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Performance of two CANDU-6 Fuel Bundles Containing Elements with Pellet-Density and Clearance Variances

Comportement de deux grappes de combustible CANDU 6 constituées d'éléments présentant des variations d'écartement et de densité des pastilles

M.R. Floyd, Z. He, E. Kohn, J. Montin

Paper presented at the 6th International Conference on CANDU Fuel, 1999 September, Niagara Falls, Canada

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M.R. Floyd, Z. He, E. Kohn* and J. Montin

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COMPORTEMENT DE DEUX GRAPPES DE COMBUSTIBLE CANDU 6 CONSTITUÉES D'ÉLÉMENTS PRÉSENTANT DES VARIATIONS D'ÉCARTEMENT ET DE DENSITÉ DES PASTILLES

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Résumé

On a fabriqué deux grappes présentant la géométrie du combustible des réacteurs CANDU 6 et mesuré les variations de densité des pastilles et l'écartement pastille-gaine à proximité des limites inférieures et supérieures des spécifications. Les grappes ont été irradiées à la centrale de Pointe Lepreau au cours de 1994 et ont été examinées dernièrement dans les cellules chaudes aux laboratoires d'EACL à Chalk River. Elles ont atteint des combustions massiques moyennes par grappe de 150 et 161 MWh/kgU et ont été utilisées à des puissances de pointe des éléments extérieurs de ~ 50 kW/m. L'objectif principal de cette étude était d'évaluer l'effet de la variation de la densité des pastilles est des écartements sur le comportement du combustible.

On a montré que les écarts diamétraux internes avaient un effet prédominant sur les déformations circonférentielles des gaines (généralement de -0,05 % par accroissement de 0,01 mm de l'écart diamétral à l'endroit de la pastille du milieu). Dans les cas où les écarts étaient voisins de la limite supérieure des spécifications, la déformation résiduelle de la gaine à l'endroit de la pastille du milieu de l'élément extérieur était principalement due à la compression; dans les cas où les écarts étaient voisins de la limite inférieure des spécifications, la déformation de la gaine à l'endroit de la pastille du milieu était due à la traction. On a noté des tendances semblables de déformation d'interface des pastilles (boursouflure). Les variations de densité des pastilles avaient un effet secondaire sur la déformation des gaines (généralement de 0,01 % par accroissement de 0,01 Mg/m^3 à l'endroit de la pastille du milieu). Le combustible de haute densité libérait légèrement moins de gaz de fission que le combustible de faible densité (2 % au lieu de 3 %).

L'étude a été financée par le Groupe des propriétaires de centrales CANDU (GPC)

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Abstract

Two CANDU-6 geometry bundles were manufactured with controlled variances in pellet density and internal pellet-to-sheath clearances close to the upper and lower limits of the design specification. These were irradiated in the Point Lepreau Generating Station during 1994 and recently examined in the hot cells at AECL Chalk River. The bundles achieved bundle-average burnups of 150 and 161 MWh/kgU, and operated at peak outer-element powers of ~ 50 kW/m. The primary objective of the investigation was to evaluate the effect of variation in pellet density and clearances on fuel performance.

Internal diametral clearance variations were shown to have a dominant effect on circumferential sheath strain (typically -0.05% per 0.01 mm increment in diametral clearance at the midpellet location). When clearances were close to the upper limit of the specification, outer-element midpellet residual sheath strain was predominantly compressive; when clearances were close to the lower limit of the specification, midpellet sheath strain was tensile. Similar trends were observed in pellet interface (ridge) strain. Pellet-density variations had a secondary effect on sheath strain (typically 0.01% per 0.01 Mg/m^3 increment at the midpellet location). High-density fuel exhibited slightly less fission-gas release than did low-density fuel (2% vs. 3%).

This investigation was funded by the CANDU Owners Group (COG).

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1. INTRODUCTION

The specifications for CANDU* 37-element natural UO_2 fuel permit variances in parameters such as pellet density and internal pellet-to-sheath clearances. Recently, the CANDU Owners Group (COG), in cooperation with the Point Lepreau Generating Station (PLGS), completed an investigation to empirically demonstrate the effects of varied pellet density and internal clearances on fuel performance parameters including sheath strain and fission-gas release (FGR).

Two CANDU-6 natural UO_2 bundles were manufactured containing elements with controlled variances in pellet density and axial/diametral clearances, close to the upper or lower limits of the design specification. These were irradiated in PLGS during 1994, and subsequently examined in the hot-cell facilities at AECL Chalk River. This paper presents the results of the investigation.

2. FUEL DESCRIPTION

Two bundles were manufactured to meet the design specifications of standard CANDU-6 (37-element, natural UO_2) fuel. The outer and intermediate rings of the bundles contained elements with pellets of either high density (HD) or low density (LD), and high and low diametral/axial clearances (HC and LC, respectively). As a result, four element types were present in the outer and intermediate rings of each bundle (HD/HC, HD/LC, LD/HC and LD/LC, see Figure 1). The variances in density and clearances in these elements were close to the upper and lower limits permitted by the design specification (Table 1). The seven inner/centre elements of both bundles were made from standard production fuel. The internal sheath surfaces of all elements from both bundles were coated with CANLUB.

3. IRRADIATION HISTORY

The two bundles were irradiated in PLGS in 1994 June-December in axial position 6 of Channels H15 and M14 at peak outer-element powers of 51 and 48 kW/m to bundle-average discharge burnups of 150 and 161 MWh/kgU, respectively (Figures 2 and 3). The intermediate elements achieved peak powers of 42 and 39 kW/m, respectively.

4. POST-IRRADIATION EXAMINATION RESULTS

Hot-cell examinations were conducted at AECL Chalk River on the various element types contained in the outer and intermediate rings of both bundles. No examinations were conducted on the seven inner/centre standard production elements. The highlights of the examination results are presented below.

* CANDU: CANada Deuterium Uranium; registered trademark of Atomic Energy of Canada Limited.

4.1 Sheath Strain

Post-irradiation element diameters were measured on all the outer elements and four intermediate elements from each bundle. Sheath strain (δ) was calculated using the measured post-irradiation diameters (D_I) and the as-manufactured sheath diameters (D_o) as follows:

$$\delta = (D_I - D_o)/D_o \quad (1)$$

The resulting calculated strains (Table 1) reflect changes in internal clearance, pellet density and fuel power, as discussed below.

4.1.1 Midpellet Sheath Strain

Element internal clearances were observed to have a dominant effect on midpellet sheath strain (Figure 4); decreasing the clearances from high to low (at constant pellet density and fuel power) typically resulted in an increase in midpellet sheath strain of 0.5%. When clearances were close to the upper limit of the specification, outer-element midpellet residual sheath strain was compressive; when clearances were close to the lower limit of the specification, midpellet strain was tensile. Past studies have shown that the effect of axial clearance variation on midpellet sheath strain is negligible compared to that of diametral clearance.[1,2] In the absence of pellet swelling or densification, the effect of eliminating all diametral clearance on sheath strain would be -0.076% per 0.01 mm increment in diametral clearance. The observed rate of change of midpellet sheath strain is ~ -0.05% per 0.01 mm increment in diametral clearance; hence, the majority of strain can be attributed to elimination of the as-fabricated diametral clearance.

Pellet-density variances had a secondary effect on midpellet sheath strain (Figure 4); increasing the density from low to high (for constant internal clearances and fuel power), typically resulted in an increase in midpellet sheath strain of 0.2%. This corresponds to a rate of change of midpellet sheath strain of ~ 0.01% per 0.01 Mg/m^3 increment.

The effect of power (for constant internal clearnaves and pellet density) is observed in Figure 4 by comparing the behaviour of the intermediate elements with that of the outer elements; an increase in power from ~ 40 kW/m to ~ 50 kW/m is observed to result in an increase in midpellet strain of 0.1%. This corresponds to a midpellet strain rate of 0.01% per kW/m over the range of 40-50 kW/m.

The observed effect of pellet-density variance on midpellet sheath strain (~ 0.01% per 0.01 Mg/m^3 increment) is considerably lower than that calculated by Palleck et al. (0.056% per 0.01 Mg/m^3 increment).[1] In-reactor sintering of small, unstable pores is responsible for reduction of sheath strain in LD fuel.[3,4] The amount of sintering/densification is dependent on fuel temperature (power), as well as the size and distribution of pores. The LD fuel under investigation was generally observed to incorporate large stable pores that did not experience extensive in-reactor sintering typical of LD fuel incorporating smaller, unstable pores. This may be one reason for the observed difference in strain/density increment relative to that calculated by

Palleck et al. In addition, the calculation by Palleck et al. did not account for variations in diametral clearances (nominal production values were assumed), and attempted to normalize the effect of different operating powers (for fuel operating up to ~ 60 kW/m) using a constant factor of 0.019% per kW/m. This strain/power factor is considerably higher than that observed in Figure 4 (0.01% per kW/m over the range of 40-50 kW/m).

4.1.2 Pellet-Interface (Ridge) Strain

Figure 5 illustrates that the trends in ridge strain are generally similar to that of midpellet sheath strain (Figure 4). Element internal clearances were again observed to have a dominant effect on ridge strain; decreasing the clearances from high to low (at constant pellet density and fuel power) typically resulted in an increase in ridge strain of 0.7%. The observed rate of change of ridge strain in Figure 5 is ~ -0.07% per 0.01 mm increment in diametral clearance.

Pellet-density variances had a secondary effect on ridge strain (Figure 5); increasing the density from low to high (for constant internal clearances and fuel power), typically resulted in an increase in ridge strain of 0.2%. This corresponds to a rate of change of ridge strain of ~ 0.01% per 0.01 Mg/m^3 increment.

An increase in power from ~ 40 kW/m to ~ 50 kW/m (in elements having constant clearances and density) resulted in an increase in ridge strain of 0.3%. This corresponds to a ridge strain rate of 0.03% per kW/m over the range of 40-50 kW/m.

4.2 Fission-Gas Release

Gas puncture was performed and samples compositionally analyzed on four outer elements from each bundle (one from each element type per bundle). Table 1 lists the average FGR observed for each element type. HD fuel exhibited slightly less FGR than did LD fuel (2% vs. 3%). Higher FGR in LD fuel is generally attributed to lower relative thermal conductivity that results from higher pore density.[5] Clearance variations had a negligible effect on FGR.

The difference in FGR for HD and LD pellets was of no apparent consequence to the overall performance of this fuel. These bundles operated at outer element powers of ~ 50 kW/m to burnups of 150 and 161 MWh/kgU; it would be expected that higher operating powers and/or burnups would amplify the FGR differences in HD and LD fuel. Failures have been attributed to internal overpressure resulting from high FGR in fuel operating at peak powers > 50 kW/m to burnups > 500 MWh/kgU.[6] In view of this, caution should should be used in extrapolating the observations made in this report. Similar investigations may be required under more severe operating conditions to understand when density/FGR effects may become detrimental to performance. This may be particularly important to the development of CANDU fuel cycles that are designed to operate to high burnups.

4.3 Other Observations

Other fuel-performance parameters, including grain growth, CANLUB retention, sheath hydriding, deuteriding and oxidation, pellet cracking, element bow and axial strain showed little or no dependence on density and clearance variations. There was no evidence of endplate cracking. Bearing-pad and spacer-pad wear were negligible.

5. SUMMARY AND CONCLUSIONS

Two bundles that contained elements with variances in pellet density and internal clearances close to the upper or lower limit of the design specification were irradiated in Channels H15 and M14 of PLGS during 1994 at peak outer-element linear powers of ~ 50 kW/m to bundle-average discharge burnups of 150 and 161 MWh/kgU. The performance of this fuel, with manufacturing parameters at the extremes of the specification, was acceptable/good. Post-irradiation examination of the bundles showed that diametral clearance variations had a dominant effect on residual sheath strain (typically ~ -0.05% per 0.01 mm increment in diametral clearance at the midpellet location). Pellet-density variances had a secondary effect on strain (typically ~ 0.01% per 0.01 Mg/m^3 increment at the midpellet location). HD fuel exhibited slightly less FGR than did LD fuel (2% vs. 3%). Other fuel-performance parameters showed little or no dependence on density/clearance variations.

6. ACKNOWLEDGEMENTS

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TABLE 1. MANUFACTURING AND PIE DATA

Element Type (Power)	Variables	Avg. Density (Mg/m^3)	Avg. Axial Clearance (mm)	Avg. Dia. Clearance (mm)	Avg. Midpellet Strain (%)	Avg. Ridge Strain (%)	Avg. FGR (%)
Outer	HD/HC	10.71	2.7	0.13	0.0	0.2	2.0
(~ 50 kW/m)	HD/LC	10.71	1.3	0.04	0.5	0.9	2.2
	LD/HC	10.51	2.7	0.13	-0.2	0.0	3.1
	LD/LC	10.51	1.3	0.04	0.3	0.6	3.2
Intermediate	HD/HC	10.71	2.7	0.13	-0.1	-0.1	
(~ 40 kW/m)	HD/LC	10.71	1.3	0.04	0.4	0.6	
	LD/HC	10.51	2.7	0.13	-0.3	-0.3	
	LD/LC	10.51	1.3	0.04	0.2	0.4	

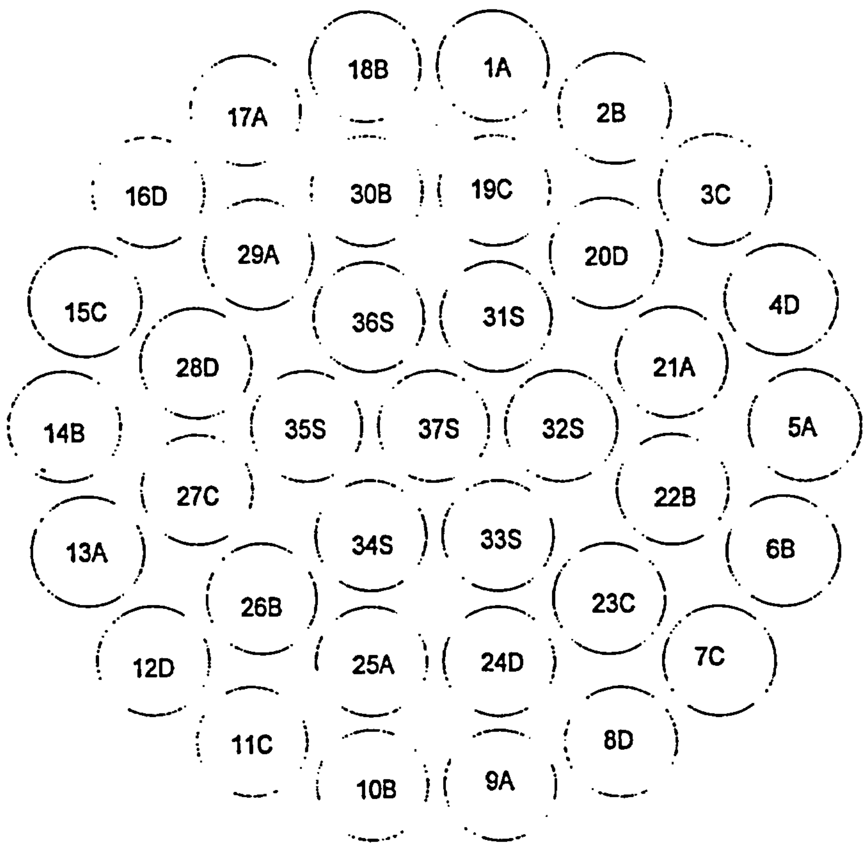

FIGURE 1. TYPICAL ELEMENT ARRANGEMENT OF TWO BUNDLES WITH CLEARANCE/DENSITY VARIATIONS IRRADIATED IN PLGS (numeric = element number; alpha = element type: A= HD/HC; B=HD/LC; C=LD/HC; D=LD/LC; S=Standard).

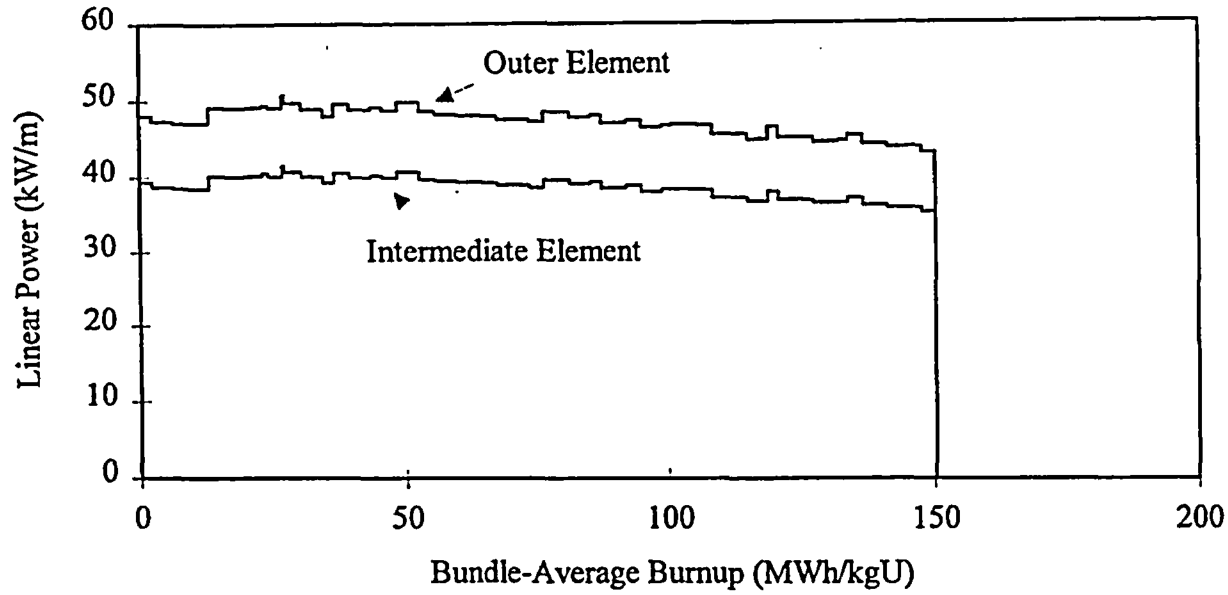

FIGURE 2. POWER HISTORY OF BUNDLE IRRADIATED IN PLGS, CHANNEL H15, AXIAL POSITION 6, 1994 JUNE-DECEMBER (Peak Power = 51 kW/m - Outers; 42 kW/m - Intermediates).

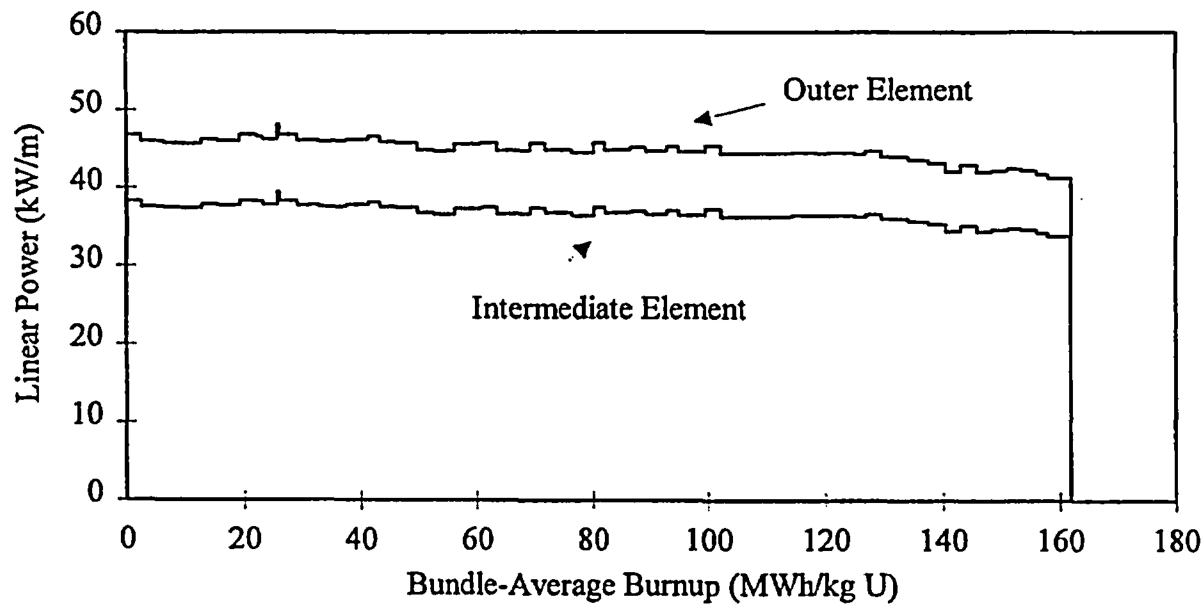

FIGURE 3. POWER HISTORY OF BUNDLE IRRADIATED IN PLGS, CHANNEL M14, AXIAL POSITION 6, 1994 JUNE-DECEMBER (Peak Power = 48 kW/m - Outers; 39 kW/m - Intermediates).

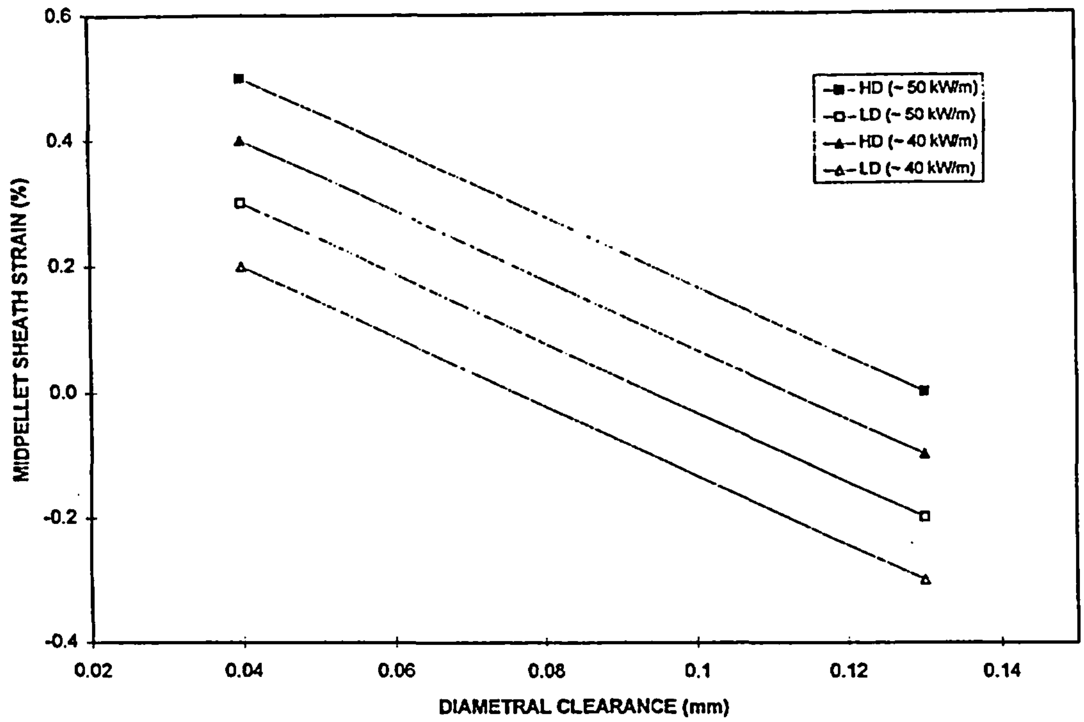

FIGURE 4. MIDPELLET SHEATH STRAIN VS. DIAMETRAL CLEARANCE

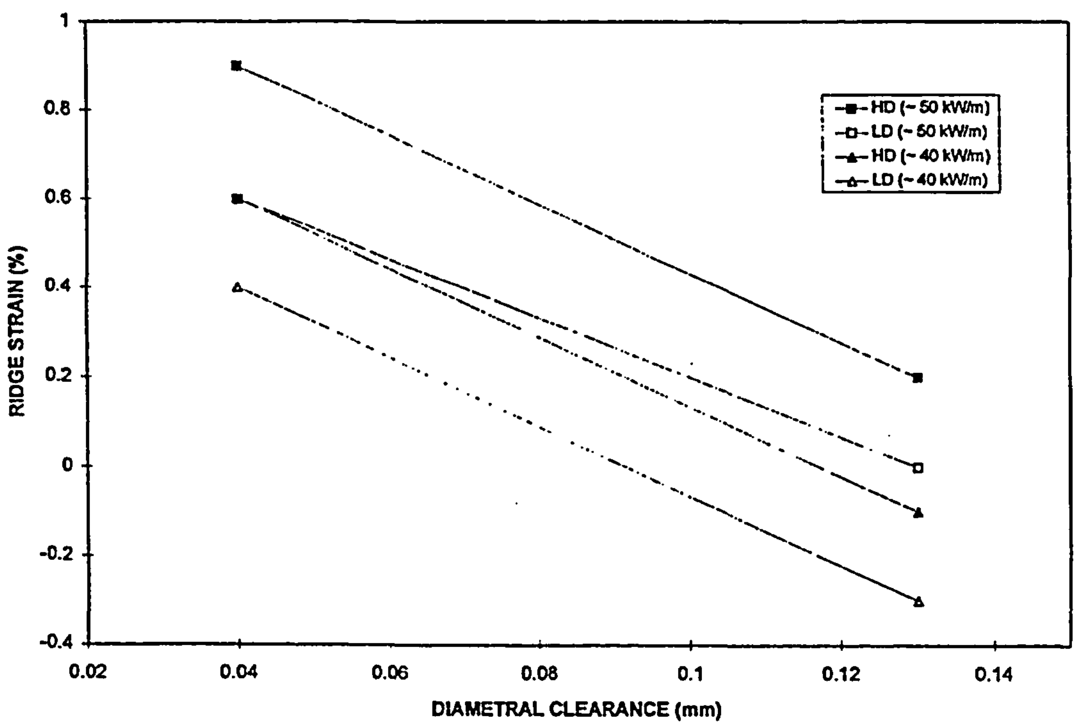

FIGURE 5. RIDGE STRAIN VS. DIAMETRAL CLEARANCE

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