BUNDLE URANIUM CONTENT AND PERFORMANCE OF CANDU FUEL

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ABSTRACT

Between 1970 and 1988, the mass of uranium in CANDU bundles increased by 2 to 3%. To assess the effects of the increase, post-irradiation examination data for 1970 to 1996 fuel with a range of uranium contents were evaluated. The results show a sheath strain increase with increasing UO_2 density and burnup. Other factors that affect the content of uranium, could not be quantitatively evaluated from the data.

Bundle uranium mass is affected by several contributing parameters, which have either positive or negative effects on the fuel sheath strain and bundle subchannel cross-sections. The ELESTRES fuel modelling code has been used to determine the relative effect on sheath strain of the design parameters that control uranium mass, namely, pellet density, diametral clearance, axial gap, and pellet face geometry (chamfer, dish depth, and land width).

The increases in uranium mass achieved between 1970 and 1988 caused increases in fuel element diameter which in turn has an effect on the margin to dryout. A limiting bundle mass was calculated for an overall average of zero element strain in a fuel channel in a previous study. For comparison, this paper presents a revised calculation by including midpellet as well as ridge strains to determine a weighted average sheath strain.

We have re-evaluated the current fuel technical specifications with respect to the margin to dryout, and examined uranium mass as a simplified indicator for bundle acceptability. Links between uranium content and fuel performance are discussed.

1. Introduction

The 2 to 3% increase in bundle uranium content caused concerns about negative effects on fuel performance, such as increased susceptibility to stress-corrosion cracking (SCC) and decreased dryout margin. This paper reports the results of a post-irradiation examination (PIE) database review, and discusses them with respect to uranium content and fuel performance.

The relative effects on sheath strain of the design parameters that control uranium mass, namely; pellet density, diametral clearance, axial gap, and pellet face geometry (chamfer, dish depth, and land width), have been calculated and are presented here.

The case for limiting bundle uranium content due to the potential of a decreased margin to dryout is re-examined. The methodology of the previous determination of the limiting uranium content has been followed, but with a modification to the determination of the effective sheath strain.

2. Performance Factors Evaluated Using PIE Data

2.1 Database

The PIE database we used for the evaluation includes fuel irradiated between 1970 and the early 1990s. It was compiled in the AECL Fuel Development Branch and Fuel Design Branch [1]. It lists manufacturing and PIE data from the final PIE reports of CANDU fuel irradiated in power reactors.

Bundle mass, UO_2 density, and plastic sheath strain are plotted against a date line from 1970 to 1996 in Figures 1 to 3. The data points do not always correspond between the graphs, depending on the availability of the parameters in the database. In some cases, nominal fabrication values for sheath outside diameter prior to irradiation were used to calculate the strain. This is consistent with manufacturing data, which normally list average batch values, rather than individually measured sheath diameters.

The uranium mass was increasing as the fuel manufacturers' capabilities were improving, and there was an economic incentive to increase the uranium content in the fuel. The increase has been mainly due to higher densities, though dimensional refinements have contributed as well. Figure 1 illustrates the bundle uranium mass showing a steady increase, from about 18.8 kg U in the late 1970s to about 19.3 kg U in the late 1980s for 37-element power reactor fuel. Pickering fuel ranged between 19.8 and 19.85 kg U per bundle in the early 1970s, and increased to 20.2 kg U per bundle in the 1980s. Figure 2 shows the trend in UO_2 density, increasing from 10.60 Mg/m^3 in the early 1970s to about 10.73 Mg/m^3 in the mid 1980s. Figure 3 plots the measured sheath strain (midpellet average). The strain shows an upward trend, from an even distribution between compressive and tensile permanent strains during the 1970s to mainly tensile strains (with a mean near 0.3 %) in the late 1980s.

2.2 Sheath Strain: Effect of Uranium Mass, Power and Burnup

The mid-pellet average sheath strain increased with operating power. To evaluate the strain vs. uranium mass correlation, we normalized the effect of different operating powers (from actual peak power to 50 kW/m, typical of peak element ratings for outer elements), using a factor of 0.019% midpellet sheath strain/(kW/m) for both Pickering and 37-element fuel types [2, 3]. The result is shown in Figure 4.

Figure 4 excludes the data for three bundles with the lowest density in this data set (10.6 Mg/m^3) and low power. In all three cases, normalization to 50 kW/m produced inordinately high strains (up to 0.9%). This brings into question the accuracy of the data or the applicability of the normalizing factor to low powers.

Figure 4 indicates, for all fuel types, an upward trend in strain with increasing density, a rise of about 0.56% per 0.1 Mg/m^3 density increment. This is higher than the theoretical coefficient (0.31% per 0.1 Mg/m^3). Obviously, the trendline in Figure 4 is affected by changes of additional parameters that occurred in parallel with the increase of density.

Figure 5 plots normalized strains (as above) against burnup. The figure indicates, for all fuel types, an upward trend in strain with increasing burnup, a rise of about 0.15% per 100 MW·h/kg U in Figure 5. Again the same data as in Figure 4 for UO_2 densities of 10.6 Mg/m^3 and low power have been excluded.

2.3 Ridge Height

The average ridge height at pellet interfaces is the average of the measured ridges for each element. The ridge height is one half of the differential between the measured midpellet diameter and pellet interface diameter. Figure 6 shows the average ridge height for "low uranium" fuel irradiated in NRU in the early 1970s, and in "high uranium" reactor fuel irradiated in the 1980s and 1990s. Though the overall element strains have been seen to increase with increased uranium mass, the differential between the pellet interface ridge heights and midpellet diameters has remained unchanged over the years. Pickering fuel exhibited average ridge heights between 13 and 41 μm; for 37-element fuel, the average ridge heights were between 9 and 27 μm.

2.4 SCC Defect Threshold

The database includes a number of power-ramp defects. Only three of them have the reported power-burnup combination or the power ramp-burnup combination below the 1% defect probability line from the 1982 CANDU 6 defect threshold curves (all three belonging to the 1988 Pickering-1 incident where more than 290 elements failed [4, 5]). All other power ramp defects experienced power-power ramp-burnup combinations above the threshold.

3. Parametric Evaluation of Factors Affecting Bundle Uranium Mass

3.1 Input Data

We considered pellet density, pellet outside diameter, diametral clearance between the pellet and the sheath, the axial gap between the pellet stack length and the sheath internal length between end caps, and the pellet face geometry (chamfer, dish depth, and land width) for their effect on bundle uranium mass and sheath strain. The ranges of values for the parameters under consideration were chosen for relevance to the CANDU fuel in use today. "Low", "middle" and "high" values were chosen for each of the parameters, considering production values and the range of interest. These variables along with the fixed input parameters are listed in Table 1.

3.2 Method

ELESTRES, version M13B.8 [6], has been used in the evaluations of the effects of the parameters on uranium mass and sheath strain.

The parameters were evaluated one at a time, varying each to their "low", and "high" values, while keeping the other parameters fixed at the "middle" value.

The reference high-power envelope for CANDU 6 fuel, from the Fuel Design Manual for CANDU-6 Reactors, was used for each of the cases. This power history was chosen to illustrate the relative effects of the studied parameters on sheath strain and uranium content.

3.3 Parametric Evaluation Results

The evaluation included a comparison of the individual parameter's effect on bundle uranium mass, Table 2.1, and on element hoop strain, Tables 2.2 and 2.3. Table 2.4 presents a weighted average sheath strain from the values in Tables 2.2 and 2.3. This was calculated by considering the ridge strain affecting one third of the sheath length and the midplane strain affecting two thirds of the sheath. These proportions were approximated from profilometry charts recorded in PIE reports from CRL. To show the relative effect of each of the parameters, the "percent uranium" differences between "lows" and "highs" (Table 2.1), and the magnitude of strain increase (Table 2.4) were combined. Their product was used to give a relative reading on the effect of each parameter. The relative effect is listed under "Factor" in Table 2.5 and shown graphically in Figure 7.

The parametric evaluation used ELESTRES calculations of the identified parameters' effect on bundle uranium mass and sheath strain. For the range of interest within the current specifications and manufacturing practices, the parametric evaluation shows that, for the fuel element diameter of 13.10 mm in use today, the main factors affecting bundle uranium mass and sheath strain are pellet density and diametral clearance. To consider a limitation on bundle uranium masses with respect to dryout, diametral clearance is limited by the ability to load fuel stacks into the fuel sheath where the clearance falls into the range of about 0.05 mm to 0.09 mm. The parameters considered here are those allowable within the current fuel specifications for 37-element fuel.

These ELESTRES calculations show that the design parameters fall into two groups; (i) those where the increase in uranium mass is accompanied by an increase in sheath strain, and (ii) those where the increase in uranium mass has a negligible effect on sheath strain. Minimizing the axial gap and dish depth would increase the bundle uranium mass without a significant increase in on-power sheath strain.

4. Evaluation of Basis for Uranium Content Limit

There are two areas of concern with high density pellets and with fuel manufactured with small gaps between the pellets and sheath:

- high tensile strains increase the sheath diameters and thus increase hydraulic resistance of the fuel string and lower the margin to dryout, and
- high tensile stresses and strains of the sheath may lower the power ramp threshold for SCC failure.

4.1 Evaluation of Uranium Mass Limit Affecting the Margin to Dryout

Because of the concern for a lower margin for dryout due to increased uranium mass, an earlier assessment estimated the bundle average sheath ridge strain as a function of average uranium content for a column of 12 bundles operating at the dryout channel power [7]. The ELESTRES and NUCIRC computer codes were used to assess the change in the margin to dryout, and shown graphically is the channel average zero strain intercept in Figure 8. The critical uranium content corresponding to a bundle average ridge strain of zero along the fuel column was determined to be 19.25 kg U. It should be noted that the NUCIRC analysis does not include any potential fuel element diameter effect on Critical Heat Flux.

The previous determination was a lower bound (conservative) approach by considering only bundle average ridge strains in the determination of channel flow impedance. A more realistic approach would be to use a perimeter weighted average approach in simulating the bundle deformation profile. In this paper, a modification to the strain determination is used, considering that the flow impedance to the channel is determined by the fuel element diameters both at the ridges and pellet midplanes. The perimeter averaging method to determine element strains is consistent with the overall approach in determining channel flow restriction, where the average bundle strains of twelve bundles in a fuel channel are used, rather than just the strains of the highest power central bundles.

To determine the bundle average zero strain value for bundle uranium mass in a fuel channel operating at dryout, the bundle average cross section ridge strains in Table 3 are converted to perimeter weighted average strains in Table 4. The bundle powers for the position 12 bundles in these two tables was modified to reflect the powers for the position 4 bundles prior to an 8 bundle shift in order to more accurately reflect the sheath strains in these bundles. The relationship between the weighted average sheath strains to the ridge strains determined by ELESTRES was used to determine the factor for converting the ridge strains to the weighted average strains. Figure 8 plots the Reference7 ridge strain, and shows the shift in average sheath strain when midplane hoop strain is included. The bundle average zero strain point for the fuel channel shifts from a bundle weight of 19.25 kg U to 19.40 kg U.

4.2 Evaluation of Uranium Mass Limit Because of SCC Considerations

In general terms, lower density and higher diametral clearance fuel induces compressive sheath strain due to sheath collapse and pellet densification while higher density and lower diametral clearance fuel induces tensile sheath strain from pellet expansion. However, these are initial conditions and most fuel densification occurs early in fuel life. During constant power irradiation the stress in the sheath is close to zero as the effects of density and diametral clearance are significantly reduced due to sheath creep and stress relaxation. In-reactor Diameter Measuring Rig (IRDMR) tests have shown diameter increases during a power ramp following a low power soak at about 30 kW/m to a burnup of 100 MW·h/kg U were independent of initial fuel density [8].

With the exception of the Pickering-1 failures from overpowering and the Point Lepreau defects with uncured Canlub, there have been no power ramp failures attributable to SCC since 1972 in Canadian reactors, as the overall fuel failure rate has been decreasing while the bundle uranium masses were increasing.

The size of ridges, where the power-ramp defects are usually initiated, has not changed with the increase of uranium mass (Figure 6). This observation indicates no change or a small change in the threshold.

5. Conclusions

1. The available PIE data show an increase in residual sheath strain with increasing pellet density, at about 0.56% per 0.1 Mg/m^3 density increment. Other factors affecting sheath strains, such as pellet and sheath dimensions, could not be quantitatively evaluated from the available data and are believed to have affected the density factor.

2. The PIE data show an increase in residual sheath strain with increasing burnup, a rise of about 0.15% strain for each increase of 100 MW·h/kg U burnup. As in the case of strain vs. density above, it was not possible to separate the effect of pellet and sheath dimensions.

3. The database has yielded little evidence about changes of the power ramp defect threshold with uranium mass. Based on the performance of all "heavy fuel" we believe that, for the ranges of uranium mass experienced between 1970 and 1988, the margins for power ramp SCC are sufficient.

4. Heavy fuel will increase the element diameters at power. A re-evaluation of previous analyses, where only ridge strain is considered, determined that the limiting uranium mass increases when the overall average sheath strain is used to determine the flow impedance in a fuel channel. The re-evaluation determined that the dryout performance of the fuel is not expected to be reduced for 37-element fuel bundles with uranium contents below 19.40 kg U. Current production practices and compliance to AECL's technical specifications produces 37-element fuel bundles with an average uranium content of 19.3 kg U, with a ±3 sigma range from 19.27 to 19.33 kg U.

5. There are some difficulties with uranium content as a design parameter because it can be controlled by several factors. Uranium mass is a complex function of several elementary parameters, and depending on their particular combinations, it may distort the intent of the fuel design. We therefore do not recommend uranium mass be included among the requirements of fuel technical specifications. The parametric evaluation shows that the bundle uranium mass is practically controlled by pellet density and pellet diameter (diametral clearance), the two parameters that also have the largest effect on sheath strain.

6. Acknowledgments

The authors thank D.E. Teed (GEC) for supplying data on uranium mass; Z. He, M.R. Floyd (AECL-CRL), P.L. Purdy and A.M. Manzer (AECL-SP) for their assistance with the PIE database and helpful comments; J.H.K. Lau, D. Cox, and P.G. Boczar for their review and comments. Financial support by COG (Working Party 9) is acknowledged.

7. References

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Table 1: ELESTRES Input for "Low", "Middle" and "High" Values

Variable	"Low"	"Middle"	"High"
Density (Mg/m^3)	10.55	10.65	10.75
Land Width (mm)	0	0.46	0.85
Axial Gap (mm)	1	2	3
Diam. Clear. (mm)	0.038	0.08	0.13
Chamfer -Radial (mm)	n/a	0.85	0.45
- Axial (mm)	n/a	0.15	0.055
Dish depth (mm)	0.2	0.26	0.33
Fixed Input Para.'s			
Sheath o.d. (mm)		13.10	
Sheath Wall (mm)		0.41	
Axial Length (mm)		483.0	

Table 2.1: Impact of Change in Single Variable on 37-element CANDU Fuel Bundle Uranium Content

Variable	Bundle U Mass (kg) 'Low'	'Middle'	'High'	Percent Difference between low and high
Density (Mg/m^3)	19.11	19.29	19.47	1.88
Land Width (mm)	19.25	19.29	19.32	0.37
Axial Gap (mm)	19.33	19.29	19.25	0.42
Diametral Clearance (mm)	19.42	19.29	19.13	1.51
Chamfer (mm)	na	19.29	19.29	
Dish Depth (mm)	19.33	19.29	19.23	0.51

Table 2.2: Impact of Change in Single Variable on Sheath Ridge Strain

Variable	Ridge Strains (%) 'Low'	'Middle'	'High'	Difference (%) (High to Low)
Density (Mg/m^3)	0.96	1.133	1.447	0.487
Land Width (mm)	1.188	1.133	1.043	0.145
Axial Gap (mm)	1.125	1.133	1.138	0.013
Diametral Clearance (mm)	1.47	1.133	0.729	0.741
Chamfer (mm)	na	1.133	1.252	0.119
Dish Depth (mm)	1.112	1.133	1.1	0.033

Table 2.3: Impact of Change in Single Variable on Sheath Midplane Strain

Variable	Midplane Strains (%) 'Low'	'Middle'	'High'	Difference (%) (High to Low)
Density (Mg/m^3)	0.457	0.673	0.948	0.491
Land Width (mm)	0.654	0.673	0.72	0.066
Axial Gap (mm)	0.694	0.673	0.653	0.041
Diametral Clearance (mm)	1.03	0.673	0.301	0.729
Chamfer (mm)	na	0.673	0.632	0.041
Dish Depth (mm)	0.695	0.673	0.642	0.053

Table 2.4: Weighted Average of Strain Differences, from Tables 2.2 & 2.3

Variable	"Weighted Average of Strain differences" calculation	Weighted Av. Difference (%) (High to Low)
Density (Mg/m^3)	(2/3 Midplane + 1/3 Ridge) =	0.490
Land Width (mm)	"	0.092
Axial Gap (mm)	"	0.032
Diametral Clearance (mm)	"	0.733
Chamfer (mm)	"	0.067
Dish Depth (mm)	"	0.046

Table 2.5: Determination of Factor to Show Relative Impact of Variables on Uranium Content & Strain

Variable	(A) %U diff. from Table 2.1	(B) Strain Diff % from Table 2.4	Factor (A)*(B)	Factor (A)/(B)
Density (Mg/m^3)	1.88	0.49	0.921	3.837
Land Width (mm)	0.37	0.092	0.034	4.022
Axial Gap (mm)	0.42	0.032	0.013	13.125
Diametral Clearance (mm)	1.51	0.733	1.107	2.060
Chamfer (mm)		0.067	0.000	0.000
Dish Depth (mm)	0.51	0.046	0.023	11.087

Para_ins

Table 3

Average % X-section Ridge Strain*				
U-mass (kg U)	18.8	19.1	19.4	19.7
Bundle Power at CCP (kW):				
267	-2.256	-1.904	-1.552	-1.200
616	-1.080	-0.728	-0.376	-0.024
822	-0.385	-0.034	0.318	0.670
880	-0.190	0.162	0.514	0.866
973	0.123	0.475	0.827	1.179
1045	0.366	0.718	1.070	1.422
1045	0.366	0.718	1.070	1.422
972	0.120	0.472	0.824	1.176
855	-0.274	0.078	0.430	0.781
759	-0.598	-0.246	0.106	0.458
561	-1.265	-0.913	-0.561	-0.209
600	-1.145	-0.793	-0.441	-0.089
Channel Av	-0.518	-0.166	0.186	0.538

*Data from Reference 6

Table 4

Average % X-section Hoop Strain - Weighted Average				
U-mass (kg U)	18.8	19.1	19.4	19.7
Bundle Power at CCP (kW):				
267	-2.256	-2.090	-1.738	-1.200
616	-1.265	-0.913	-0.562	-0.024
822	-0.571	-0.219	0.133	0.670
880	-0.376	-0.024	0.328	0.866
973	-0.062	0.290	0.642	1.179
1045	0.180	0.532	0.884	1.422
1045	0.180	0.532	0.884	1.422
972	-0.066	0.286	0.638	1.176
855	-0.460	-0.108	0.244	0.781
759	-0.783	-0.432	-0.080	0.458
561	-1.451	-1.099	-0.747	-0.209
600	-1.331	-0.979	-0.627	-0.089
Channel Av	-0.704	-0.352	0.000	0.352

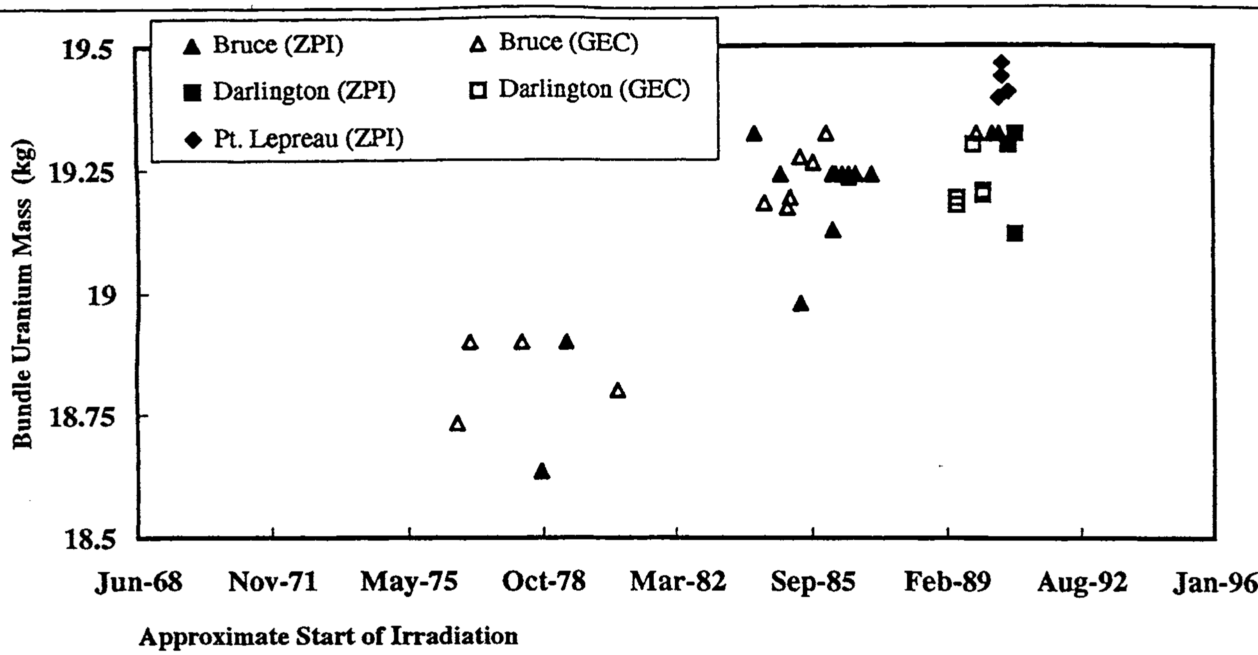

FIGURE 1: Bundle Uranium Mass vs. Irradiation Start Date for 37-Element Bundles.

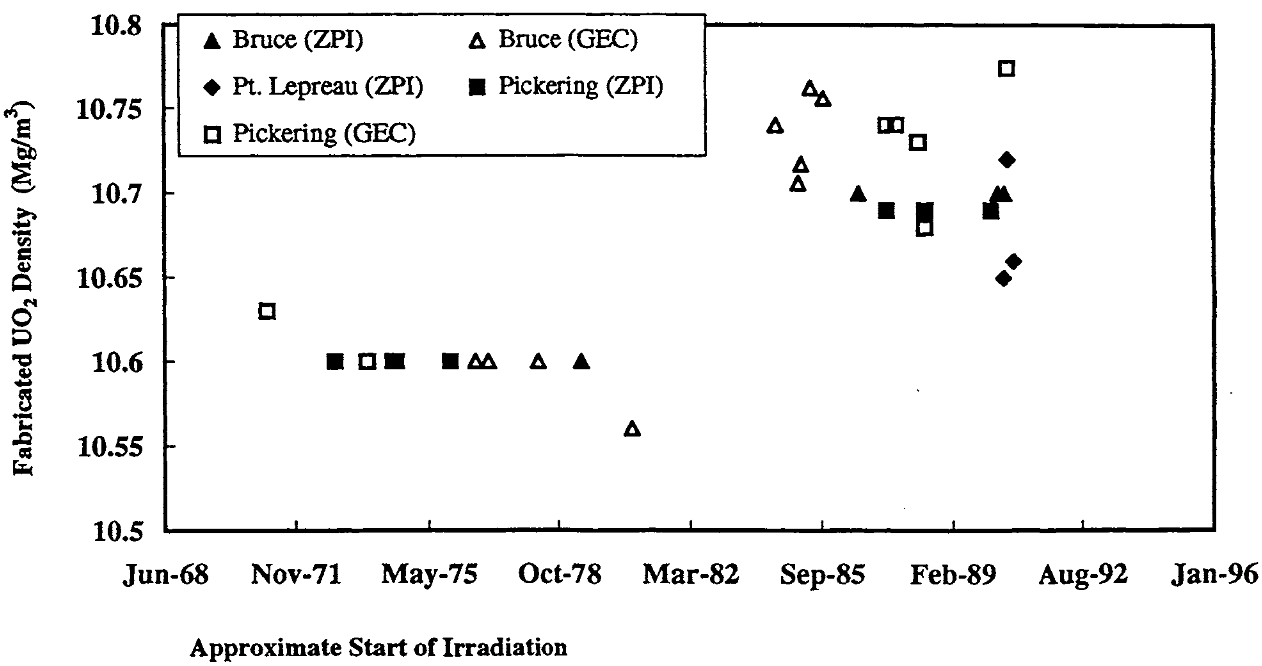

FIGURE 2: Fabricated UO_2 Density vs. Irradiation Start Date for 37-element and 28-Element Bundles.

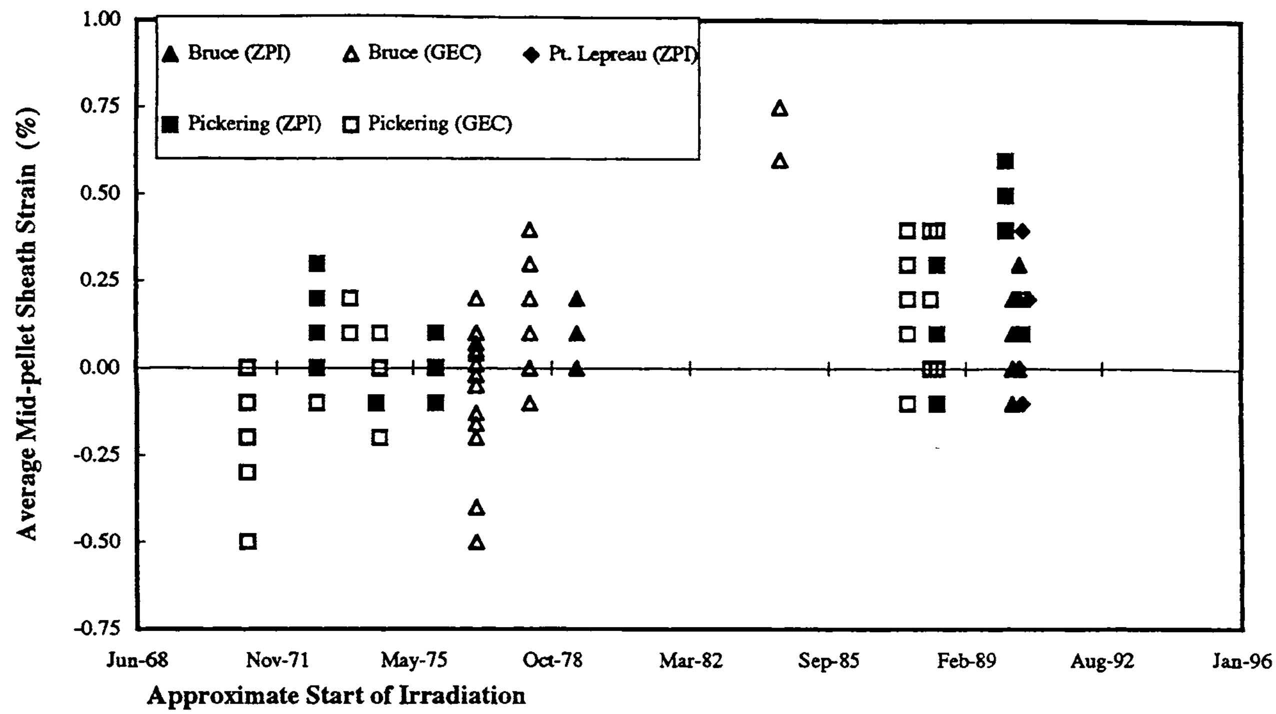

FIGURE 3: Average Midpellet Sheath Strain vs. Irradiation Start Date for Intact Outer Elements (burnup <450 MWh/kgU).

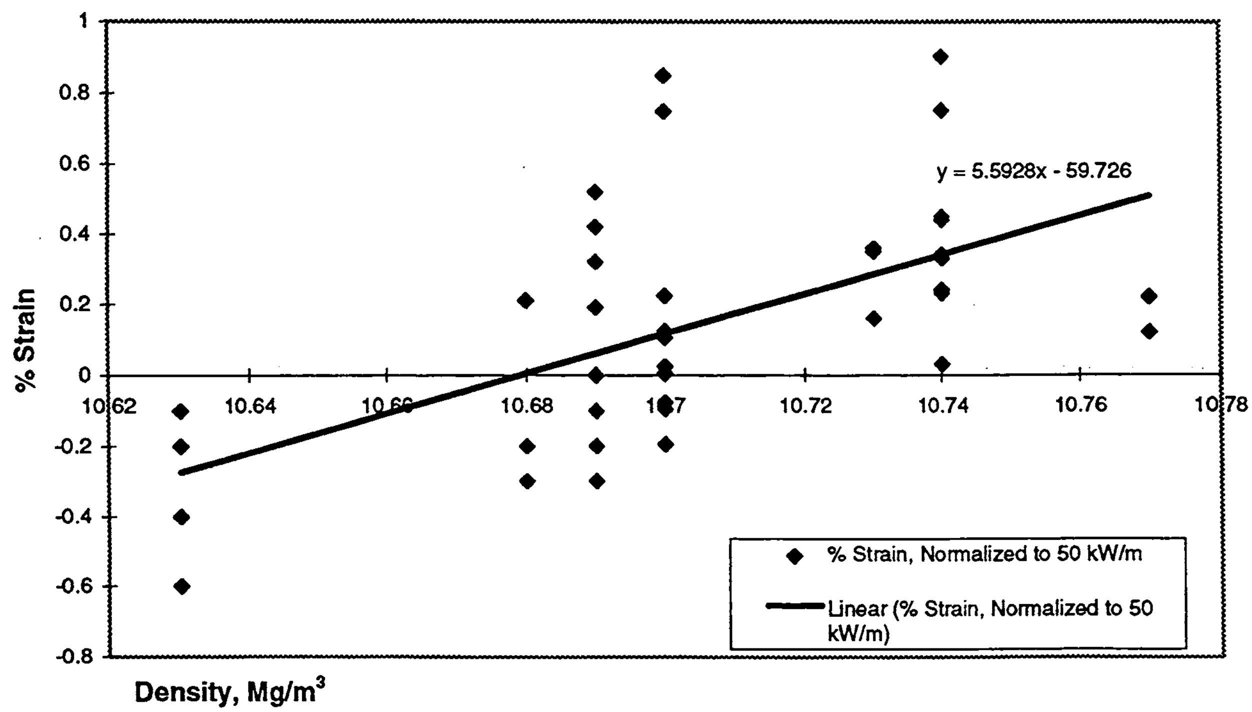

Figure 4: Midpellet Sheath Strain, normalized to 50 kW/m, vs. UO_2 Density.

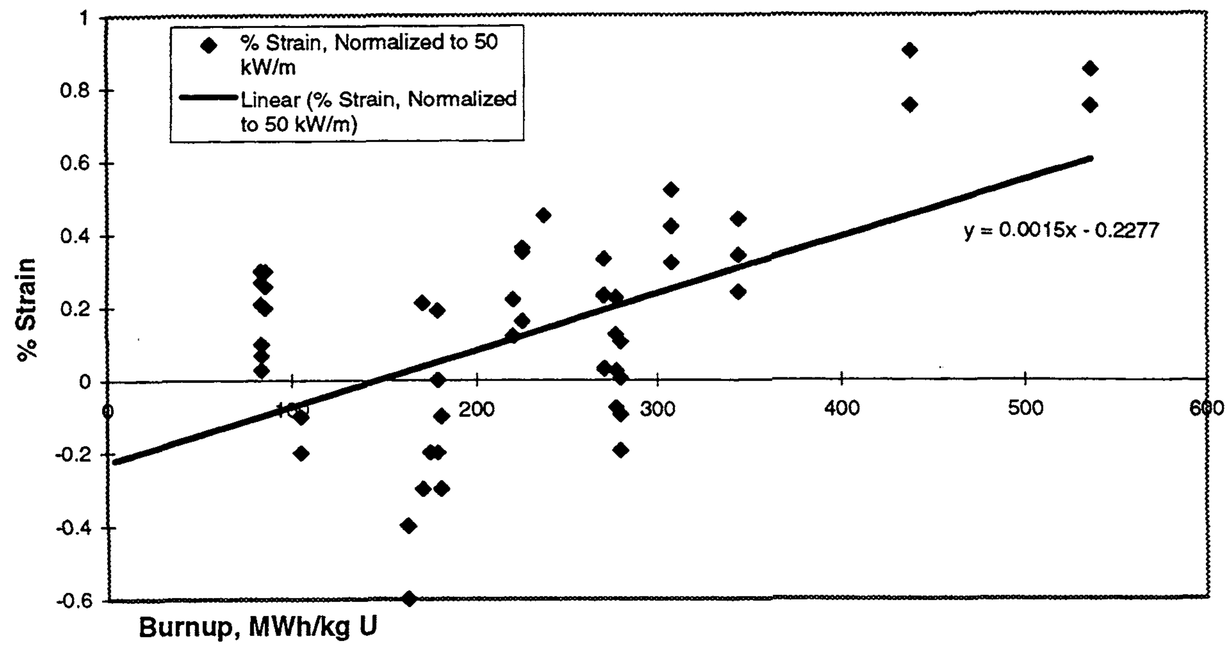

Figure 5: Average Midpellet Sheath Strain for All Fuel, normalized to 50 kW/m element linear power, vs. Discharge Burnup.

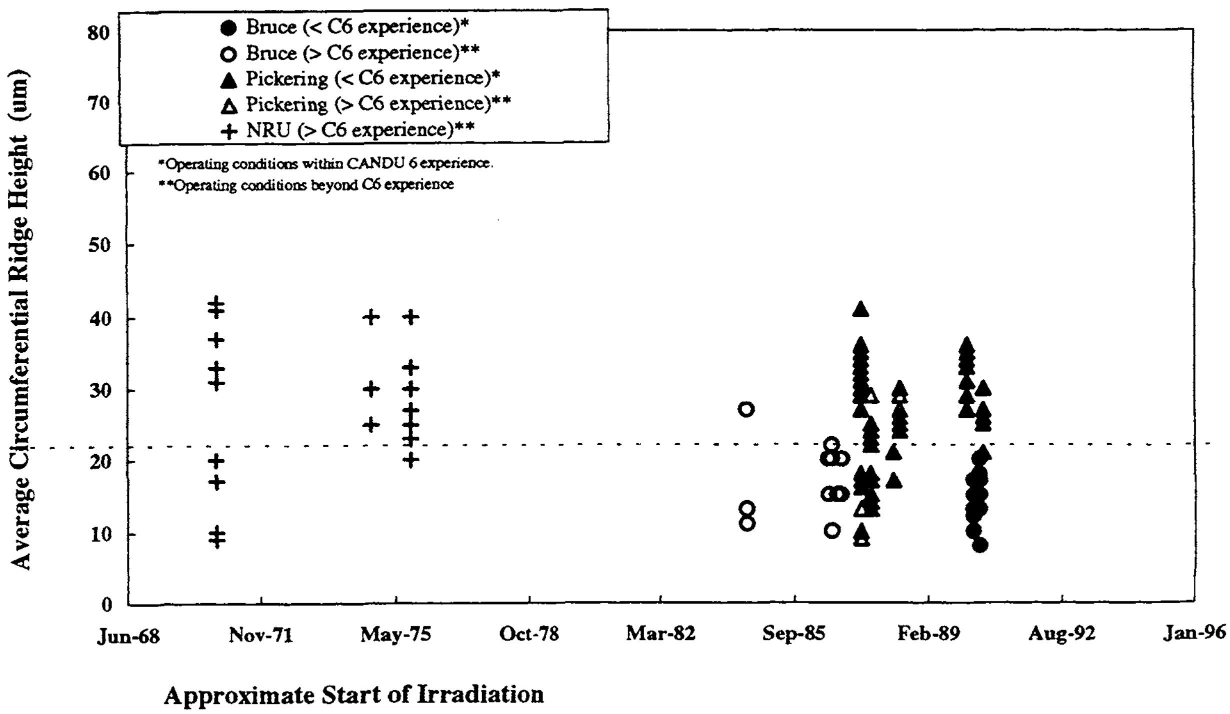

Figure 6: Comparison of Ridge Heights Produced in Low Density Fuel (NRU data) to Higher Density Fuel (power reactor deta).

Figure 7: Relative Importance of Each Parameter's Effect on Both U-mass and Strain

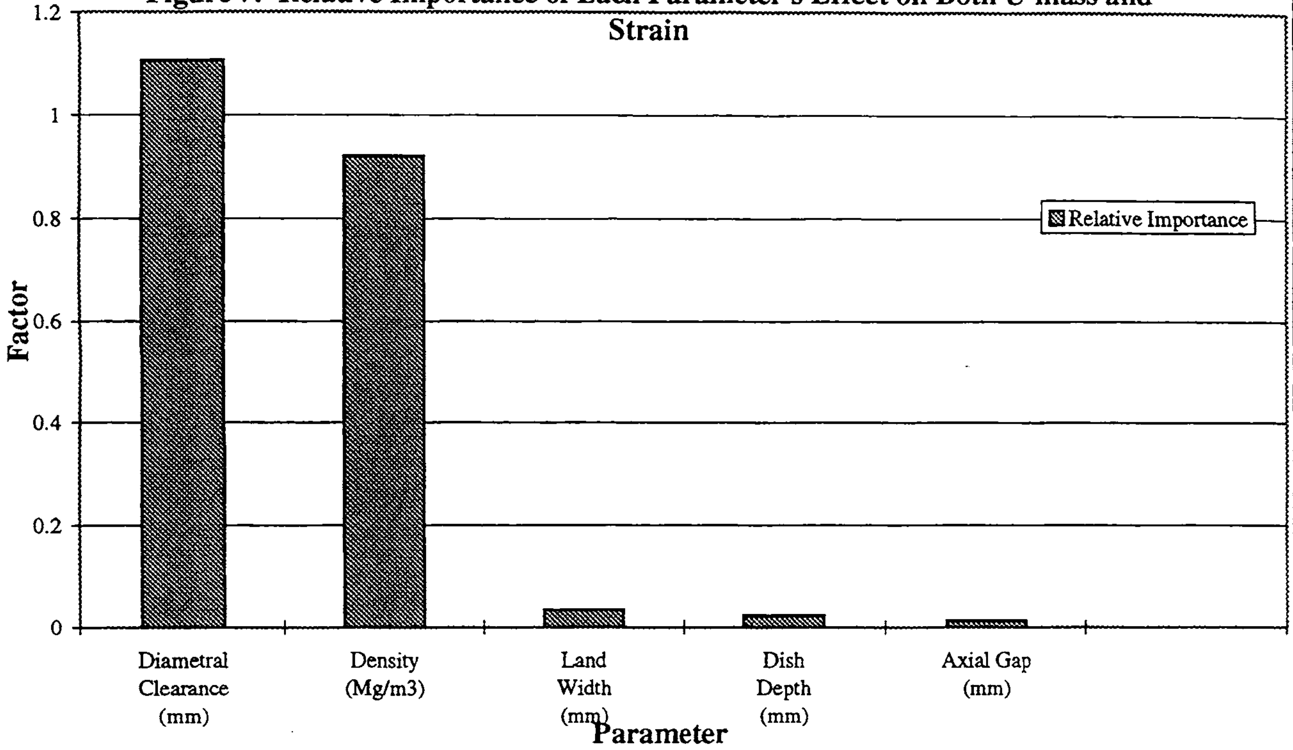

Figure 8: Comparison of ELESTRES Calculated Weighted Average Strains to Reference 7 Average Ridge Strains