FUEL ELEMENT SHEATH STRAINS AT HIGH POWERS AND BURNUPS: *RATIONALISING THE REFERENCE BUNDLE OVERPOWER ENVELOPE*

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ABSTRACT

A methodology is derived and described for calculating a revised 'Reference Design Bundle Overpower' envelope to a bundle burnup of 450 MW.h/kg U. This envelope is based on the criterion that average diametral sheath strains, measured at the pellet mid-plane positions, should not exceed 0.4 %. The algorithm for calculating strains is based on normalisation of measured strains, to allow for the effects of fuel density, power and burnup.

1 INTRODUCTION

The fuel bundles in CANDU power reactors normally operate within a power / burnup envelope that was derived by 'bounding' operating experience and increasing the operating power to provide a margin. Based on BNGS-A at 100% power, a maximum limiting bundle power of 1035 kW was specified (this occurs at the 'plutonium peak, at about 60 MW.h/kg U burnup). Values at other burnups were defined by normalising to the shape of the fueling simulations of power / burnup histories during reactor operation (the "bounding envelope"). The curve was defined to 300 MW.h/kg U.

Normally, fuel is discharged with burnups below about 200 MW.h/kg U, but occasionally may remain in reactor for abnormally long periods due to operational constraints such as unavailability of refueling access. A few bundles have achieved burnups over 500 MW.h/kg U at significant power levels. It was therefore judged necessary to extend the allowable power / burnup limiting envelope to 500 MW.h/kg U (outer element).

Since the original envelope was derived on a reactor basis rather than a bundle basis, an attempt was made to derive a new envelope that was consistent with performance constraints (i.e. so as to avoid an increased probability of fuel failure).

2 METHODOLOGY

There are many fuel elements that have operated at high powers to high burnups and show significant sheath strain; the higher the stress and / or strain, the higher the probability of sheath failure. About 40 fuel irradiations were selected, from Ontario Hydro, Point Lepreau and AECL experimental irradiations that had operated at significant power and burnup conditions and for which fuel density, gas release and post-irradiation sheath strain measurements were available. A method of normalising the data was devised so as to allow for the influence on sheath strain of:

- density
- burnup
- and power,

and thereby derive an algorithm which predicted sheath strain as a function of the above variables. The resulting algorithm was then used to predict the strain for the existing 'Reference Design Overpower Envelope' (assuming a fuel density of 10.75 Mg/m^3 as reference), and where the predicted strain exceeds the selected criterion for average sheath strain, the power of the revised envelope was reduced accordingly.

The data indicates that the total amount of gas in the element (original fill gas plus that released during operation) also influences the probability that an element might defect. However as discussed in section 4.1, a limiting criterion could not be formulated in terms of restricting the power / burnup envelope without imposing undue conservatism.

Ideally a fuel modeling code such as ELESIM [1] should have been used to calculate the sheath strains and hence the limiting power / burnup envelope. However, at high power / burnup combinations, ELESIM predictions of sheath strain appeared to be significantly higher than the available measurements would indicate, so this approach would have been unduly restrictive. Therefore a simple algorithm was devised to normalise data and create an experimentally-based limiting envelope, as detailed in section 2.

2.1 Effect of Fuel Power.

Direct in-reactor measurements [2,3] show that the sheath diametral strain (measured at the pellet mid-plane positions) changes by between 0.01 and 0.02 % per kW/m power change (the 'correlation' factor).

Almost all the strain data were generated from fuel where the final power was less than the earlier powers, therefore there could be uncertainty as to where in the history the maximum strain was generated. However, for the histories under consideration, the decrease in strain due to decreasing power is generally less than the increasing strain due to burnup (see 2.3 below). Therefore generally it was the final power and burnup of a power history that defined the sheath strain. To normalise to any given power (the 'reference' power), the measured strain is therefore decreased by the difference between the final power and the reference power times the correlation factor between strain and power. Thus if the final power is less than the reference power, the estimated strain at the reference power level would be higher than the measured strain.

2.2 Correlation between Volumetric Expansion and Diametral Expansion.

If fuel expansion due to volume swelling minus densification is isotropic, the radial expansion is approximately a third of the net volume expansion. However if the expanding fuel acts like a fluid, there is little axial expansion and the radial expansion is approximately a half of the volume expansion. The latter assumption was made for the present study, as it results in slightly higher sheath strains and is therefore conservative.

2.3 Effect of Fuel Density

A fraction of the volumetric fuel expansion that is caused by heating up to power or increasing the burnup (section 2.4), can be accommodated in the as-fabricated porosity. However only about one third [4] to one fifth of the porosity [5][1] is available to accommodate fuel expansion. Thus, if the density of the measured fuel were less than 10.75 Mg/m^3 (the reference condition), the expected strain would be that of the measured fuel, increased by the percentage difference in density times the accommodation factor, times the correlation factor between volume and diametral expansion (section 2.2).

2.4 Effect of Fuel Burnup

MATPRO [6] indicates that solid fission product swelling is approximately 0.275 % by volume per 100 MW.h/kg U burnup. As in section 2.2 above, it is assumed that the sheath diametral strain increases by half of the increase in volumetric expansion (after allowing for densification, section 2.3). Thus if the burnup of the measured fuel were less than that for the reference, the sheath strain under the reference conditions would be estimated by increasing strain by half the increase due to swelling.

[1] The lower density fuel in reference [5] was made in a manner that yielded larger-than-normal porosity. These pores are more stable and would be expected to densify less than those in normal CANDU fuel.

3 DATA NORMALISATION

The preceding is summarised in the following equation:

$$\varepsilon = \varepsilon_m + (p_r - p_m) \times f_{power} + [(b_r - b_m) \times 0.00275 + (\rho_r - \rho_m)/\rho_r \times 100 \times f_{density})] \times 0.5$$

where

ε	= sheath diametral strain
subscript m	= measured
subscript r	= reference
b	= burnup (MW.h/kg U)
p	= element linear power (kW/m)
f_{power}	= power factor (% strain per kW/m power difference)
$f_{density}$	= density factor (fraction of porosity available to accommodate fuel expansion)
ρ	= density (Mg/m^3)

The data was all normalised to a common power and burnup and a density of 10.75 Mg/m^3, using different sets of power and density factors, in the range

Power factor 0.01 to 0.02 % per kW/m
Density factor 0.5 to 0.2

The 'best fit' values for the power and density factors were found by minimising the standard deviation of the data set.

A power factor of 0.012 % strain per kW/m, associated with a density factor of 0.4 (fourty percent of the available porosity is available to accommodate fuel expansion) yielded the best 'fit' to the data. Use of the density factors in the range 0.33 to 0.2 indicated in the literature [4,5] caused slightly poorer 'fits'. Agreement between the derived factors and those deduced from the literature indicates that the methodology is reasonable.

The average of the resulting normalized strains represents the predicted strain under the given conditions. The scatter about the average is 0.175 % (one standard deviation) with a range (minimum to maximum) of 0.74 %. The scatter is in part attributed to uncertainty in the input parameters, primarily fuel density and diametral clearance.

- A decrease in fuel density of 0.1 Mg/m^3 results in a decrease in sheath strain of < 0.2%.
- The range of diametral clearance in fuel manufacture is up to 0.08 mm, which corresponds to an uncertainty in the predicted sheath strain of up to 0.6 %

4 DERIVATION OF A BOUNDING POWER / BURNUP HISTORY

4.1 Limiting Criteria

Historically, the OPG Fuel Design Manuals have given a guideline that 0.5 % sheath diametral strain (measured at the pellet mid-plane) is a limit for acceptable performance. The data base shows that fuel failures did not occur where the maximum (permanent) pellet midplane strain was less than 0.5%, but above this value, the frequency of failures increased significantly. For conservatism and to allow for the normal variation in strain along an element length, a limit of 0.4 % strain was selected as the criterion to define the revised power / burnup envelope.

The data base also indicates that fuel defects occur more frequently where the volume of free gas (filling gas plus released gas) within the fuel element is more than about 40 to 60 ml. This figure is only applicable to current production CANDU fuel elements without a gas plenum; the data shows that inclusion of a plenum can alleviate the effect at high burnups (high gas releases). It is not possible to devise a limiting power / burnup envelope that restricts gas release to 40 ml without unnecessarily penalizing high power operation at burnups above about 230 MW.h/kg U [7]. However bundles normally follow a power / burnup history that is significantly lower than the Reference Bundle Overpower envelope and therefore will be able to operate to burnups higher than 230 MW.h/kg U without exceeding the 40 ml criterion.

Although the maximum fabricated fuel density for Ontario Power Generation reactors is limited to 10.72 Mg/m^3, the study was performed for a density of 10.75 Mg/m^3 to maintain consistency with the existing AECL Fuel Specifications. Lower fuel densities would decrease sheath strain and enable higher powers.

4.2 Maximum Power / Burnup Envelope

The sheath strains predicted by the algorithm in Section 3 were calculated using the original power history (the 'Reference Design Bundle Overpower envelope). Where the predicted diametral strain was more than 0.4 % the power was reduced until the strain equaled 0.4 %. The original Reference Bundle Design Overpower envelope is calculated to give 0.4 percent average diametral strain at 56.8 kW/m, 253 MW.h/kg U outer element burnup, so at burnups higher than this, the revised envelope has lower powers than the original.

The original and modified 37-element Fuel Bundle power / burnup envelopes are shown in Table 1 and Figure 1.

Continuous operation at or near the revised Reference Bundle Overpower envelope to burnups exceeding 230 MW.h/kg U will result in released gas volumes over 40 ml. However the data indicates that the release of 80 ml of gas does not have a large effect on sheath strain or defect probability.

5 SUMMARY

An algorithm has been developed to assess the effects of element power, burnup and density on diametral sheath strain, based on extrapolation from existing high power / high burnup data. Using this model and assuming a limiting strain of 0.4 %, the original Reference Design Bundle Overpower envelope has been extrapolated to an outer element burnup of 500 MW.h/kg U (bundle burnup of 450 MW.h/kg U). The calculations were performed assuming a fuel density of 10.75 Mg/m^3 ; a lower density would decrease the predicted sheath strain.

The defect probability for a standard CANDU fuel element appears to increase if the total free gas (filling gas plus released gas) inside a fuel element exceeds about 40 ml. This may cause some fuel to defect if it operates at high powers to burnups > 230 MW.h/kg U (bundle burnups > 205 MW.h/kg U), but each situation has to be assessed individually.

6 REFERENCES

1] Notley M.J.F, "ELESIM: A Computer Code for Predicting the Performance of Nuclear Fuel Elements", Nuclear Technology, November 1979.
2] Fehrenbach P.J, Morel P.A. and Sage R.D, "In-Reactor Measurements of Cladding Strain: Fuel Density and Relocation Effects", Nucl. Tech. 56, p.112, (1982) also AECL-7341
3] Notley M.J.F, Pettigrew M. and Vidal H, "Measurements of the Circumferential Elongation of Fuel Element Sheathing during Reactor Operation", AECL Report AECL 4072 (1972)
4] Hastings I.J, Fehrenbach P.J. and Hosbons R.R, "Irradiation Induced Densification in Irradiated UO_2 Fuel", J.Amer. Ceram. Soc., 67,pC24, (1984), also AECL report AECL-8230
5] Floyd M, He Z, Kohn E and Montin J, "Performance of Two CANDU-6 Bundles Containing Elements with Pellet Density and Clearance Variables", Paper presented at 6th. International Conference on CANDU Fuel, Niagara Falls, September 1999. Also AECL-12033
6] MATPRO - Version 11. " A Handbook of Materials Properties for Use in the Analysis of Light-Water Reactor Fuel Behaviour" USNRC report NUREG-0497, also TREE-1280 Rev. 2, (1981)
7] Meadowcroft R.R, Kelm J.R, Elder R.R, Hunton A.E. and Berthiaume L.C, "The Performance of Gentilly-2 Prototype Bundle NR: Irradiated at Continuous High Power", Exp-BDL-402, AECL Proprietary report CRNL-1524, (1977)

TABLE 1 MODIFIED REFERENCE DESIGN BUNDLE OVERPOWER ENVELOPE

Bundle Average Burnup (MWh/kgU)	Outer Element Burnup (MW.h/kg U)	Outer Element / Bundle Power, Burnup Ratio	Bundle Power (kW) Original	Outer Element Linear Power (kW/m) Original	Bundle Power (kW) Modified	Outer Element Linear Power (kW/m) Modified
0	0	1.1252	-	-	-	-
10	11.2	1.1245	1014	64.20	1014	64.20
20	22.5	1.1279	1025	65.04	1025	65.04
30	33.8	1.1302	1032	65.61	1032	65.61
40	45.1	1.1311	1035	65.90	1035	65.90
50	56.4	1.1312	1035	65.92	1035	65.92
60	67.7	1.1309	1033	65.76	1033	65.76
70	79.0	1.1304	1029	65.50	1029	65.50
80	90.3	1.1293	1020	64.85	1020	64.85
90	101.6	1.1281	1015	64.49	1015	64.49
100	112.9	1.1267	1009	63.97	1009	63.97
110	124.1	1.1253	1000	63.38	1000	63.38
120	135.4	1.1239	992	62.79	992	62.79
130	146.6	1.1226	983	62.14	983	62.14
140	157.8	1.1213	974	61.49	974	61.49
150	169.0	1.1201	966	60.91	966	60.91
160	180.2	1.1190	957	60.34	957	60.34
170	191.4	1.1181	949	59.76	949	59.76
180	202.6	1.1173	941	59.18	941	59.18
190	213.7	1.1166	932	58.60	932	58.60
200	224.9	1.1161	924	58.02	924	58.02
210	236.0	1.1157	917	57.5	917	57.5
220	247.2	1.1154	909	57.05	909	57.05
230	258.4	1.1153	902	56.61	895	56.19
240	269.5	1.1153	895	56.17	875	54.91
250	280.7	1.1153	888	55.74	854	53.63
260	291.8	1.1155	882	55.39	834	52.35
270	303.0	1.1159	876	55.04	813	51.07
280	314.1	1.1164	871	54.60	792	49.79
290	325.3	1.1169	865	54.26	772	48.51
300	336.5	1.1175	860	53.77	751	47.23
310	347.6	1.1180	851	53.54	730	45.95
320	358.8	1.1182			710	44.67
330	370.0	1.1182			689	43.39
340	381.2	1.1182			669	42.11
350	392.4	1.1182			649	40.83
360	403.6	1.1182			628	39.55
370	414.7	1.1182			608	38.27
380	425.9	1.1182			588	36.99
390	437.1	1.1182			567	35.7
400	448.3	1.1182			547	34.42
410	459.5	1.1182			526	33.14
420	470.7	1.1182			506	31.86
430	481.8	1.1182			486	30.58
440	493.0	1.1182			465	29.3
450	504.2	1.1182			445	28.02

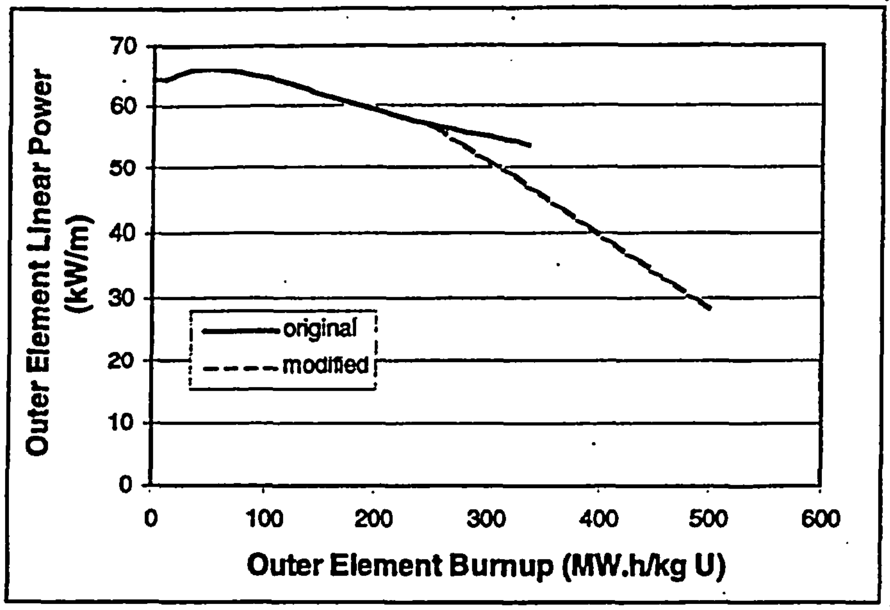

FIGURE 1. REFERENCE DESIGN BUNDLE OVERPOWER ENVELOPE, FOR A DENSITY OF 10.75 Mg/m^3.