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MOX Fuel Pin Measuring Apparatus

R.N. Morris
C.A. Baldwin

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Fissile Materials Disposition Program

Notice

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OAK RIDGE NATIONAL LABORATORY
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FOR THE U.S. DEPARTMENT OF ENERGY

BLDG. 3525, M/S 6295, ROOM 106
POST OFFICE BOX 2008
OAK RIDGE, TENNESSEE 37831-6295
TELEPHONE: 423-241-4237
FACSIMILE: 423-576-7862

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Distribution

MOX Fuel Pin Measuring Apparatus

The enclosed document details the MOX Fuel Pin Measuring Apparatus that was designed to measure the fuel pin outer dimensions for the 30 GWd/MT and later capsules. This effort was sponsored by the Fissile Materials Disposition Program (FMDP). This work was carried out at the Irradiated Fuels Examination Laboratory by the staff of the Metals and Ceramics Division of the Oak Ridge National Laboratory during the period from July 2000 though March 2001. Assistance for calibration and test procedures was provided by Engineering Technology Division Staff.

This is a Level-2 document as defined in the Fissile Materials Disposition Program Light-Water Reactor Mixed-Oxide Fuel Irradiation Test Project Plan, ORNL/MD/LTR-78.

Sincerely,

Robert N. Morris
Fissile Materials Disposition Program

Enclosure

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ORNL/MD/LTR-209

MOX Fuel Pin Measuring Apparatus

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March 2001

Oak Ridge National Laboratory

CONTENTS

FIGURES

ACRONYMS

ATR	Advanced Test Reactor
FGPMA	Fission Gas Pressure Measuring Apparatus
FMDP	Fissile Materials Disposition Program
FPMA	Fuel Pin Measurement Apparatus
INEEL	Idaho National Engineering and Environmental Laboratory
GWd/MT	Giga-Watt Days per Metric Ton
LANL	Los Alamos National Laboratory
LHGR	Linear Heat Generation Rate
LWR	Light Water Reactor
MOX	Mixed Oxide
ORNL	Oak Ridge National Laboratory
PIE	Post Irradiation Examination
RG	Reactor Grade
TIGR	Thermally Induced Gallium Removal
WG	Weapons Grade

ABSTRACT

This report summarizes the design of the ATR MOX Test Fuel Pin Measuring Device. This device makes use of four Magnescale probes and a precision sliding table to make three-dimensional measurements of a short fuel pin (approximately 8 inches) with an accuracy of better than 0.0003 inches. Mathematical fitting is then used to determine the diameter and bowing of the fuel pin as a function of length. This device is currently being applied to fuel pins irradiated in the Advanced Test Reactor (ATR) as part of the Light Water Mixed Oxide Fuel Irradiation Test sponsored by the Department of Energy.

1. INTRODUCTION

1.1 General

The Fuel Pin Measuring Apparatus (FPMA) was developed to provide high accuracy diameter measurements (±0.0003) of the ATR MOX fuel pins to assist in determination of clad performance. The apparatus consists of a precision measuring head comprising four Magnescale probes mounted on a high accuracy sliding table and the associated control motor and software. During measurement, the fuel pin remains stationary while the measuring head moves along the fuel pin with the four probes taking four simultaneous measurements. This method establishes an absolute three-dimensional coordinate system that allows the mathematical reconstruction of the fuel pin from the measurements. Thus, bowing as well as diametral information can be obtained.

Mathematical shape fitting software allows the determination of the diameter of the fuel pin as a function of axial position and can compensate for small deviations from the vertical, as the locus of points composing the axis of the pin is determined as well. Figure 1 shows a sketch of the apparatus in its measuring configuration. Figure 2 shown a photograph of the device, and Figure 3 shows the apparatus being applied to measure a dummy fuel pin.

The heart of the device is the measuring head with its four Magnescale digital gauging probes [Reference 1]. These probes use a graduated ferromagnetic material and a special magnetic flux reader to form a rugged measuring unit with an accuracy of 0.78×10^{-4} inches (2μM). The head is moved by a sliding table [Reference 2] with a flatness movement accuracy of 3×10^{-4} inches. Together, the head and the sliding table define the high accuracy coordinate system necessary to collect measurement data. The head is the primary driver for determining diametral accuracy, while the table is the primary driver for axial variations (such as pin bending or bowing).

The fuel pin is mounted in a rotating vise that allows the fuel pin to be rotated about its axis so that measurements can be taken at several angular orientations. Because the vise rotation is not concentric within the accuracy demanded of the measurements, the data collected at various rotation angles cannot be directly combined into one mathematical model; however, the calculated diametric information can be combined to infer actual surface conditions.

1.2 Operation

The apparatus begins operation by moving the measurement head to the bottom of the slide and measuring a calibrated reference rod held in the vise. This rod establishes both the center of the coordinate system and the unit length. The fuel pin then replaces the rod. The slide moves the measurement head (either upward or downward as desired) along the fuel pin taking four measurements at predetermined locations. At each location a circle is fitted to the measurement by determining the circle center (x,y) and its radius.

It is important to recognize that the fuel pin does not have to be straight or perfectly centered along the axis of the apparatus. Because of the configuration of the MOX ATR fuel pins, the device does not have to handle significant out-of-roundness (oval shape), so four probes are considered sufficient for the measurements of interest. (If measurement of oval or complex shapes were desired, more probes could be added to the design.)

Once the measurement is complete, one has the fitted radius as a function of length, the axis of the fuel pin (the set of circle centers), and the four original probe position measurements. Examination of the pin axis will allow one to determine if the pin is bowed, and a review of the fitted radius as a function of length will provide an estimation of any bambooing. By comparing the fitted radius with the original measurements, one can determine whether the pin cross-section deviates from a circle, especially if the fuel pin has been incrementally rotated, so that measurements at more than one vise angle have been taken.

Chapter 2 describes the mathematical basis for use of the probe measurements. The test and calibration procedure employed prior to the initial application of the apparatus is described in Chapter 3. Chapter 4 details the measurement of two irradiated ATR MOX fuel pins. Conclusions and recommendations for possible future improvements are discussed in Chapter 5. Future measurements for actual irradiated fuel pins from the ATR MOX irradiation experiment will be reported in the Final PIE reports for capsules withdrawn at 40 and 50 GWd/MT burnups.

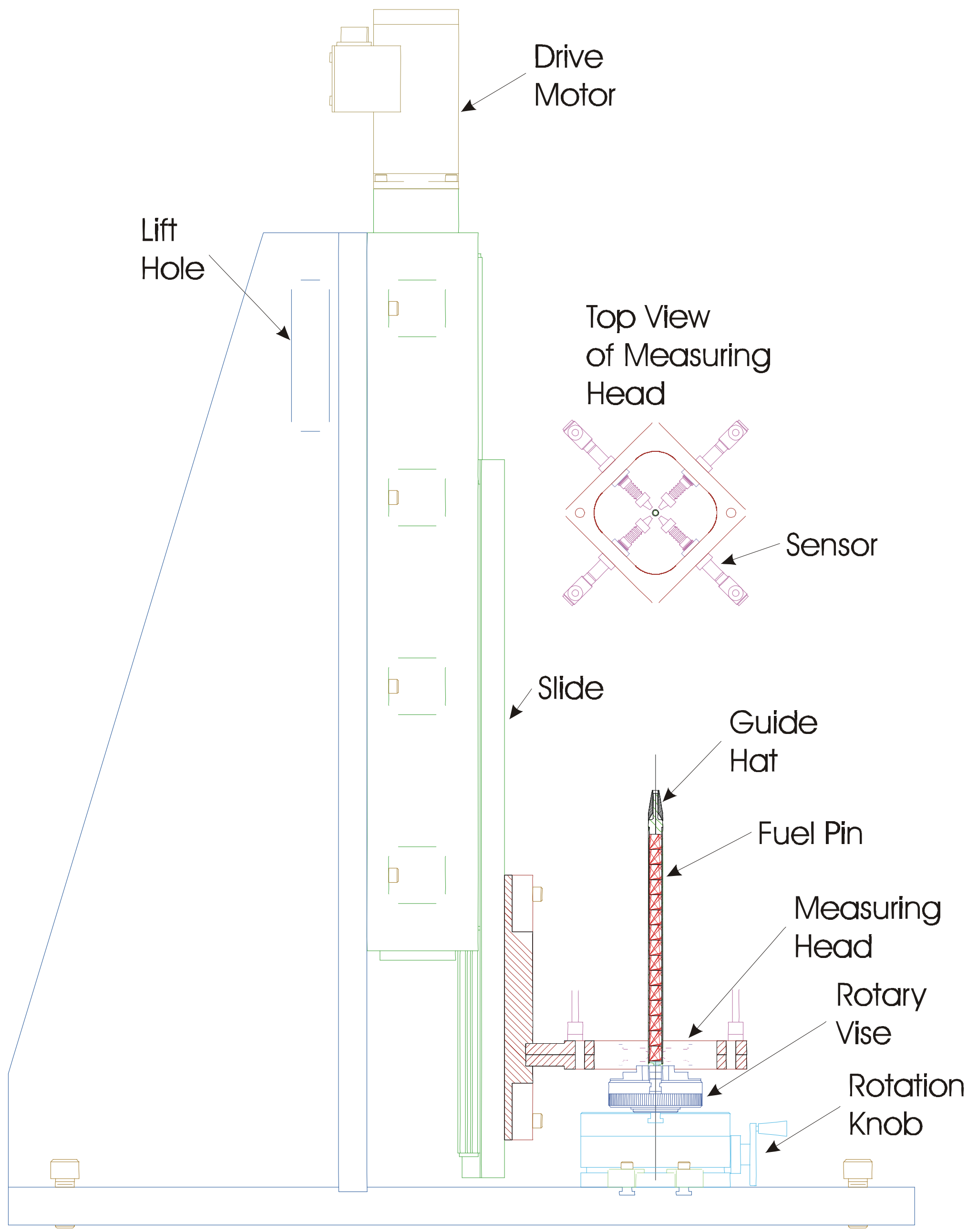

Figure 1. Schematic of the Fuel Pin Measuring Apparatus.

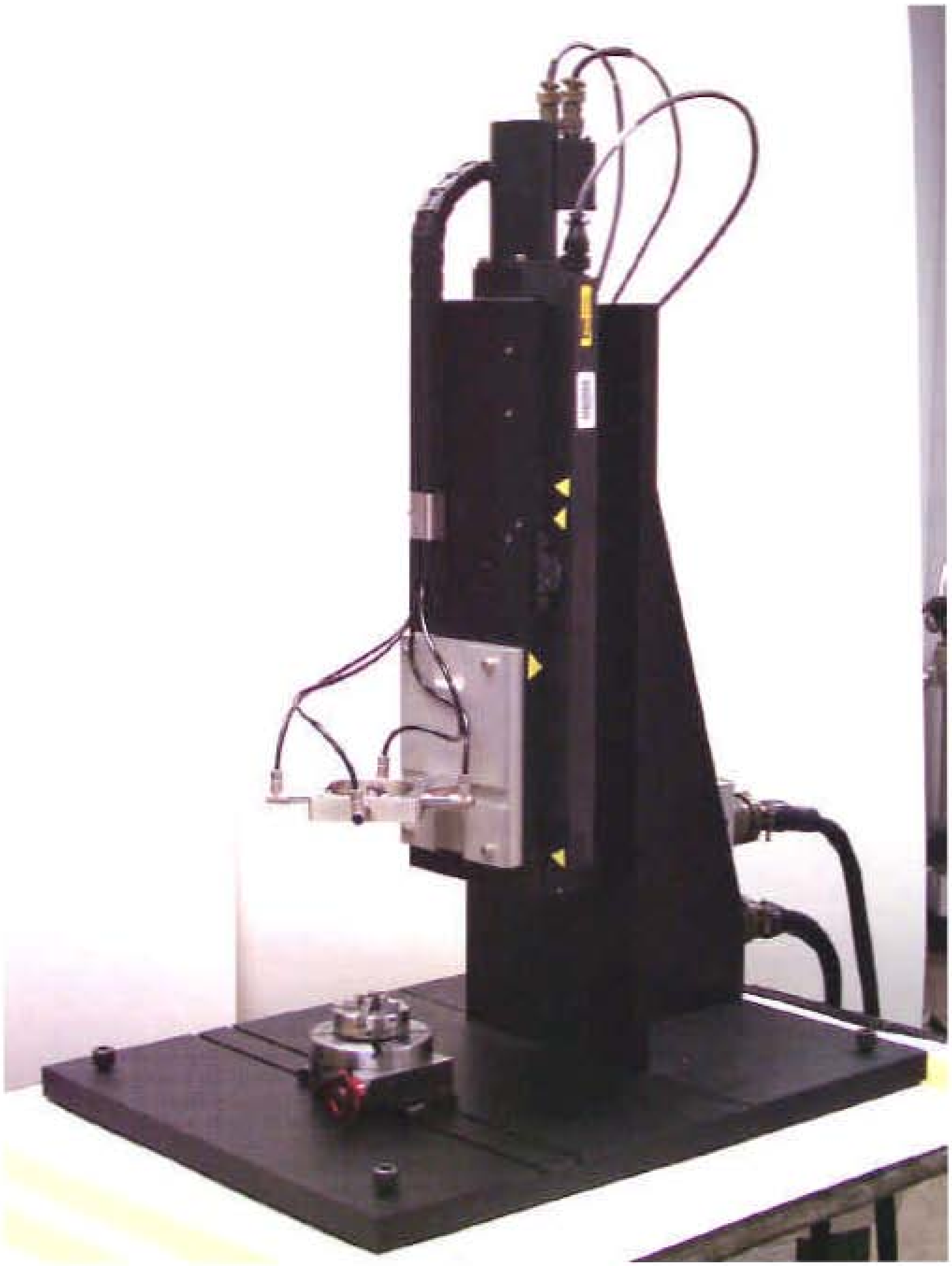

Figure 2. Photograph of the Fuel Pin Measuring Apparatus.

Figure 3. FPMA measuring a dummy fuel pin. Note that the guide hat is absent.

2. BASIS OF OPERATION

2.1 Measurement and Determination of Radius

The MOX Fuel Pin Measuring Apparatus performs measurements at a user-selected number of axial positions. At each axial position, four measurements are made relative to the coordinate system of the measuring head. These measurements are then recorded for later analysis as well as for use in fitting a circle to the four measurements. Figure 4 details the measurements.

At each axial location three parameters are determined: the radius of a circle fitting the four measurements, the offset in the *x*-axis, and the offset in the *y*-axis. These radius values may be used to examine the pin for swelling, creep, and bambooing by observing the change in radius as a function of axial position. The offsets may be used to estimate the extent of bowing (if any) by observing their slopes as a function of axial position. A linear slope indicates a straight pin, while a quadratic slope indicates a bowed pin.

An important advantage of this technique is that it is not dependant on the precise orientation of the fuel pin relative to the sliding table. The measurement coordinate system is defined by the measurement head and the sliding table, thus any small misalignment between the table and pin will show up as a linear change in the offsets as a function of axial variation, which can be easily observed (and discounted).

2.2 Mathematics of Parameter Fitting

A nonlinear least squares approach is used to fit circle parameters to the measurement data. The four measurements, P_A through P_D (in inches), are entered in the equation of an offset circle to generate four equations for the differences between the calculated and measured values. The three parameters, r, X_0, Y_0, are then varied to minimize the sum of the squared errors (E). (Note that the probe measurements are always positive.):

$$
\begin{aligned}
&X_0^2 + (P_A - Y_0)^2 - r^2 = e_1 \\
&(P_B - X_0)^2 + Y_0^2 - r^2 = e_2 \\
&X_0^2 + (P_C + Y_0)^2 - r^2 = e_3 \\
&(P_D + X_0)^2 + Y_0^2 - r^2 = e_4 \\
&\mathrm{E} = e_1^2 + e_2^2 + e_3^2 + e_4^2
\end{aligned}
$$

This is done for each axial location. The particular minimization algorithm used is the downhill simplex method because it is simple and adequate for this modest problem [Reference 3].

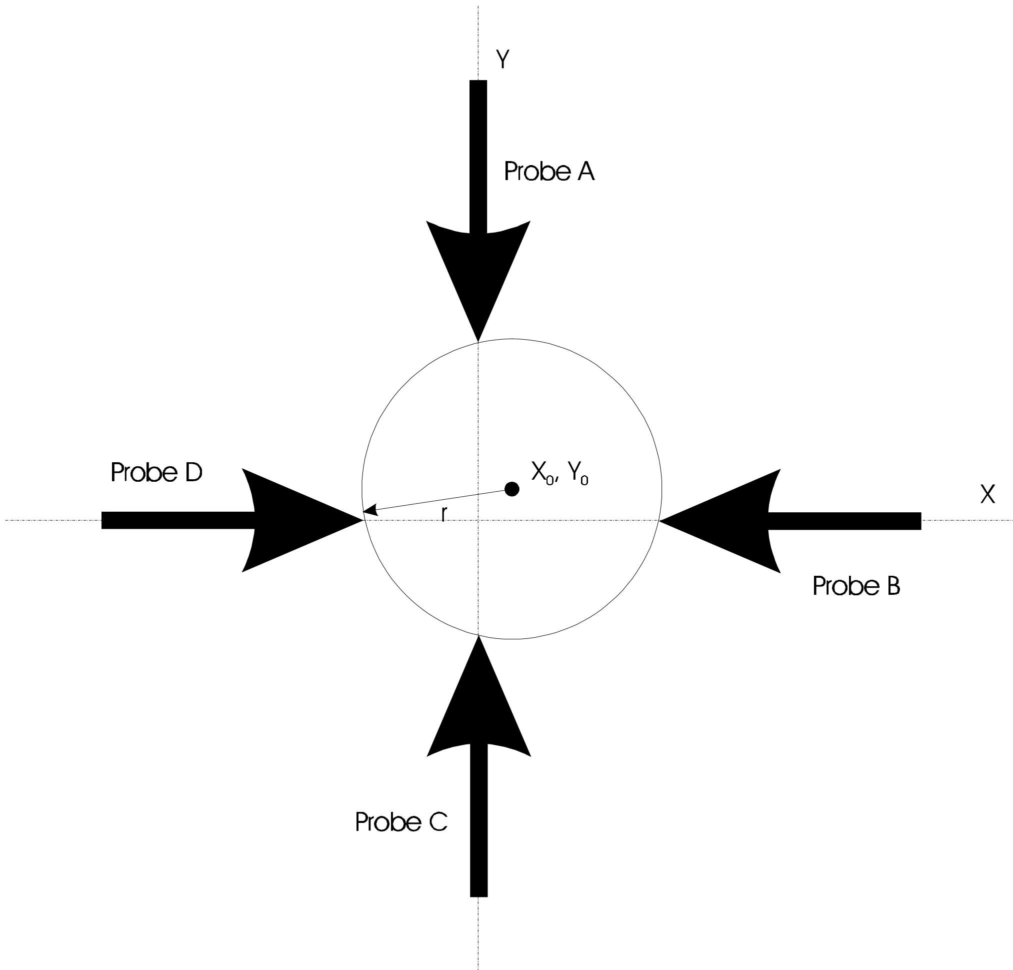

Figure 4. Schematic of measuring configuration showing the four measurement probes and the possible off center measuring case; r, X_0, and Y_0 are computed values. Probe A, B, C, and D are the measured values.

In principal, only three measurements are required to solve for *r*, X_0, Y_0, but with three measurements the parameters can become sensitive to minor errors in the measurements and the apparatus alignment. Section 2.4 will show that the alignment of the center of the calibration standard and the apparatus coordinate system generally contains some uncertainty. By collecting more information than the minimum and treating the fitting as an optimization problem, one is able to reduce the sensitivity to minor errors and to better model the surface as a whole (greater sampling). If significant cross-sectional deviation from a circle were expected, the appropriate model might be an ellipse with five fitting parameters and six or more measurement points. However, the ATR MOX fuel pins are known to have little out-of-roundness by virtue of their design and fit in the irradiation capsule, so four measurements are believed to be sufficient for this technique.

Once the offsets have been determined for all the axial points, a line of the form:

$$X(z) = X_a + S_x z$$
$$Y(z) = Y_a + S_y z$$

is fit through the offsets to approximate the axis of the fuel pin. The parameters X_a, Y_a, S_x and S_y are again determined using a least squares type fit to minimize the error, *E,* over the number of data points, *n*:

$$\mathrm{E} = \sum_{i=0}^{n} \left[\left(X(z_i) - X_{0i} \right)^2 + \left(Y(z_i) - Y_{0i} \right)^2 \right]$$

This fitted line allows the operator to estimate the tilt of the pin in the apparatus for basic analysis, and to determine if the pin has been properly clamped in the vise (useful to the operator). However, determination of the extent of any bowing will require more extensive analysis. Because the pin could be bowed in a number of ways, a standard method for more complex bowing analysis is not included in the basic operation of the apparatus. The analyst will need to examine the offsets on a case-by-case basis to determine the best way to model the data.

The tilt of the pin relative to the apparatus coordinate system is:

$$Tilt(inches\ \ per\ \ inch) = \sqrt{S_x^2 + S_y^2}$$

Once the diametric data has been fit, it is important to determine how well the fit models the pin cross-section. The first approach is to individually compare the four measurements to the fitted parameters to determine how closely they fall on the circle. Using the offsets as the circle center, the four measurements can be used with the equation of a circle to compute an effective probe radius:

$$R_A^{effective} = \sqrt{X_0^2 + \left(P_A - Y_0 \right)^2}$$
$$R_B^{effective} = \sqrt{\left(P_B - X_0 \right)^2 + Y_0^2}$$
$$R_C^{effective} = \sqrt{X_0^2 + \left(P_C + Y_0 \right)^2}$$
$$R_D^{effective} = \sqrt{\left(P_D + X_0 \right)^2 + Y_0^2}$$

This set of four radii can then be compared with the fitted radius to determine how well a circle models the fuel pin cross section – a measure of out-of-roundness for minor deviations, *D*, and an indicator of problems for major deviations:

$$D_A = \left| r - R_A^{effective} \right|$$
$$D_B = \left| r - R_B^{effective} \right|$$
$$D_C = \left| r - R_C^{effective} \right|$$
$$D_D = \left| r - R_D^{effective} \right|$$

By comparing both the fitted radius and the set of effective probe radii for two or more angular measurements (vise rotation), one can estimate the out-of-roundness and determine how well the circle model fits the pin cross section.

In principle, the data from several angular measurements could be combined into one large data set by mathematical rotation and translation, but the vise rotation lacks the accuracy (approximately 0.002-0.003" run out) of the rest of the system and such a combination could introduce unacceptable uncertainty.

The software outputs the probe data, the fitted circle parameters, the fitted line parameters, the length of the measured region, and the number of points. The tilt and the out-of-roundness (point by point) along with a graphical presentation of the pin profile are displayed on screen for the operator.

2.3 Calibration Set Up

The vise is aligned with the measuring head during apparatus assembly. The apparatus is calibrated with the measuring head at its lower slide position by placing a standard of known diameter in the vise (set at zero degrees). The probes are then set to the standard radius.

2.4 Center Accuracy

While the standard can be prepared to great accuracy (less than 0.0001"), the center of the standard cannot be aligned with the center of the measuring head to as great a degree. This misalignment, in exaggerated form, is shown in Figure 5.

To provide an estimate of the error in radius, assume that the calibration standard is misaligned only in the x direction. In that case, Probes A and C will be measuring the same value, but slightly off the centerline of the standard and thus smaller than the actual radius. The equation for our circle in this case now becomes:

$$(\Delta_X)^2 + P^2 = a^2$$

where *P* represents the apparent radius (y axis) and *a* is the actual radius of the standard. Solving for P gives:

$$P = \sqrt{a^2 - (\Delta x)^2} \approx a\left[1 - \frac{1}{2}\left(\frac{\Delta x}{a}\right)^2\right]$$

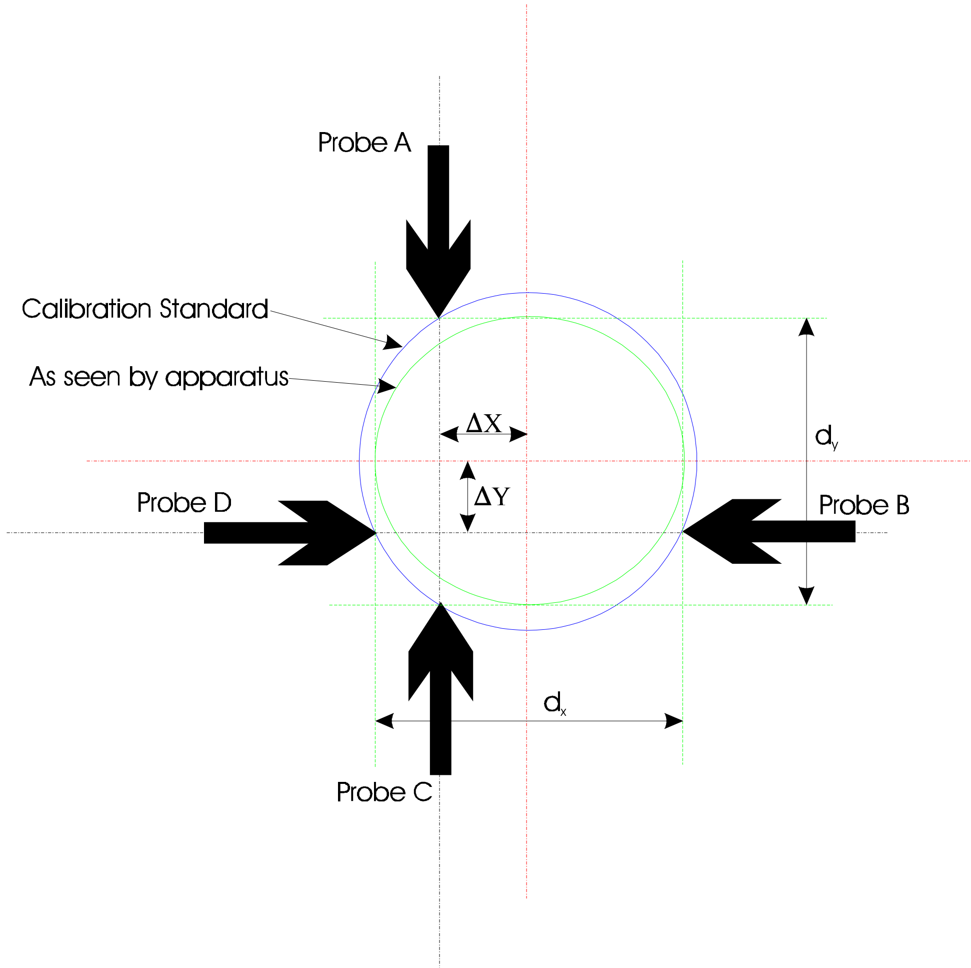

Figure 5. Geometry of probe alignment.

Thus, the error is proportional to the square of the misalignment and is small. Likewise, any misalignment in the y direction leads to a similar result. The effect of the misalignment is that the apparatus detects a slightly smaller ellipse rather than a circle.

The approximate horizontal, d_x, and vertical, d_y, dimensions of the ellipse are:

$$d_x = 2a\left[1 - \frac{1}{2}\left(\frac{\Delta y}{a}\right)^2\right]$$

$$d_y = 2a\left[1 - \frac{1}{2}\left(\frac{\Delta x}{a}\right)^2\right]$$

Note that these values are always smaller than the calibration diameter. This is a mathematical inconsistency, because the device is aligned with all probes set to the same value and zero offset.

The result of these misalignments is increased uncertainty in the measured radial dimensions. This practical situation favors curve fitting based on optimization, rather than direct solution and minimal data as discussed in Section 2.2.

To guide the design and use of the apparatus, it is useful to estimate the maximum tolerable offset. One needs to examine the magnitude of:

$$\frac{(\Delta s)^2}{2a}$$

where *Ds* is the maximum misalignment in *x* or *y*. Since the desired accuracy is on the order of 0.0001 inches, one should select a maximum *Ds* based on:

$$\frac{(\Delta s)^2}{2a} = 10^{-4}$$

For an error of no more than 10^{-4} inches with a radius of approximately 0.2 inches, *Ds* < 6 x 10^{-3} inches. Keeping within this level of misalignment is achievable with standard fixturing.

Note that the error in determining the absolute circle center (X_0, Y_0) is linear with the misalignment and thus the location of the circle center is the least accurate measurement. The same mathematics that result in minor diameter dependence on centering alignment also results in greater uncertainty in determining the center of the coordinate system.

In principle, mounting a very small diameter calibration rod in the vise and using it to define the center could circumvent this problem. However, practical considerations such as the limited movement of the probes and inadequate rod rigidity would hamper any such efforts to absolutely define the center. For these reasons, combining *x* and *y* data from several vise rotations may introduce significant uncertainty – the center point of the coordinate system is not precisely known. The relative changes, however, are useful as they contain information about the pin axial variation.

Practical alignment of the vise can be done by clamping a known standard in the vise and moving the vise perpendicular to a set of two probes until a maximum of the sum of the two probe readings is noted. The movement is then repeated along the other axis. The process is iterated until no further improvement is obtained. Figure 6 illustrates the method.

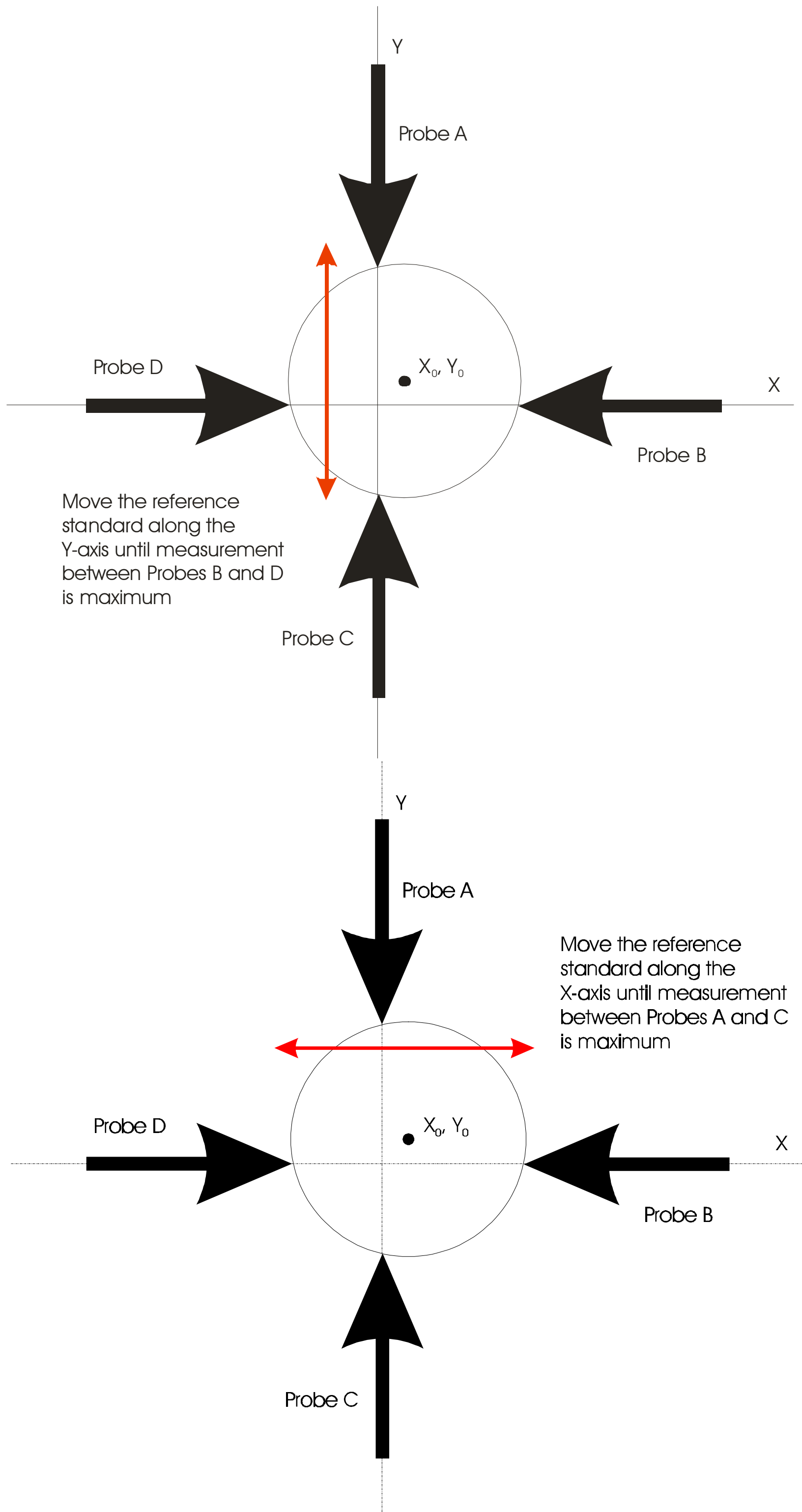

Figure 6. Method of aligning the vise by use of a standard and monitoring probe readings.

3. TESTING

3.1 Method

A dummy fuel pin was fabricated from Zircaloy and inspected to determine its diameter profile within an accuracy of 0.0001 inches for use as a measurement standard. In general, standards of accuracies 0.0001 inches or better were used to calibrate the FPMA Magnescale probes.

The apparatus testing was done in the following manner: the equipment was turned on and the slide moved to the face of the vise; a standard was clamped in the vise (set at 0 degrees) and the apparatus calibrated; the standard was removed and the fuel pin clamped in the vise; measurements were then taken at various vise rotations with and without calibrations at the new vise angle.

Two items are important to note. To perform practical measurements, a guide hat must be placed on the fuel pin so that the probes can be gently guided onto the fuel pin to preclude any damage to them. The guide hat is included in the Figure 1 schematic, and an actual guide hat is shown in Figure 7. The second item is that the fuel pin is measured upside down (with the gas plenum at the bottom), because this is the most convenient way to hold the fuel pin, and this arrangement allows the greatest measuring range.

Figure 7. Detail showing guide hat on the dummy fuel pin (cone shaped object). Note that the dummy fuel pin is mounted upside down.

3.2 Measurements

Two different tests were conducted, one to determine the performance of the apparatus with recalibration whenever the vise angle is changed, and one to determine the performance with only a single calibration at the initial vise setting (0 degrees). In the case of recalibration at different vise angles, the calibration standard and the dummy fuel pin were inserted and removed from the vise several times, so the measurements include the effects of vise jaw position changes.

In general, the apparatus was observed to produce repeatable measurements on a day-to-day basis, including the effects of minor room temperature changes and vise rotations, to approximately 0.00015 inches. Once calibrated, variations were negligible during the course of a day's testing. Also noted during testing was that the apparatus tended to indicate slightly higher measured values at the extreme of travel when the vise was misaligned. When the vise was properly aligned, measured values tended to be very close to the standard or very slightly lower.

Since the resolution of the probes is 0.78 $x10^{-4}$ inches and two probes are required for a (straightforward) diameter measurement, a simple (equally random) combination of uncertainties for the two probes is 1.1 $x10^{-4}$ inches. Thus, the 1.5 $x10^{-4}$ estimation for overall repeatability is considered reasonable.

3.2.1 Multiple Calibrations

Figure 8 shows the results of the dummy fuel pin measurements both with and without recalibrations over the range of vise angles expected to be commonly used. Three hundred and one axial positions were measured at each angle. The error bars indicate the uncertainty in the measurement of the dummy fuel pin (±0.0001); the actual uncertainty of the apparatus calibration standard was better than 1 $x10^{-5}$ inches (commercial X gauge).

Note that the measurements form a band about 0.0001" wide and that a single calibration at 0 degrees appears to be sufficient; multiple calibrations at specific vise angles don't appear to improve the measurement. The width of the band is close to the resolution of a single probe and well within the design accuracy of ±0.0003 inches.

3.2.2 Single Calibration, Multiple Angles

The dummy fuel pin was measured at 6 angular positions, 0 (calibration position), 60, 120, 180, 240, and 300 degrees. No recalibrations were performed. Three hundred and one axial positions were measured at each angle. Figure 9 shows the results of the measurements and a comparison with the inspection results.

Agreement with the inspection results is quite good, well within the 0.0003 inch specification and close to 0.0001 inches. Further, note that the apparatus was able to compensate for the vise rotations (run out) with agreement between angular positions of approximately 0.0001 inches, similar to the performance described in Section 3.2.1. It was noted during initial alignment that

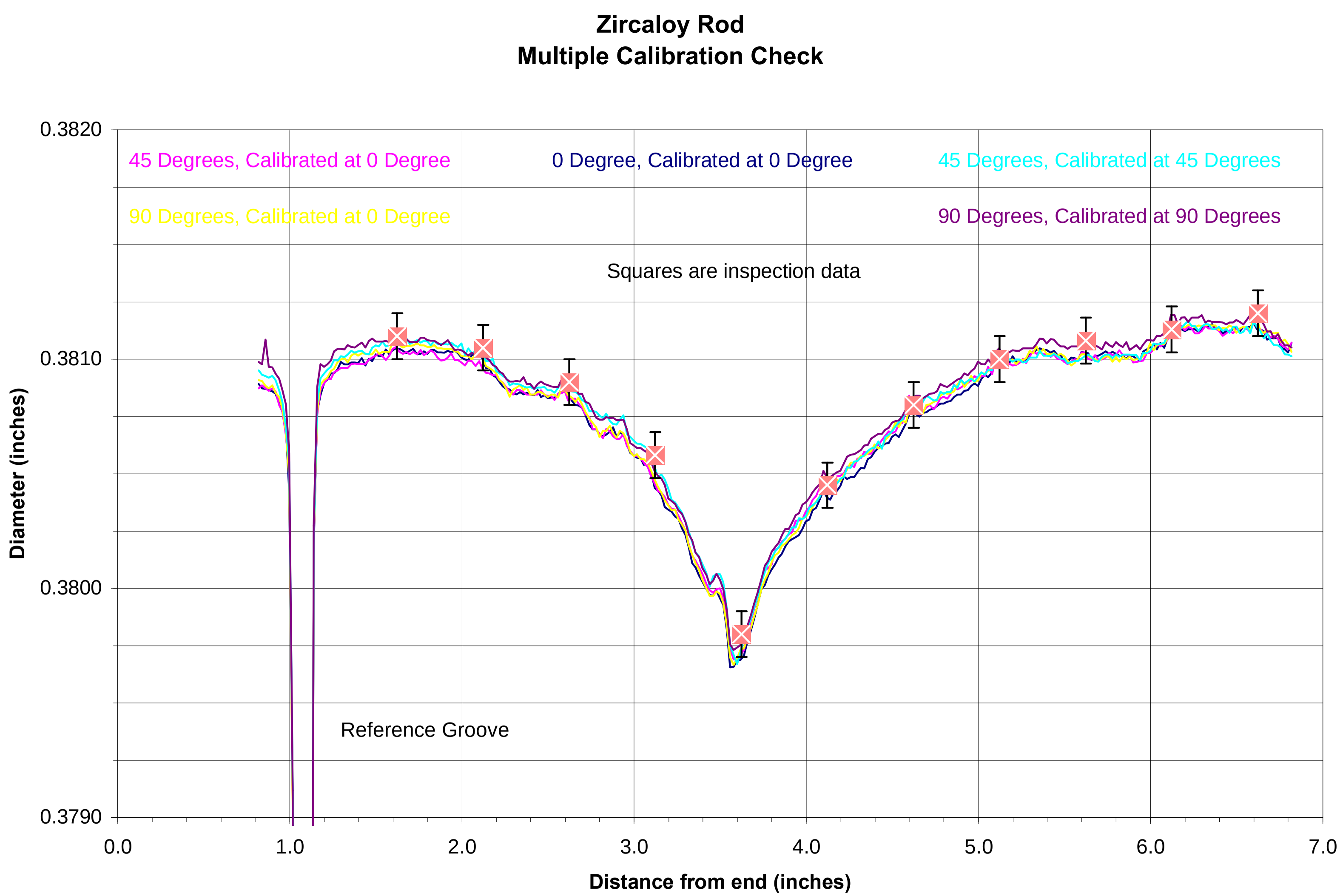

Figure 8. Diameter measurement results at different vise angles both with and without recalibration.

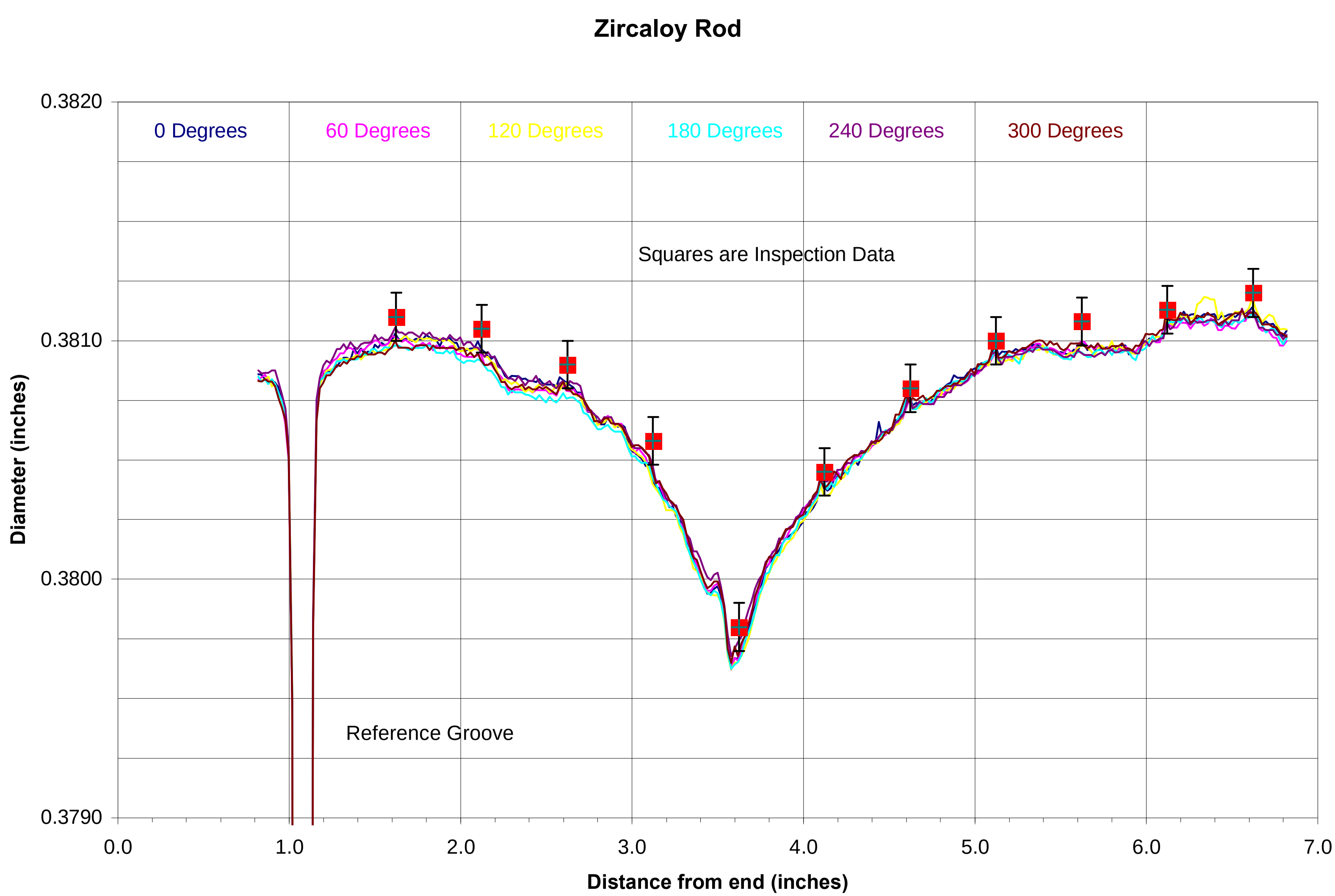

Figure 9. Diameter measurement results from 6 vise angles and inspection data for the dummy fuel pin.

aligning the vise center with the measuring head center within a few thousandths of an inch was important to get good agreement between rotations as has been discussed in the previous Sections.

The computed center offsets are shown in Figure 10. The center offsets are the square roots of the sum of the squares of the x and y offsets. Note that the change in the center position is nearly 0.007 inches at the measurement taken furthest from the vise where the calibration took place (remember that the dummy fuel pin is upside down). The red dot at the extreme lower right of this figure is the calibration position. It is not exactly zero because the data was taken with the dummy fuel pin in place, after the calibration standard had been removed, and shows the (apparent) difference between the center of the standard and the dummy fuel pin.

The offset plots are essentially straight lines with minor variations due to run out, which shows that the dummy fuel pin is essentially straight within the accuracy of this device. Since, as was noted previously, the absolute value of the offset is the least accurate parameter, changes in its value are the most useful guide to evaluating the pin axis.

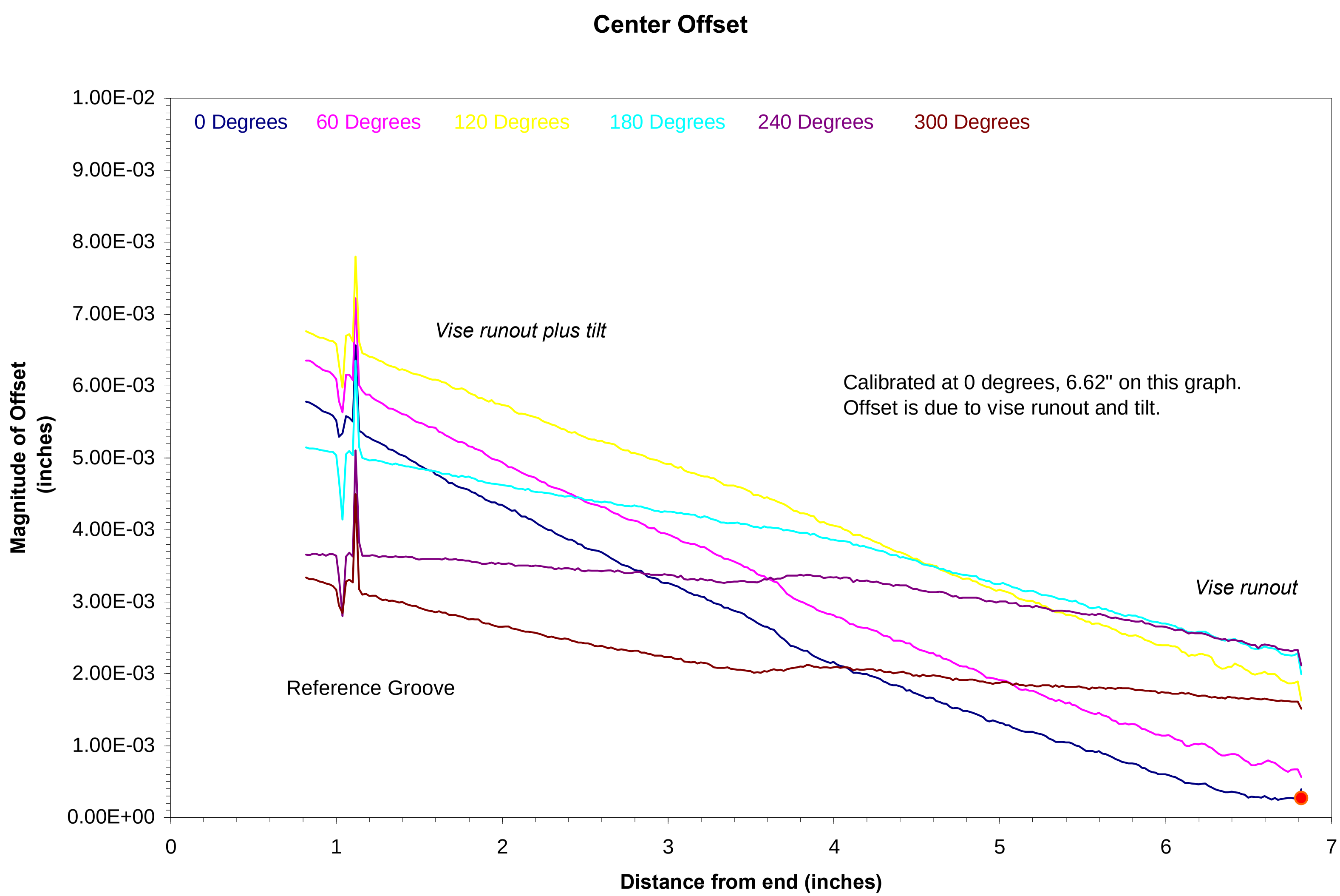

Figure 10. Computed offsets for the different vise angles. The red dot is the calibration position before inserting the dummy fuel pin (0 degrees).

4. APPLICATION

4.1 Initial Application

The first application of the Fuel Pin Measuring Apparatus (FPMA) was to determine the diameter as a function of length for two FMDP ATR MOX fuel pins. Both of these fuel pins had a burnup of approximately 30 GWd/MT, were exposed to the same irradiation conditions, and were identical except for ppm level impurities in the fuel (gallium). These fuel pins were removed in a straightforward manner from closely fitting capsules (approximately 0.002 inches clearance) so major deformities such as bowing or severe bambooing were known not to be present. They were dimensionally essentially identical to the dummy fuel pin employed for testing and used a similar guide hat.

These fuel pins are designated ATR MOX Fuel Pin 6 and Fuel Pin 13.

4.2 V Block Measurements

Before being placed into the FPMA, the pins were measured with a simple V-block and dial indicator at intervals of 0.25 inches over most of the fueled region of the pin. The very bottom of the pin could not be easily measured unless the jig was reversed, an added step that was not considered necessary for the present purpose. At each axial location four measurements 45 degrees apart were taken and averaged. A photograph of the jig is shown in Figure 11.

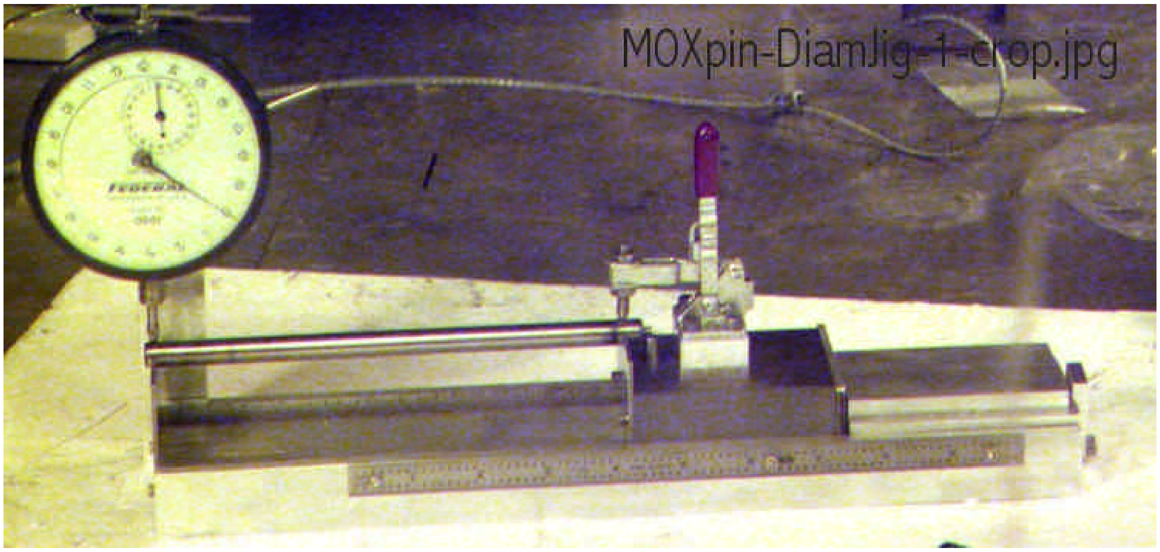

Figure 11. Dial indicator and V-block jig with Fuel Pin 6 in place.

4.3 Results

The results of the measurements are shown in Figure 12 (Fuel Pin 6) and Figure 13 (Fuel Pin 13). The pins were measured at relative vise angles of 0 and 45 degrees (unrelated to the dial indicator and V block angles) with an axial step size of 0.020 inches and the two values were then averaged. Only slight differences were seen between the two measurement angles.

Both graphs provide evidence that the fuel clad crept outward (due to the fast flux, operating temperature, and the internal pin pressure) during irradiation and that this outward displacement is slightly more pronounced at the pellet interfaces. The magnitude of the creep and variations in the creep are small and indicate that no hard pellet clad mechanical interactions took place.

It is interesting to note the excellent correspondence between the two methods of measurement. Agreement is within the error band (±0.0002 inches) in all cases. The resolution of the creep axial variation is, of course, better with the FPMA (solid line) because of the large number of axial points taken (approximately 300), but the simple dial indicator and V-block (points) are suitable whenever a relatively small number of measurements is sufficient. Also, the two independent methods serve as a useful check to provide assurances that all is working as designed.

The FMPA indicated no signs of fuel pin bowing, out-of-roundness ($< 2 \times 10^{-4}$ inches), or any indications of large axial variations as would be expected from the previous experience, i.e., that the pins were straightforwardly withdrawn from the closely fitting capsules.

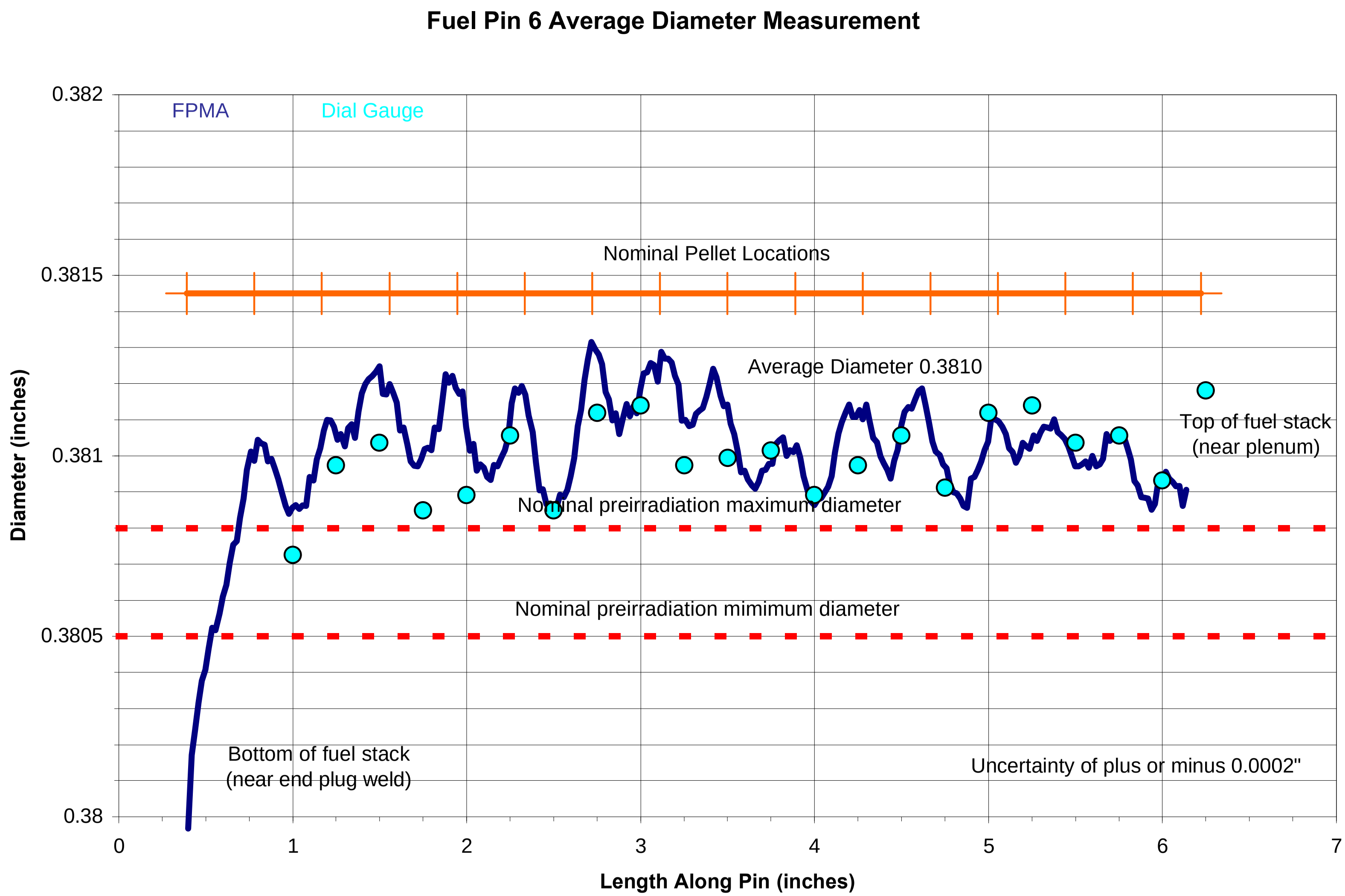

Figure 12. Results of both FPMA and dial indicator/V block measurements for Fuel Pin 6. Note the alignment between the graph peaks and the pellet locations.

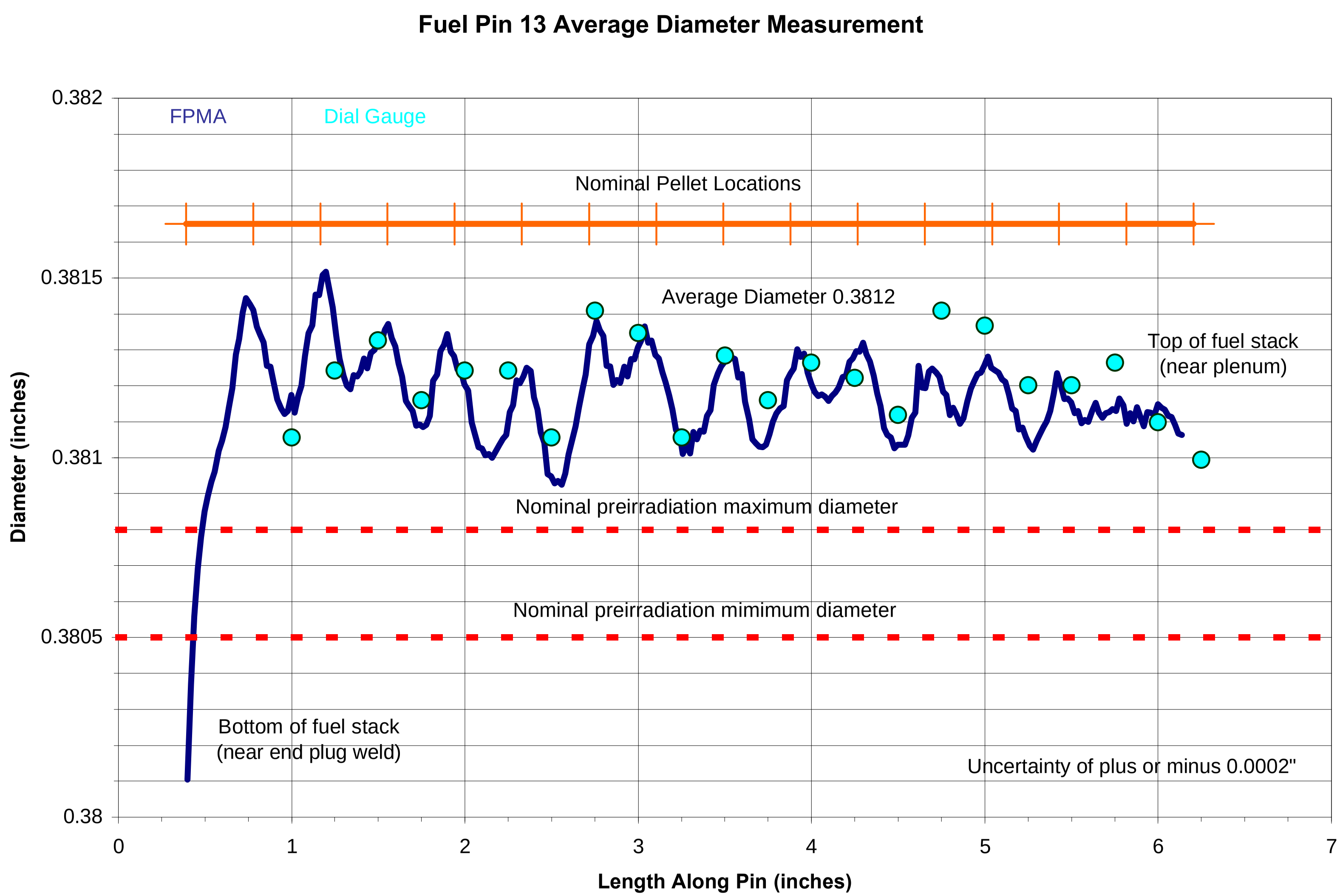

Figure 13. Results of both FPMA and dial indicator/V block measurements for Fuel Pin 13. Note the alignment between the graph peaks and the pellet locations

5. CONCLUSIONS

5.1 Results of Trials

Measurements and tests to date indicate that the FPMA is able to perform the desired fuel pin measurements within the desired accuracy (0.0003 inches), and will very likely exceed it (0.0002 inches appears to be a conservative value). It is able to compensate for vise rotations, so it will be straightforward to collect the desired fuel pin data at a large number of points at two or more angular positions about the fuel pin as was done in Chapter 4. This will be more than adequate to meet the goal of determining the fuel pin surface profile as necessary to investigate any effects of pellet-clad contact.

5.2 Potential for Improvements

One area for improvement would be to procure a vise with less runout. A collet mounting system is one way of avoiding the runout problem, but the mounting system becomes more bulky, and even then the potential for minor runout cannot be eliminated. A better approach would be to use more probes, so that a greater region would be directly measured. Although complicating, more probes would also allow the software to model the fuel pin as a more complex shape and avoid the rotation problem altogether.

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