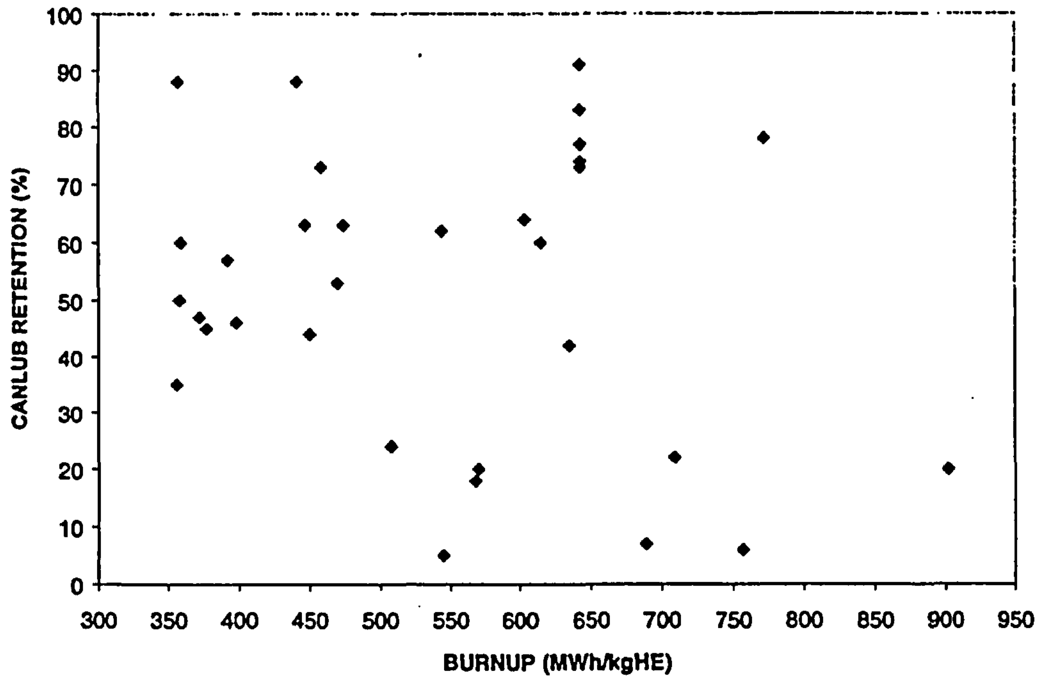

FIGURE 10. CANLUB RETENTION IN EXTENDED BURNUP UO_2 FUEL.

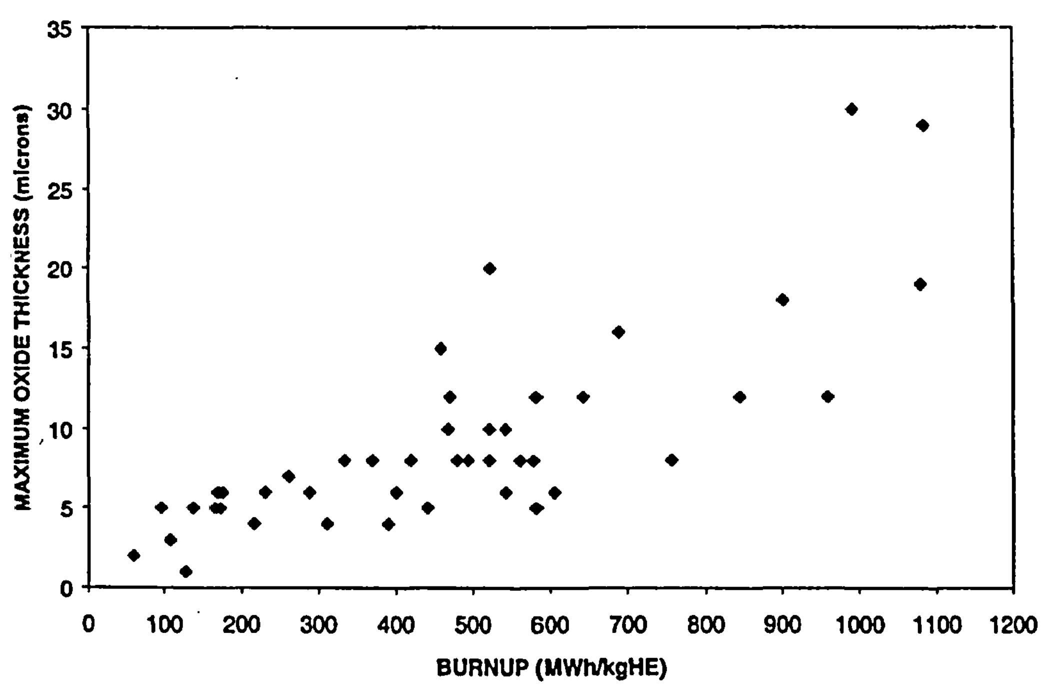

FIGURE 11. WATERSIDE CORROSION IN EXTENDED BURNUP FUEL.

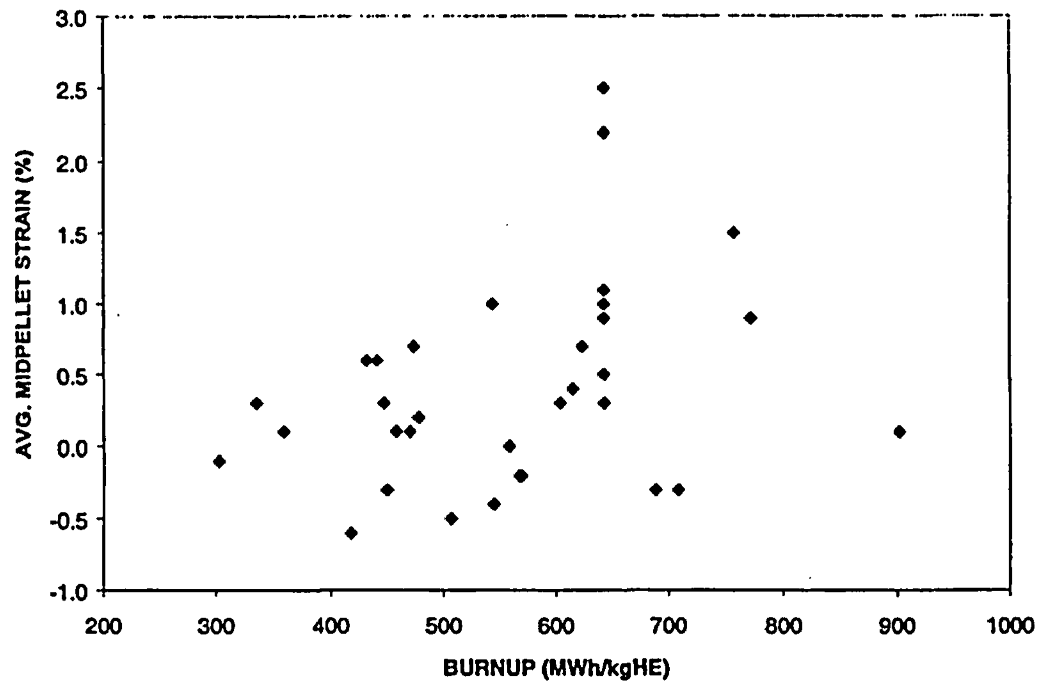

FIGURE 12. MIDPELLET SHEATH STRAIN IN EXTENDED BURNUP UO_2 FUEL (BURNUP DEPENDENCE SHOWN).

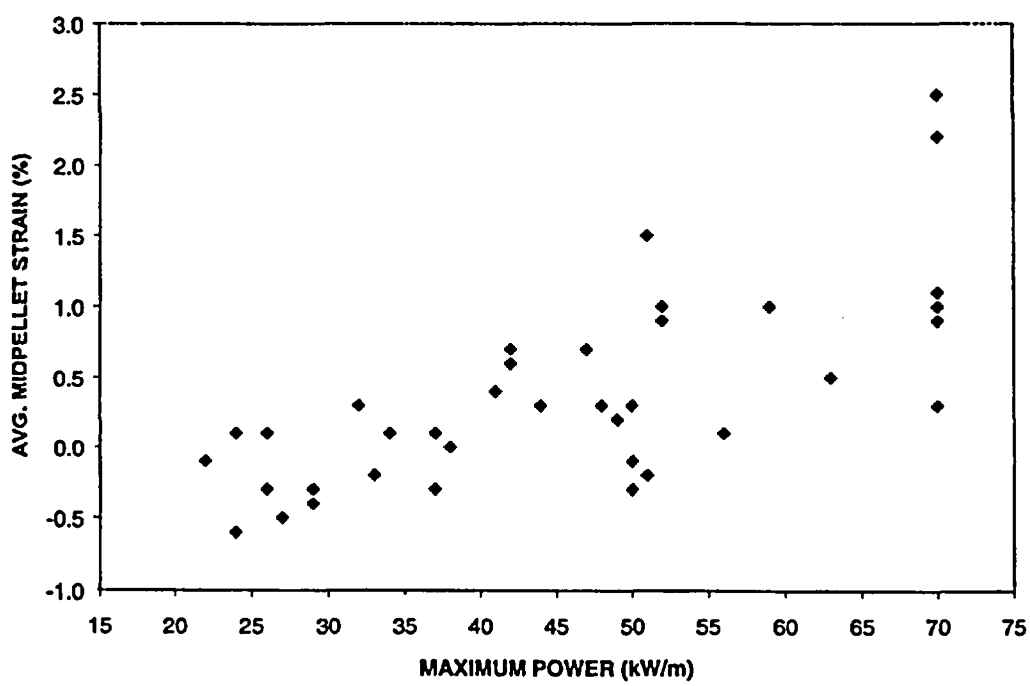

FIGURE 13. MIDPELLET SHEATH STRAIN IN EXTENDED BURNUP UO_2 FUEL (POWER DEPENDENCE SHOWN).