ELEMENT BOW PROFILES FROM NEW AND IRRADIATED CANDU FUEL BUNDLES[1]

by

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ABSTRACT

Improved methods of measuring element profiles on new CANDU® fuel bundles were developed at the Sheridan Park Engineering Laboratory, and have now been applied in the hot cells at Whiteshell Laboratories. For the first time, the outer element profiles have been compared between new, out-reactor tested, and irradiated fuel elements. The comparison shows that irradiated element deformation is similar to that observed on elements in out-reactor tested bundles. In addition to the restraints applied to the element via appendages, the element profile appears to be strongly influenced by gravity and the end loads applied by local deformation of the endplate. Irradiation creep in the direction of gravity also tends to be a dominant factor.

1 INTRODUCTION

Fuel element profiles from CANDU bundles can deviate by up to 1 mm from a straight line. Although this may appear only a small deviation over the 50 cm length of the element, the difference can reduce clearances between neighbouring elements and may affect local thermalhydraulic conditions. The bow profile may also reduce the clearance between the midplane bearing pads and the pressure tube, thereby allowing contact and possible wear of both components. It is difficult to measure small amounts of bow on flexible CANDU elements, leading to large uncertainties in predicting the true profiles when inside the pressure tube. This task is even more difficult for irradiated bundles using profilometry equipment normally available in hot cells.

During normal operation, several factors influence the element profiles, such as hydraulic drag, gravity, neutron flux, and asymmetrical thermal gradients. Additionally, the profiles of outer elements can be affected by the

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restraint of interelement spacers on neighbouring elements, the endplates and the bearing pads that support the bundle in the pressure tube.

In spite of the difficulties in measuring element bow, computer codes like BOW(1) are available to predict in-reactor element profiles. This code was developed to predict in-reactor element profiles by calculating element response to asymmetrical thermal and flux gradients, and in-service loads such as hydraulic drag, using classical beam theory. Although the code was validated against some measurements, several shortcomings contribute to experimental uncertainty, including:

1) The vertically oriented fuel elements in experimental irradiations at Chalk River were not influenced by irradiation creep under gravity, which acts at right angles to horizontally oriented power-reactor fuel elements. This effect is not incorporated into the BOW code.

2) Most element profiles measured in the hot cells were done after the bundles were dismantled. The dismantling process tends to introduce some degree of permanent deformation on the elements.

As part of the investigation into the underlying mechanisms responsible for endplate cracking and pressure tube fretting, observed at Darlington and Bruce Nuclear Generating Stations (NGS)(2), a significant amount of work has been done to measure element profiles. In support of this work, procedures were developed to measure new and out-reactor tested bundle geometries using the Coordinate Measuring Machine (CMM) at the Sheridan Park Engineering Laboratory (SPEL). Past measurements on these bundles have established the as-fabricated geometry of the bundle, and revealed the deformation of the bundle that occurs during out-reactor testing(3,4). Profilometry measurements on irradiated bundles have been performed in the hot cells at Chalk River Laboratories (CRL) and Whiteshell Laboratories (WL) since the 1960s. The profilometry rig at WL was recently modified to allow measurements of element bow in a horizontal plane, as this approach has been shown to be effective in eliminating gravity from distorting the profiles of non-irradiated elements(3). Several irradiated element profile measurements have been recently performed using this technique.

The intent of this paper is to summarize some of the techniques available for measuring element bow from irradiated and non-irradiated bundles, present the results of these most recent bow measurements, and provide an explanation for the observed differences between element bow profiles.

2 MEASUREMENT TECHNIQUE

Darlington and Bruce NGS fuel bundles are comprised of 37 fuel elements that are assembled into bundles by welding each end to a thin endplate. The endplates consist of three concentric rings joined together by several radial webs. Spacing between neighbouring elements is maintained by interelement spacers at the bundle midplane, while bearing pads are used to provide adequate clearance between the elements and the pressure tube. Each outer element fuel bundle has three bearing pads: one at the midplane and one at each end. The end bearing pads are staggered on alternate elements, with the 'outboard' pads closest to the endplates and 'inboard' pads further away.

The bundle configuration permits profilometry in the radial direction for the outer elements only because internal elements are not accessible with external probes. The techniques described below were developed to measure profiles that are representative of test and in-reactor conditions.

2.1 SPEL Measurement Technique

A technique was developed in the SPEL Metrology Laboratory to measure the dimensions of selected bundle components. The measurements are performed using a Coordinate Measuring Machine (CMM) which features a remote controlled probe linked to a computer. When the probe contacts a point on the bundle surface, it

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The profiles of each of the outer elements are measured with the bundle placed horizontally in a cradle made from a section of a pressure tube. The CMM defines a reference straight line on the element located at the 3 o'clock position on the bundle by measuring the location of each end of the element in space. The CMM then measures the location of the sheath surface in the 3 o'clock plane at several other equidistant points along the length of the element. The deviation of these measurements from the reference line represents the radial element bow profile. This technique is applied to each outer element after incrementally indexing the orientation of the bundle by 20 degrees so that the next element is located at the 3 o'clock position. Tests have shown that measurements in the 3 o'clock position eliminate the effect of gravity on element profile(4).

2.2 Whiteshell Measurement Technique

Measurements at WL were typically performed by tracing a linear variable displacement transducer (LVDT) along the top length of the sheath surface. In many cases, elements were cut from bundles prior to performing profilometry measurements. The shape of the element profile and the bearing pads are measured with the LVDT at the 12 o'clock position relative to the element. Individual irradiated elements measured in this way have routinely shown significant element bow in the direction of gravity.

Assessments of many elements having worn surfaces on all three bearing pads indicate that their worn surfaces do not conform to a single plane, as would be expected if supported by the pressure tube, but are all at different angles (see Figure 1). This suggests that the measured bow profile is not representative of the element shape when in-reactor. It appears that dismantling the bundles removes some restrictions against element bow that are inherent within the design. For example, the endplate rigidity is no longer present to resist bending of the element, and the interelement spacers from neighbouring elements no longer interfere with large element bows as they would if the bundle was intact. Additionally, the profile measurement is further skewed by taking the profile in the vertical plane, which includes the influence of gravity on the profile measurements. The combination of these factors results in a profile that is not representative of in-core conditions.

Post Irradiation Examination (PIE) measurements were performed on several irradiated bundles to investigate the underlying mechanisms behind endplate cracking and pressure tube fretting. One of the objectives of the investigation was to link the bundle geometry to fret marks measured within the channel of residence. Thus, measurements from these bundles needed to be representative of fuel while in-reactor. This imposed the requirement that the element profiles be measured while the bundles were intact. Consequently, the hot-cell profilometer set-up at Whiteshell Laboratories was modified to permit measurements of the bow of outer elements in both the horizontal (3 o'clock and 9 o'clock) and vertical (12 o'clock) planes, while the bundle was intact. The bundle was supported horizontally by clamps around the diameter of the endplate allowing access to all outer elements by the LVDT. The bundle orientation could be incremented so that any outer element could be measured at the selected orientation. The profilometry measurements are all performed with the bundles in a hot cell at ambient room temperature and pressure.

3 ELEMENT BOW MEASUREMENTS

3.1 New Bundles

The availability of quick and accurate bundle mensuration using the CMM has made bundle characterization an important tool in quantifying the geometric response of bundles to test conditions. Detailed measurements from new bundles indicate the difference in geometry between bundles from two manufacturers, and also serves as a basis for future comparison with post-test measurements. These measurements have served as a comparative basis for several projects, including endplate cracking, pressure tube fretting, and qualification of both the long bundle and advanced carrier fuel bundle designs(5,6).

The bow profiles of outer elements have been measured from new bundles produced by both Canadian fuel manufacturers. Figure 2 illustrates the profiles of the odd-numbered and even-numbered elements from manufacturer A. Both groups of elements display a prominent S-shaped profile, which is inwardly bowed at the end with the inboard bearing pad, and outwardly bowed at the end with outboard bearing pad. The elements are outwardly bowed by less than about 200 μm and are inwardly bowed by up to 300 μm. The bow profiles of new elements show that the maximum bow (either inwards or outwards) does not necessarily occur at the midplane of these bundles.

Figure 3 shows a similar breakdown for the profile of new elements from bundles produced by manufacturer B. Elements from this manufacturer show no clear common profile, except that they are generally symmetrically outwardly bowed. The maximum outward bow from the symmetric profiles of the outer elements from manufacturer B generally occurs at the midplane, and is greater than that found on bundles produced by the other manufacturer. The bow of outer elements from manufacturer B ranges from between 600 μm (outward) and 200 μm (inward). The magnitude of bow from these elements also appears to be dependent on the proximity of the elements to the radial endplate webs, with elements attached next to the radial endplate webs (elements 3, 6, 9, 12, 15, and 18) generally showing the greatest outward bow. This observation is consistent with measurements from many new bundles, although other elements may occasionally have greater outward bows. The differences between the profiles from each manufacturer can most likely be attributed to slight differences in manufacturing processes and details of the designs.

3.2 Out-Reactor Tested Bundles

Measuring the geometrical changes that occur on a bundle because of testing is extremely useful for qualifying new fuel designs, and also for identifying the response of the bundle to driving forces acting on the fuel during testing (i.e, operating temperature, pressure, coolant flow, etc). Evaluation of these changes has shown that the post-test element profile is strongly influenced by gravity, with top elements between the 8 o'clock and 4 o'clock position sagging downwards under their own weight, and bottom elements bending upwards at the midplane because of bundle droop(4). Post-test analysis has shown that the proximity of the elements to radial endplate webs also influences the element profile, with elements closest to the radial webs generally exhibiting the greatest outward bow(4).

In 1992 sixteen bundles from manufacturer A were shipped to SPEL for geometrical characterization following a 40-day zero-power endurance test in Darlington NGS-3. These bundles were characterized by the CMM using the same technique that was applied to new fuel. Figure 4 shows an example of the bow profiles from one of the bundles that was tested in the inlet position of channel O17. Most elements continue to show the characteristic S-shaped profile associated with new bundles from this manufacturer, even after testing. Additionally, elements that are closest to the radial endplate webs (elements 1, 4, 7, 10, 13, and 16 for manufacturer A) are more outwardly bowed than neighbouring elements. These observations were consistent for the majority of the bundles.

The qualification program for long fuel bundles(5) featured extensive use of the CMM to evaluate the response of long and standard bundles to rig test conditions. For the first time, bundles were characterized before and after endurance testing, providing quantification of bundle deformation. Figure 5 shows the difference between post-test and pre-test bow profiles of all the outer elements from a bundle produced by manufacturer B. Generally, the bow profiles of the elements changed in both the inwards and outwards direction in a symmetric fashion, with the peak difference near the element midplane. The trend for elements attached nearest the radial endplate webs to bow outwards during testing more than neighbouring elements, is also apparent on this bundle. This additional outward bow of elements near the radial spokes was attributed to endplate dishing due to the hydraulic drag applied by the coolant(4).

3.3 Irradiated Bundles

As part of the investigation into the cause of endplate cracking and pressure tube fretting, three irradiated bundles were shipped to the Whiteshell Laboratories for Post Irradiation Examination (PIE). These bundles were shifted from the outlet position of channel S22 of Bruce NGS-8 to the inlet position using a combination of 4-bundle and 8-bundle refuelling shifts. Channel S22 was identified as an acoustically active channel. The bundles had endplate cracks, heavy bearing pad wear, and were believed responsible for fret marks on the pressure tube.

The profiles were measured from selected elements from the outer ring of each of the bundles. One bundle was dismantled prior to these measurements so the profiles were measured with the LVDT in the vertical position, whereas profiles from the two intact bundles were measured using the latest procedure.

Figure 6 shows typical examples of element profiles from the bundle produced by manufacturer B, after it was dismantled. These profiles show that the elements are occasionally inwardly bowed in excess of 1 mm. The worn surfaces of the bearing pads were found to be parallel to the sheath, rather than to each other (as illustrated in Figure 1). This confirms that the element profile is not representative of in-core conditions, as the wear would have occurred on the single plane of the pressure tube surface.

Figure 7 illustrates the bow measurements from an intact irradiated bundle produced by manufacturer A. Each profile was taken while the element was in the 3 o'clock position. Some of the profiles were derived from bundle diameter measurements that were obtained by simultaneously taking profiles of the two outer elements at the 3 o'clock and 9 o'clock positions. These measurements showed that the wear patterns on each of the bearing pad surfaces lined up with one another on all bottom elements that had worn surfaces on all three bearing pads (see Figure 8 for an example). Note that the outboard bearing pad in this figure was loaded and deflected the element inwards, resulting in preferential wear on the end nearest the endplate. Alignment of worn surfaces on all three bearing pads has also been observed on other bottom elements that were measured using this technique. These findings suggest that the profiles measured in the 3 and 9 o'clock positions are representative of profiles in-reactor and that there was little, if any, elastic deformation while in the fuel channel.

The orientation of the irradiated bundles was estimated from the extensive fretting wear on the bearing pads. Figure 9 illustrates the midplane bow of the irradiated elements according to bundle orientation. The profiles of the elements near the 12 o'clock position (elements 18, 1, and 2) were inwardly bowed at the midplane, as were elements near the 6 o'clock position (elements 9, 10, and 11). Elements near the 4 o'clock and 8 o'clock positions (elements 7, 8, 13, and 14) were found to have outward bow at their midplane. These observations were consistent with the sag and droop responses of the elements to gravity that were observed on bundles tested in Darlington NGS-3 prior to criticality(4).

Selected elements from intact irradiated bundles had some profile measurements performed in both the 9 and 12 o'clock positions to determine the effect of gravity. Figure 10 illustrates the profiles from both sets of measurements. Figure 11 shows that irradiated elements from intact bundles sag at the midplane in the direction of gravity by about 175 to 275 μm, which is similar to that observed in out-reactor tested bundles.

4 OBSERVATIONS FROM IRRADIATED ELEMENT BOW PROFILES

The new approach to measuring irradiated element bow profiles and the confirmation of its validity allowed the first direct comparison of element bow profiles between new, out-reactor tested, and irradiated bundles. The comparison showed many similarities between the latter two types of bundles, and also showed how irradiation creep can affect the element profiles.

The degree of element constraint has a significant effect on measured element profile. The irradiated elements from an intact bundle measured at the 3 and 9 o'clock position had inward bows no greater than 500 μm, compared with up to 1000 μm of inward bow measured on separated elements (see Figures 6 and 7). Additionally, irradiated elements from intact bundles profiled at the 12 o'clock position also had much less inward bow than similar measurements from disassembled bundles (see Figure 10). The differences between the element bow profiles from intact bundles measured at both the 12 o'clock and 3 o'clock positions were similar between irradiated and out-reactor tested bundles.

Some irradiated elements that were at the 12 o'clock position while in-reactor appeared to sag more than out-reactor tested bundles. The sag of these elements was sufficient to cause a permanent "W"-shaped profile to the element, where the interelement spacer had locally restricted the magnitude of inward element bow (see element 2 on Figure 7). Generally, irradiated elements at the top of the bundle were more inwardly bowed than elements from out-reactor tested bundles. The magnitude of outward bow was found to be similar between irradiated and out-reactor tested bundles.

Out-reactor tests have shown that, regardless of the bundle manufacturer, the elements closest to the radial endplate webs tend to bow out more than neighbouring elements that are away from endplate webs. This is believed to be related to permanent dishing of the endplate by coolant hydraulic forces(3). Out-reactor testing does not appear to completely remove the S-shaped profiles evident on elements from bundles made by manufacturer A, even if the elements were next to the radial endplate webs. However, irradiated elements from this manufacturer did not show any residual evidence of the characteristic S-shaped profile. Some elements from the irradiated bundles were found to have their S-shaped profiles reversed (see elements 5 and 13 from Figure 7). This may be attributed to irradiation creep response of the element to endplate dishing, which can generate a bending moment on each end of the elements.

The element profile measurements from the intact irradiated bundles appeared to show that the bottom elements crept outwards until all the centre bearing pads were in contact with the pressure tube (see Figure 9). Based on this observation, the pressure tube radius at the bundle midplane was estimated using the element profiles and endplate design dimensions. The calculations showed a pressure tube radius of 51.71 ± 0.11 mm under normal operating (hot) conditions. This prediction is close to the 51.98 ± 0.1 mm value calculated using a CIGAR (Channel Inspection and Gauging Apparatus for Reactors) measurement from a similar channel. The difference between the two measurements may be due to uncertainties in bearing pad location arising from pressure tube fretting wear or sliding wear. The calculations also showed that the in-reactor bundle orientation could be accurately determined by choosing the orientation that produced the minimum clearance between the midplane bearing pads of all bottom elements.

These observations are based on profilometry measurements from two irradiated bundles. Future measurements may provide more detailed information to support these findings.

5 CONCLUSIONS

5.1 The latest technique for measuring the bow profiles of irradiated elements in intact bundles appears to give results that are representative of in-reactor conditions. The worn surfaces of the bearing pads from bottom elements tend to line up, as if they were still in contact with the pressure tube surface in-reactor. This suggests that the elements retain their in-reactor profiles after discharge.

5.2 Irradiated elements respond to driving forces in the same way as out-reactor tested fuel. Irradiated elements show evidence of the element sag and bundle droop caused by gravity that has been previously observed on out-reactor tested bundles, suggesting that bundle and element orientations play a significant role in the change in element bow profile. Additionally, endplate dishing caused by hydraulic drag on inner elements can affect the bow profiles of outer elements attached near endplate radial webs. The endplate design plays a major role in altering the bow profiles in-reactor. This interaction should be included in any codes designed to model element profiles.

5.3 Irradiation creep can override the internal stresses in the element that are due to manufacturing and can lead to reversal of the S-shaped element profiles observed on new bundles. The W-shaped elements near the top of the bundles indicate that interelement spacers restrict the creep of element bow at the midplane.

5.4 The sag of irradiated elements at zero power is similar to non-irradiated elements, about 175 to 275 µm.

5.5 Gravity causes the profiles of the bottom elements to creep downward until their midplane bearing pads conform to the shape of the pressure tube. The locii of points representing the worn surfaces of bottom midplane bearing pads from an intact irradiated bundle has a radius of curvature that is very close to the pressure tube radius. With further development, it may be possible to estimate radial creep of the pressure tube from the PIE of bundles.

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7 REFERENCES

(1) YU, S-D., TAYAL, M., SINGH, P.N., "Improvements, Verifications and Validations of the BOW Code", 4th International Conference on CANDU Fuel, Pembroke, Canada, 1995 October 1-4.

(2) FIELD, G.J., "The Experimental Program", 13th Annual CNS Conference, Saint John, New Brunswick, 1992 June 7-10.

(3) DENNIER, D., MANZER, A.M., OLDAKER, I.E., KØHN, E., "Deformation and Fretting Wear of CANDU Bundles From DNGS-3 Vibration Tests", 15th Annual CNS Conference, Montreal, Quebec, 1994 June 5-8.

(4) DENNIER, D., MANZER, A.M., KØHN, E., "Characteristics of CANDU Fuel Bundles That Caused Pressure Tube Fretting at the Bundle Midplane", 16th Annual CNS Conference, Saskatoon, Saskatchewan, 1995 June 4-7.

(5) FIELD, G.J., "Bruce and Darlington Power Pulse and Pressure Tube Integrity Program", 15th Annual CNS Conference, Montreal, Quebec, 1994 June 5-8.

(6) ALAVI, P., OLDAKER, I.E., "The Advanced Carrier Bundle to Irradiate Material Samples in CANDU Power Reactors", 17th Annual CNS Conference, Fredericton, New Brunswick, 1996 June 9-12.

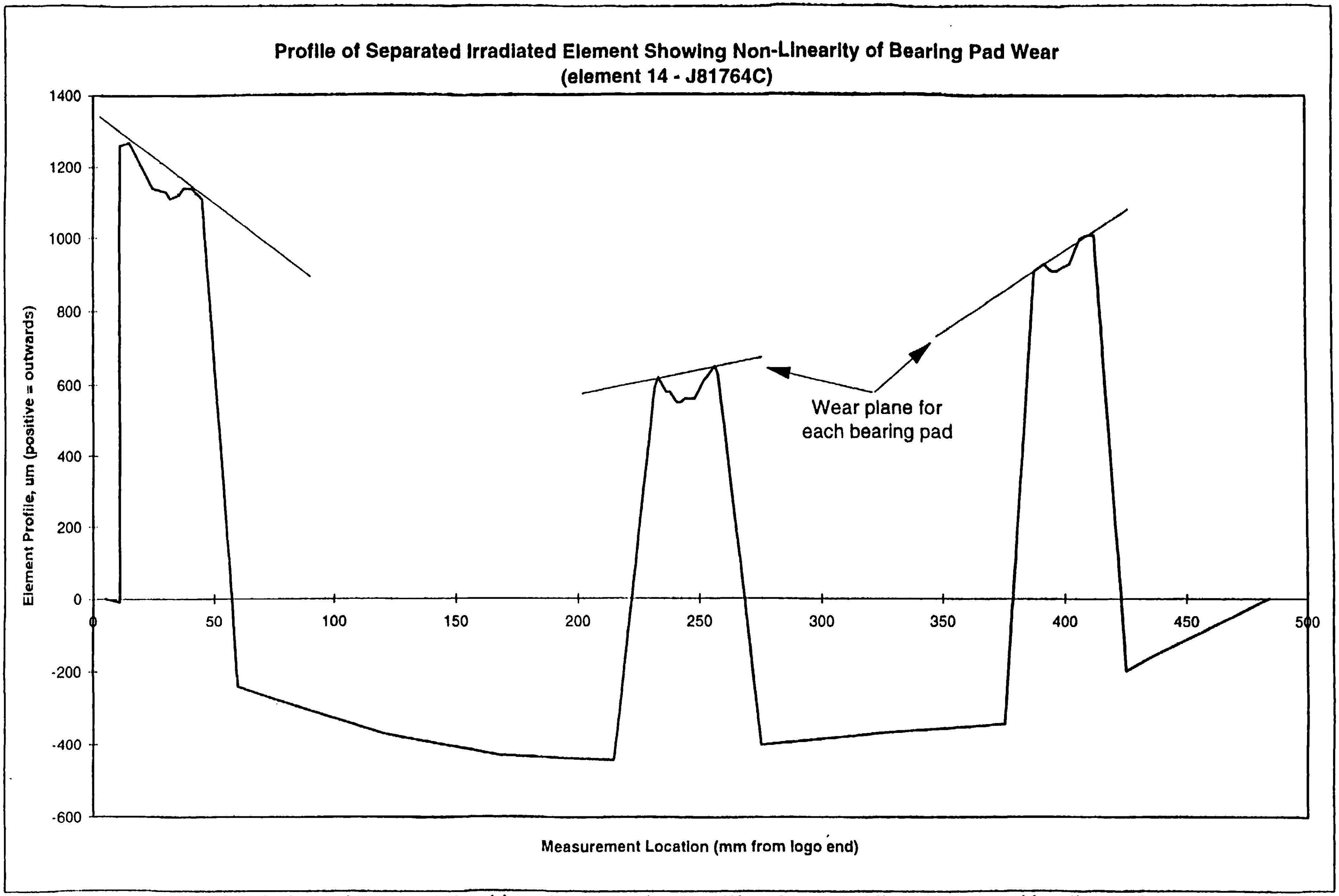
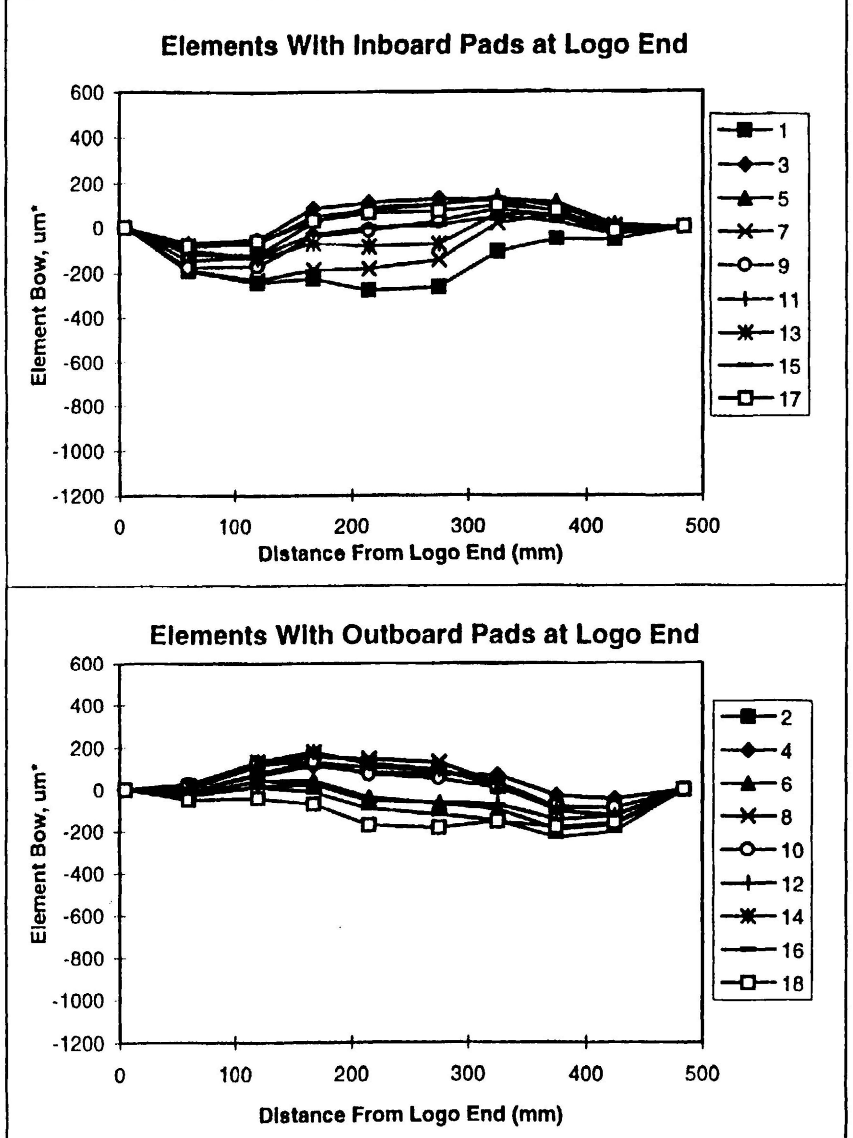
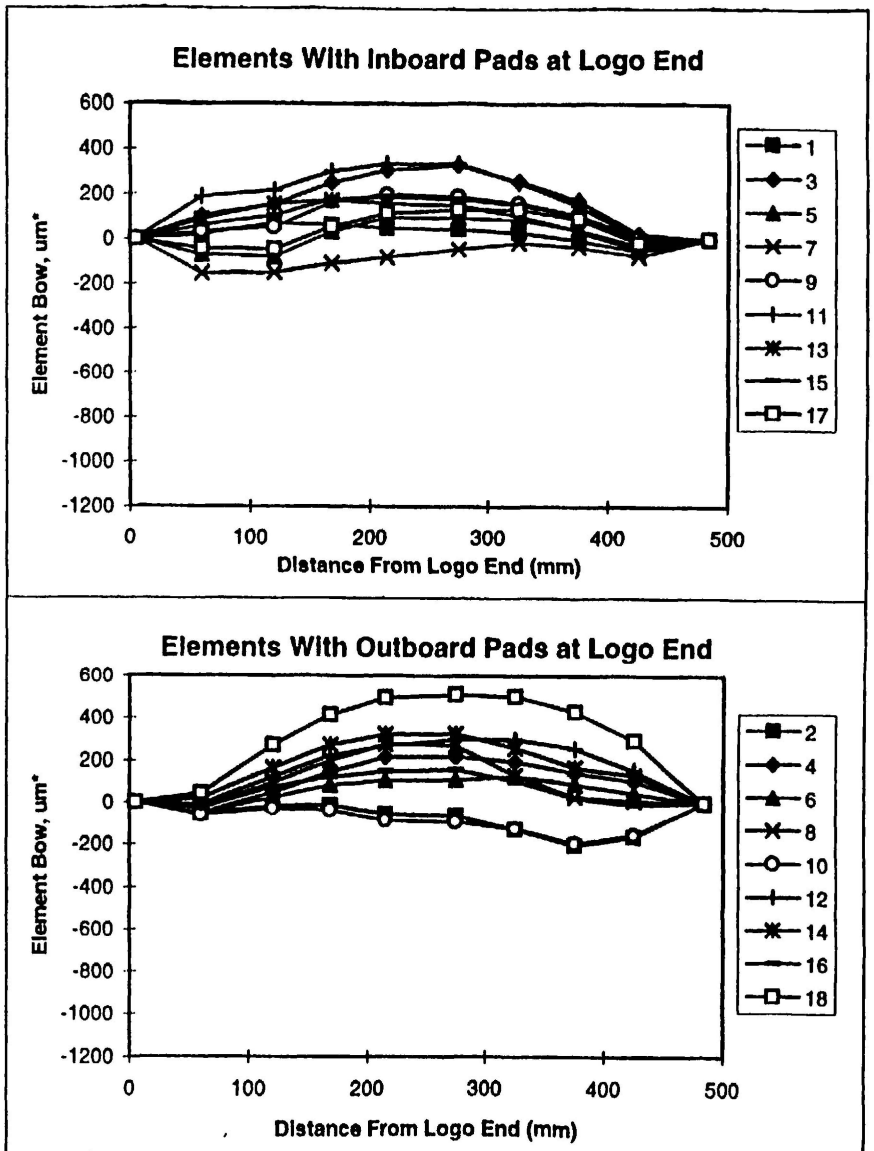


FIGURE 1: Inward Bow and Non-Linearity of Bearing Pad Wear Measured From Separated Irradiated Element



* positive bow is in outwards direction

FIGURE 2: Outer Element Profiles From NEW INTACT Bundles from Manufacturer A (K03042Z)



* positive bow is in outwards direction

FIGURE 3: Outer Element Profiles From NEW INTACT Bundles from Manufacturer B (9699C)

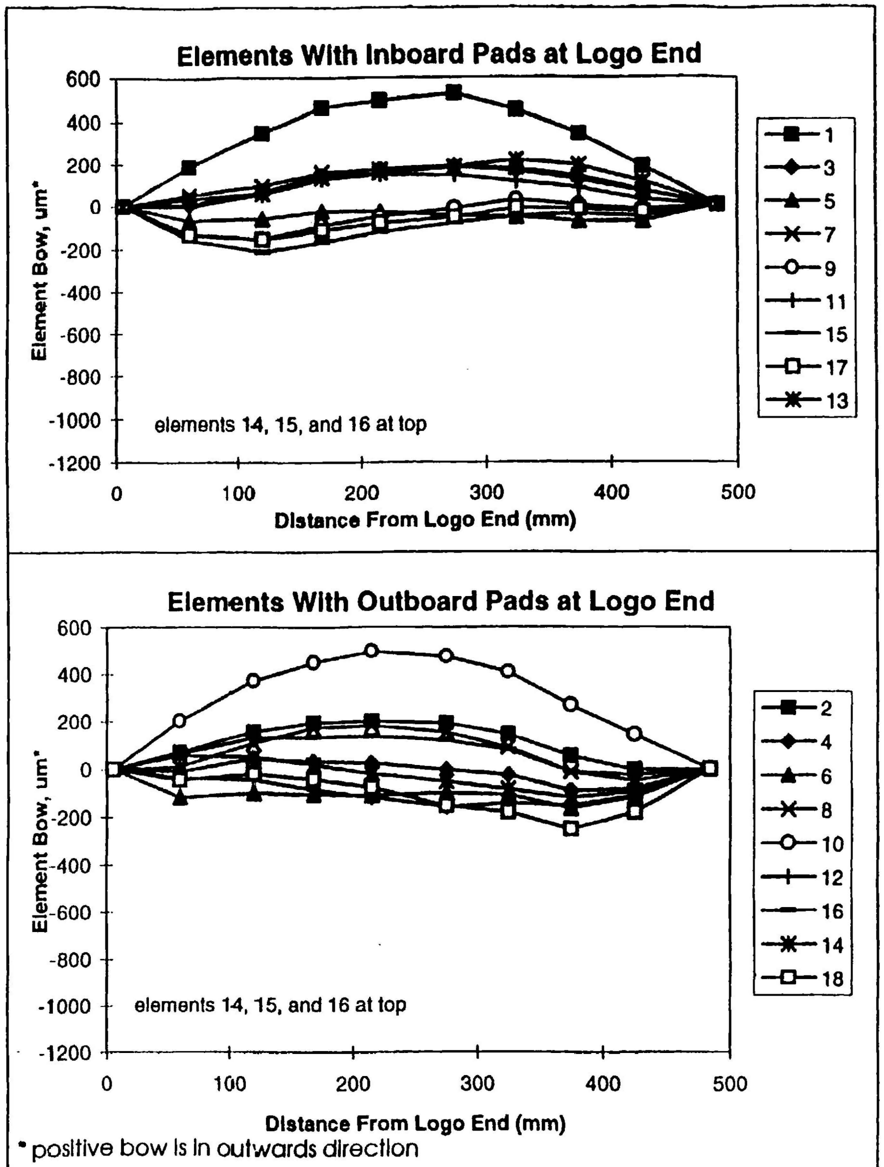


FIGURE 4: Outer Element Profiles From Manufacturer A Bundle After DNGS-3 ZPH test(3) (K42148Z)

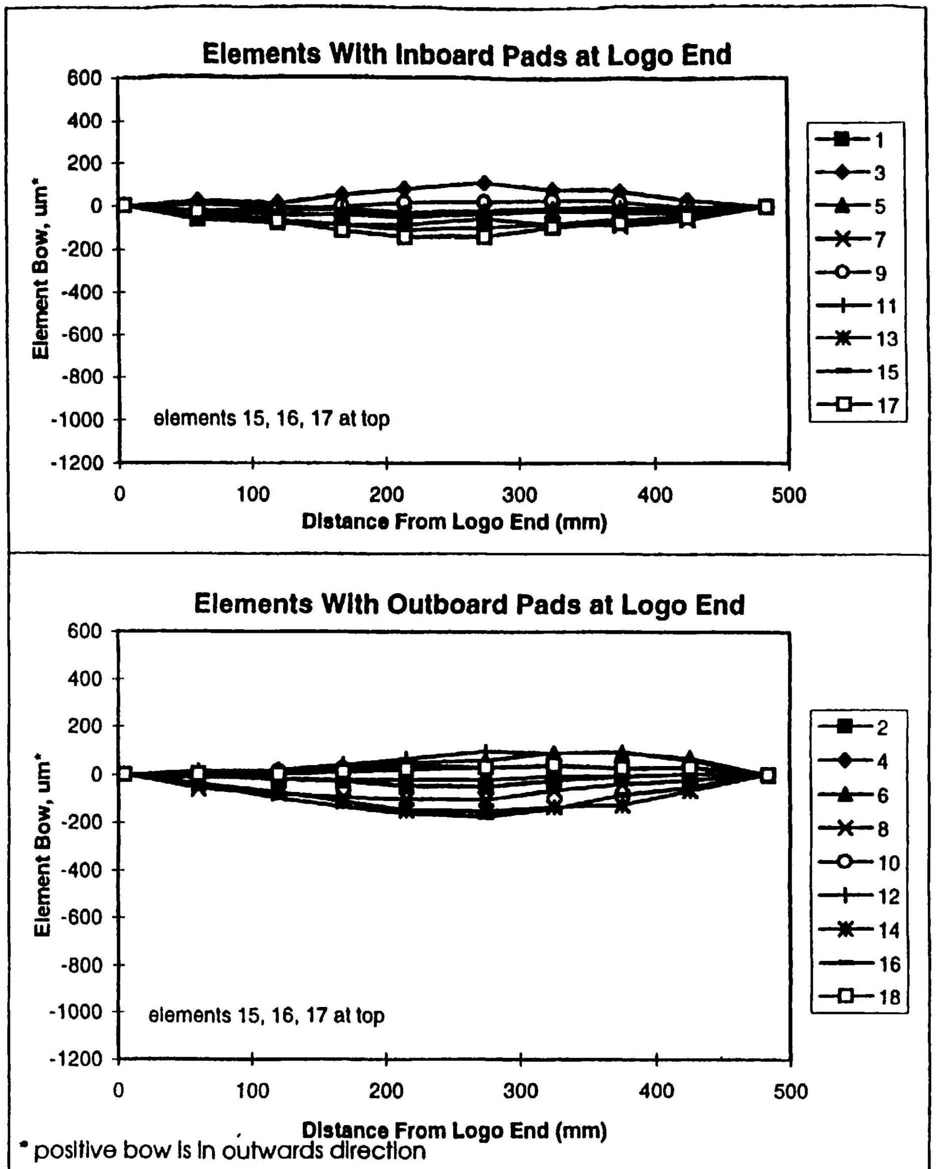
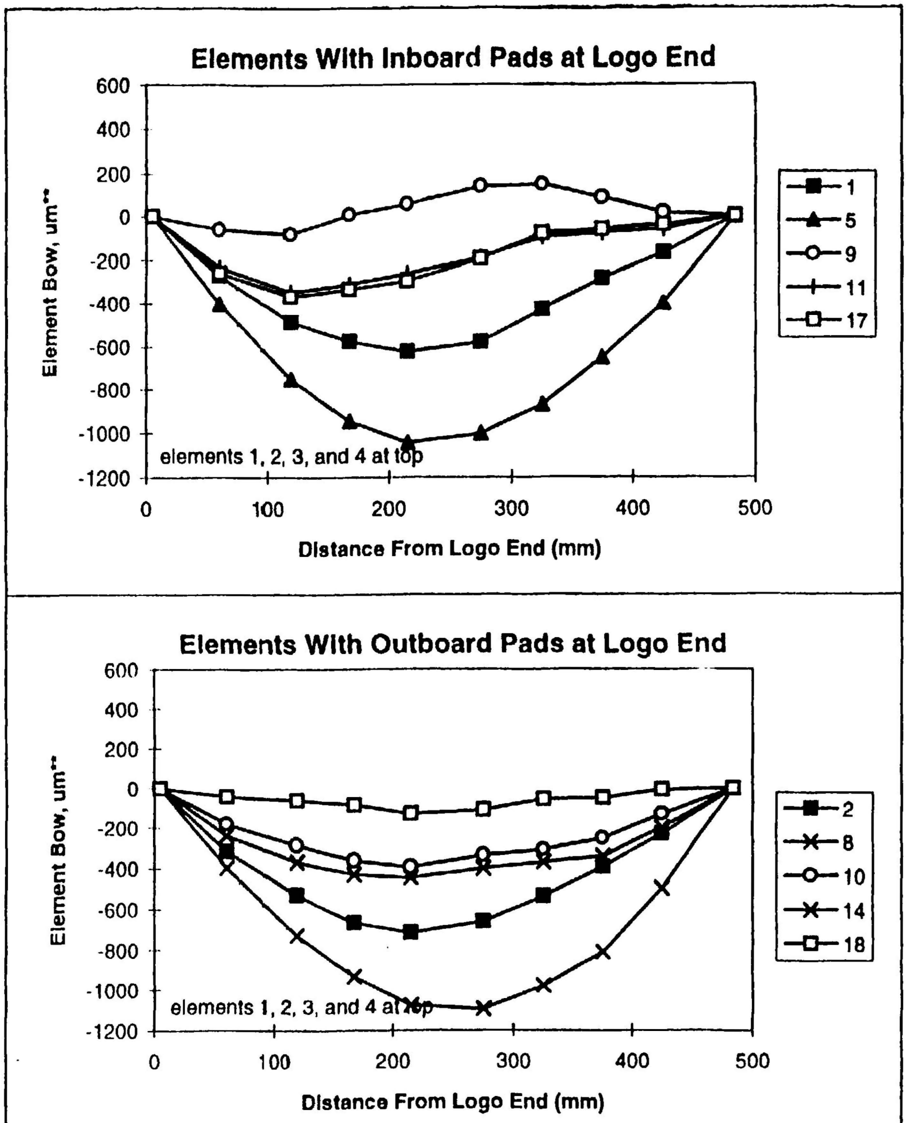
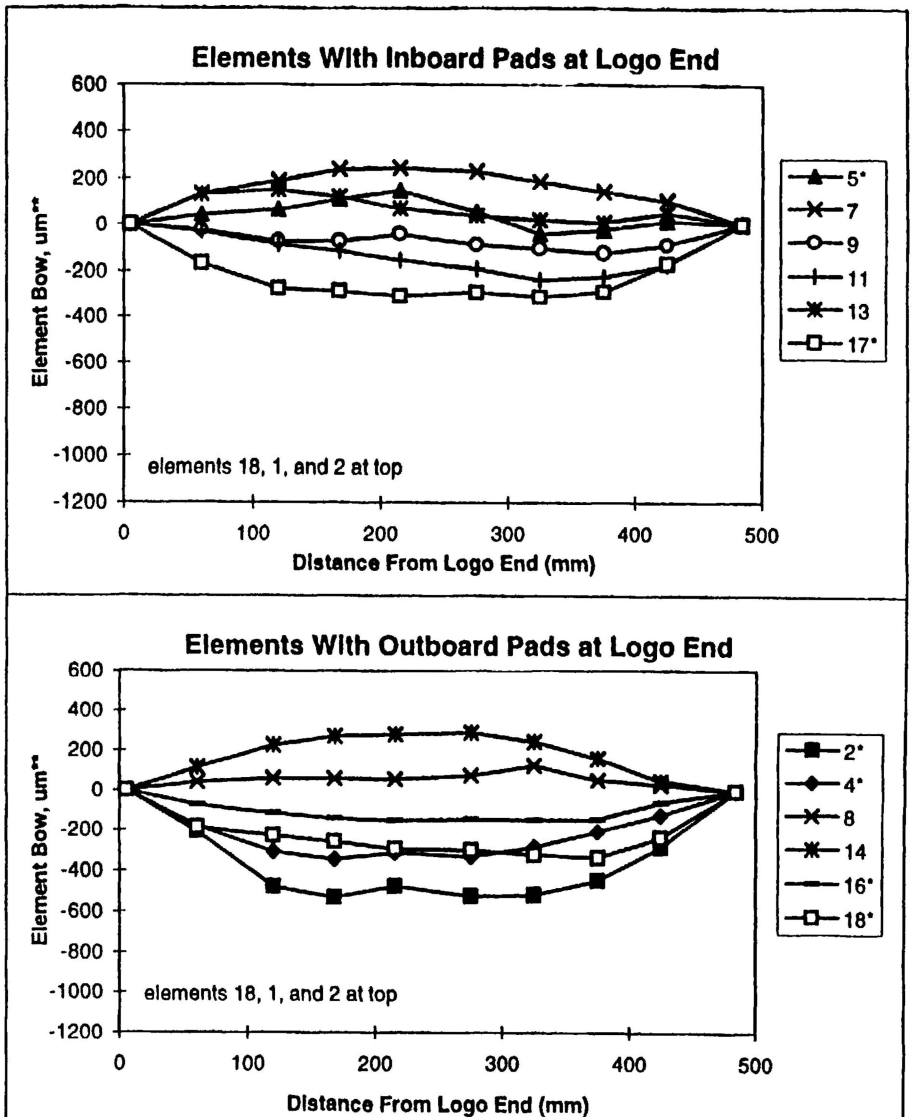


FIGURE 5: Change in Outer Element Profiles From Manufacturer B Bundle After SPEL Endurance Test (9699C)



** positive bow is in outwards direction

FIGURE 6: Element Bow of SECTIONED IRRADIATED Bundle From BNGS-8 S22 (Manufacturer B - J81764C)



* profile derived from diameter measurement

** positive bow is in outwards direction

FIGURE 7: Element Bow of INTACT IRRADIATED Bundle From BNGS-8 S22 (Manufacturer A - J77739Z)

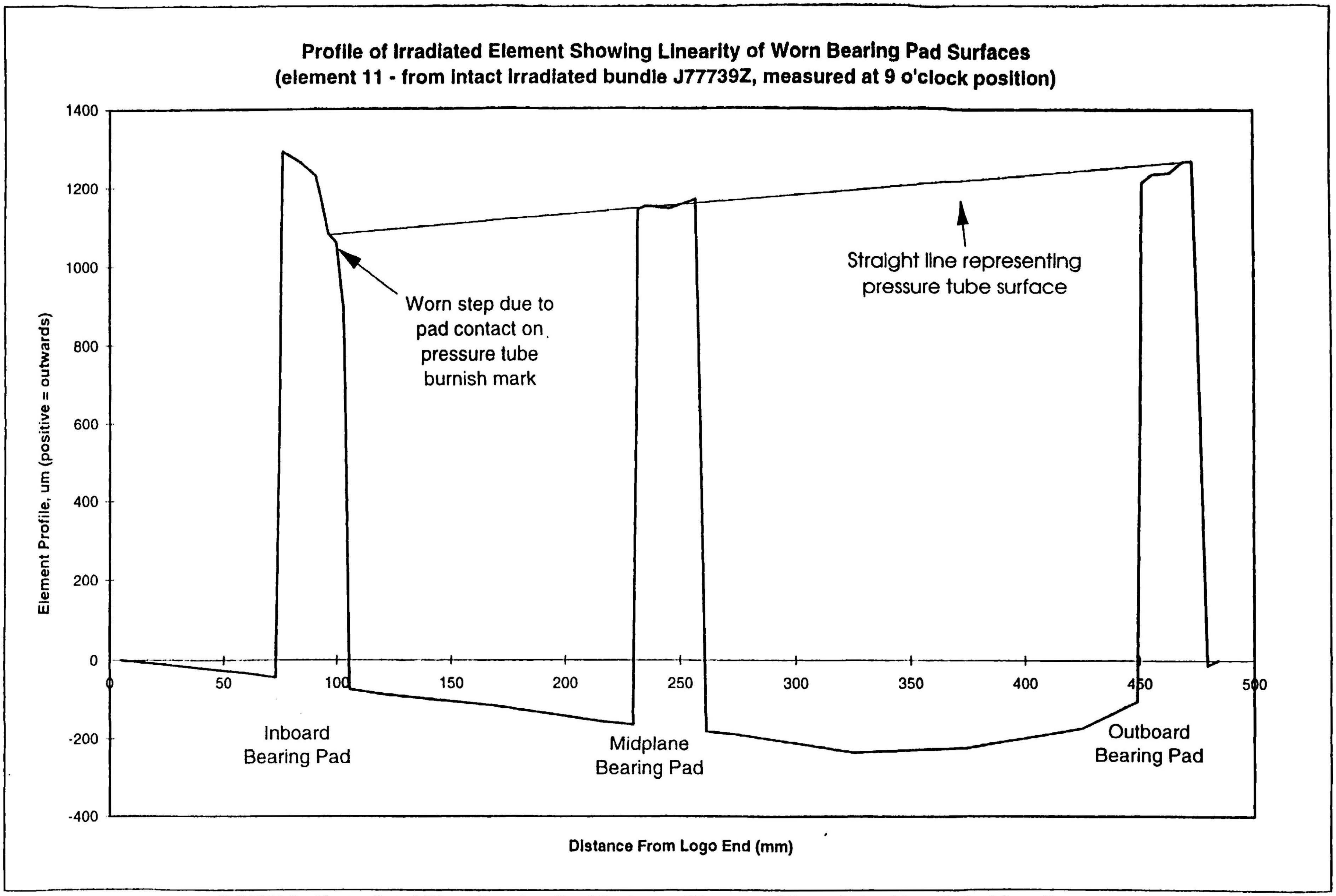


FIGURE 8: Linearity of Worn Bearing Pad Surfaces Measured From Intact Irradiated Bundle

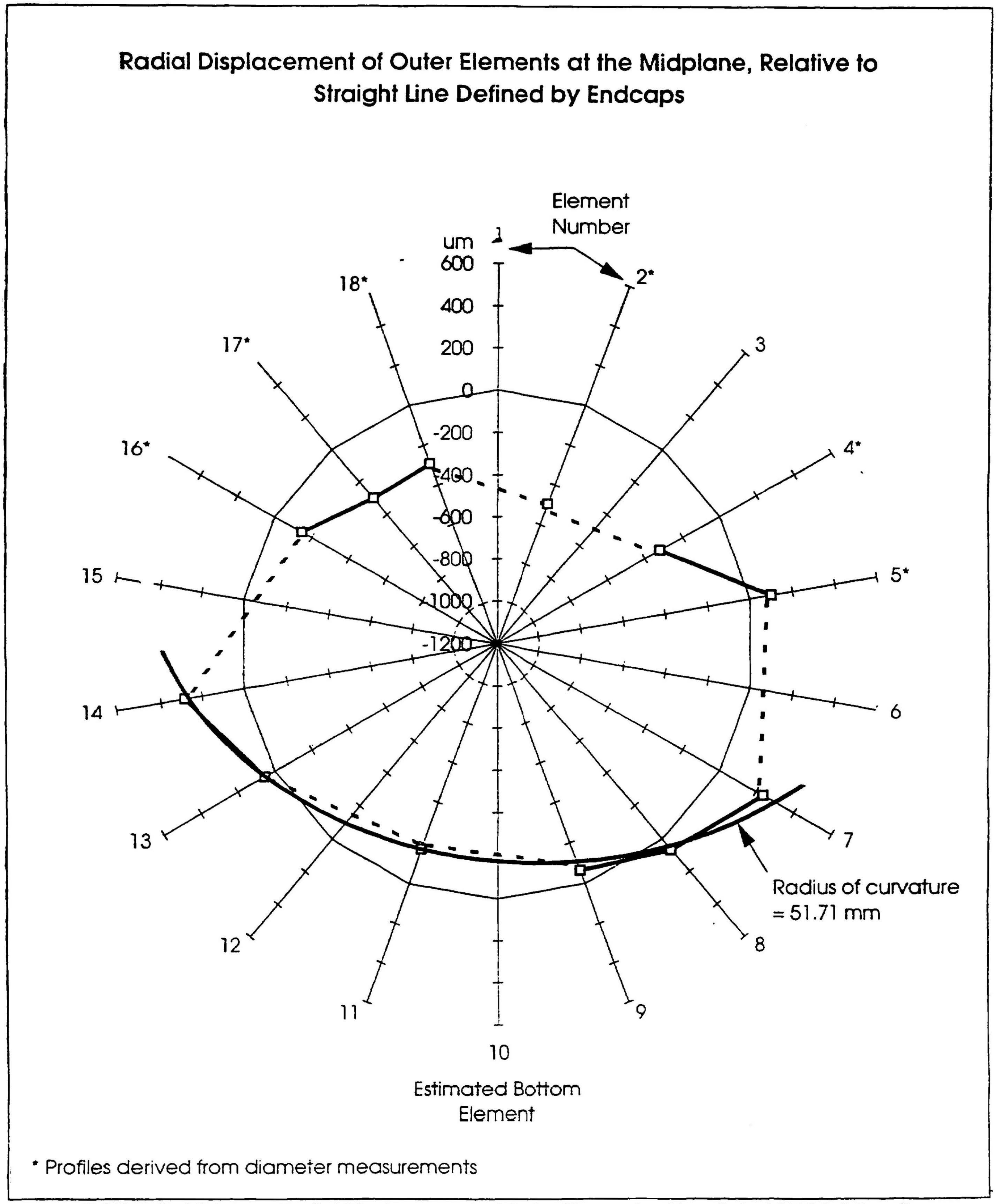


FIGURE 9: Midplane Radial Displacement of Outer Elements of Irradiated BNGS-8 Bundle Measured at 9 O'clock Position (Manufacturer A - J77739Z)

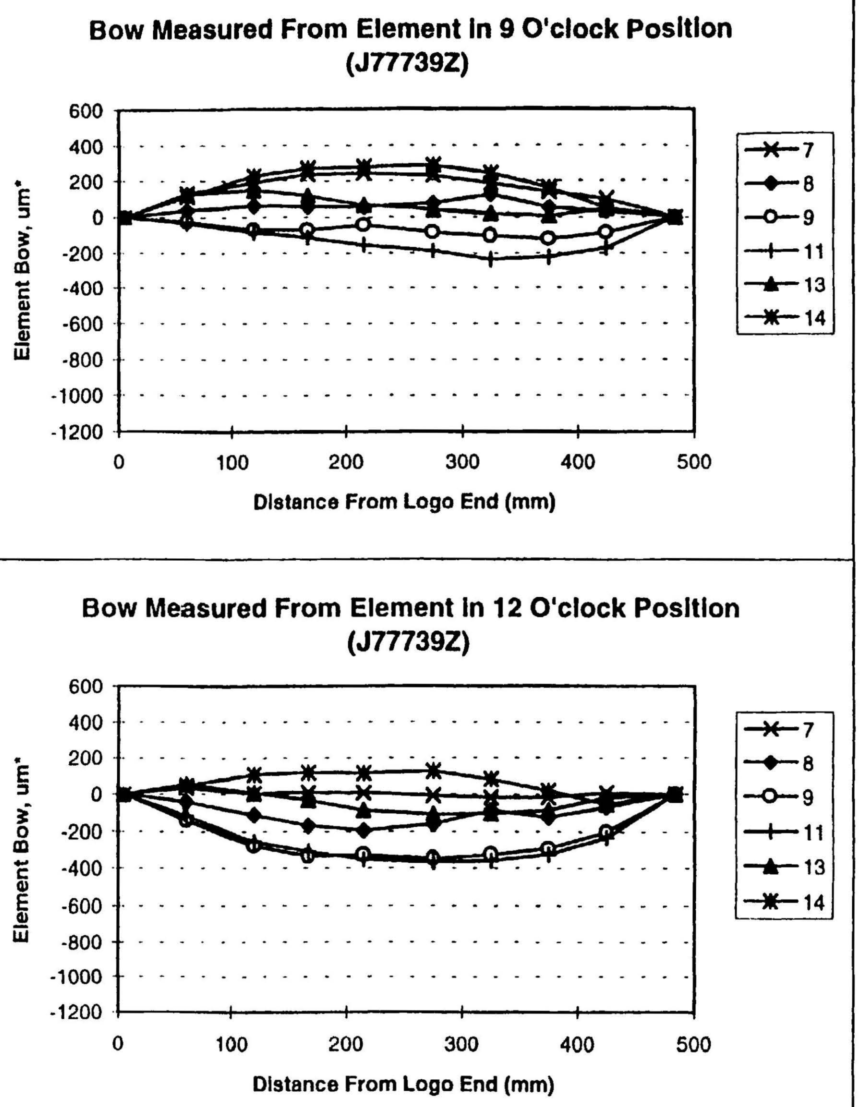


FIGURE 10: Effect of Sag Caused By Gravity on Element Profiles From Intact Irradiated Bundle

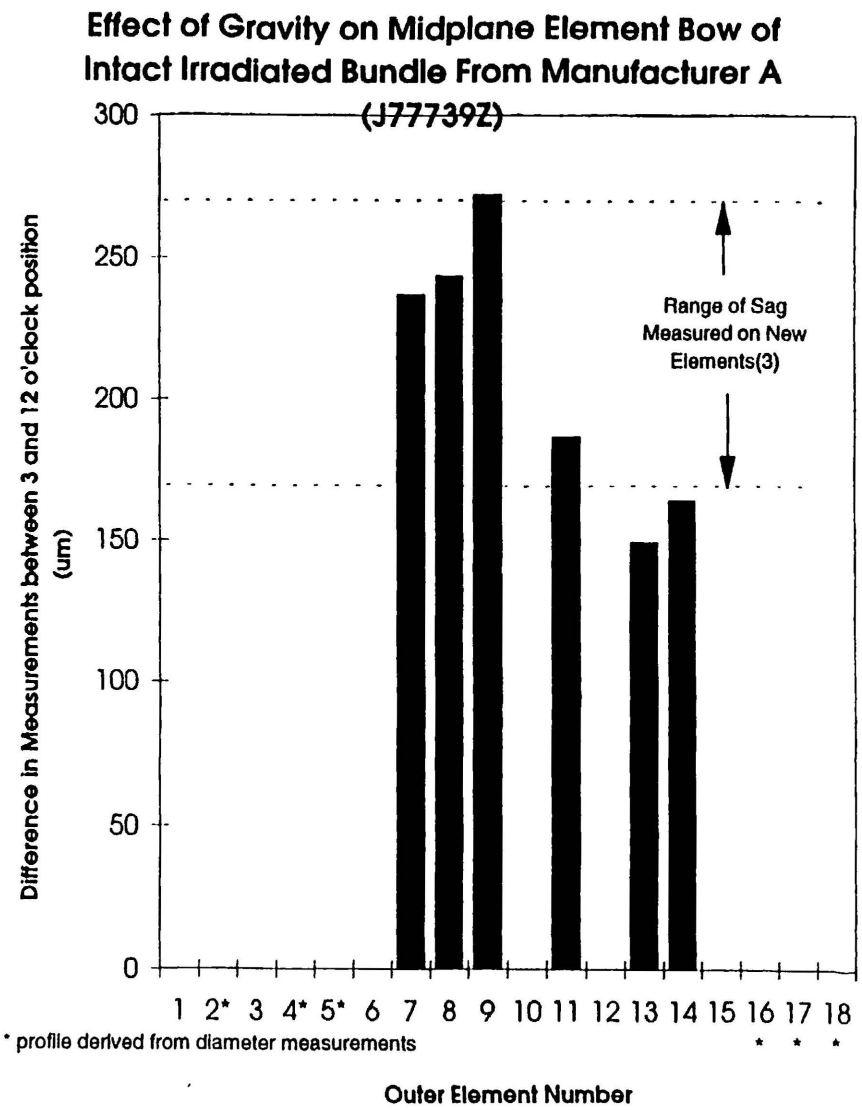


FIGURE 11: Effect of Gravity on Element Sag