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ANL/HFEF-003

A Fuel-element Profilometer for the HFEF

by

M. D. Carnes and K. G. Gill

Figures 3 and 6 were inadvertently interchanged. On page 9, the caption should read: Fig. 6. Typical Profilometer Trace. On page 19, the caption should read: Fig. 3. Sensing Head of Profilometer.

September 17, 1973

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M. D. Carnes and K. J. Gill

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Hot Fuel Examination Facility
Argonne National Laboratory
Idaho Falls, Idaho

July 1973

Work performed under the auspices of the U. S. Atomic Energy Commission

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ABSTRACT

A remotely operable direct-contact gauging unit was built to measure the diameter of irradiated EBR-II fuel elements. The unit is an electronic gauge using linear-voltage differential transformers as sensors. It produces a diameter profile by measuring diameter continuously over the element length. It can gauge elements with or without spirally wrapped spacer wires, and is adjustable over a range of element diameters from 0.174 in. to 0.805 in. It is classed as a vertical unit because the element is maintained in a vertical position. Under in-cell operating conditions its uncertainty is less than ± 0.0002 in. When it gauges calibration standards that are round in cross section and straight, the uncertainty of the measurement is less than ± 0.0001 in.

I. INTRODUCTION

Radiation-induced diametral changes in fuel elements for the Liquid Metal Fast Breeder Reactor (LMFBR) are of major concern to designers of large LMFBR demonstration plants. The diametral changes are the result of swelling of the stainless steel cladding, swelling of the fuel, and fuel/cladding interactions.

Profilometry (continuous measurement of diameter over the fuel-element length) is an essential portion of the examinations that are conducted on fuels irradiated in Experimental Breeder Reactor II (EBR-II). To meet program requirements, the profilometry must be both rapid and accurate. A new profilometer has been developed for the Hot Fuel Examination Facility (HFEF) of Argonne National Laboratory to meet these needs.

II. DESIGN REQUIREMENTS AND SYSTEM DEFINITION

A. Preliminary Considerations

The HFEF profilometer must meet the following requirements:

- (1) Have an uncertainty of less than $\pm 200 \times 10^{-6}$ in.
- (2) Be remotely operable in a hot cell
- (3) Measure capsules or elements with a spirally wrapped spacer wire
- (4) Be adjustable to accommodate capsules varying in diameter from 0.174 in. to 0.805 in. (The original design went only to 0.500 in.)
- (5) Have a linear range of at least ± 0.020 in. without readjustment, to accommodate the variation expected in a single capsule
- (6) Provide a continuous trace of diameter
- (7) Be able to measure capsules up to 61 in. long
- (8) Maintain the capsule in a vertical position
- (9) Have a capacity of at least 10 capsules per 8-hr shift
- (10) Provide the necessary correlation between preirradiation

and postirradiation measurements.

A review of four existing profilometers that had been developed for the AEC indicated that none of them met all of the essential requirements of the EBR-II Project.* It was therefore necessary to design a profilometer for the specific needs of EBR-II, incorporating, where possible, the proven desirable features of existing profilometers.

In order to ensure a successful design, several preliminary investigations were made. They included:

- (1) A thorough review of all available sensors
- (2) An investigation of the errors associated with various methods of applying the sensors
- (3) A complete evaluation of all error sources, once the system had been defined.

The results of the investigations were as follows:

B. Sensor Selection

Many types of sensors were considered; they can be classified as either contact or noncontact gauges.

The noncontact sensors were (a) capacitance proximity gauges, (b) pneumatic proximity gauges, and (c) photo-optical gauges.

The sensors requiring physical contact between the gauge and the capsule were (a) laser interferometry gauges,¹ (b) optical relay (Bausch & Lomb DE-25B),² and (c) linear-voltage differential transformers (LVDT's).

LVDT's were selected by a process of elimination. They meet all the fundamental requirements, are in common use, and are readily available. Laser interferometry also meets the fundamental requirements, but is not as commonly used as LVDT's and possesses no significant advantage over LVDT's. Appendix A gives additional information on selection of the sensors.

*The profilometers considered were those developed by NUMEC, LASL, ANL-MSD, and PNL.

C. Method of Application

The following factors were evaluated in making the design decisions:

The manner in which a sensor is applied can have deleterious effects on the system accuracy. Misapplication of a sensor can even cause the sensor to gauge the wrong parameter. For example, one of the most significant sources of error in remote profilometry is lack of perpendicularity between the axis of the sensors and the axis of the capsule, due to capsule bow. (See Fig. 1.) An LVDT whose uncertainty is of the order of $\pm 30 \times 10^{-6}$ in. may indicate the diameter of a perfectly straight rod to within $\pm 30 \times 10^{-6}$ in., provided the rod is perpendicular to the axis of the sensors. If, however, the rod has a bow in it that causes a 2° deviation from perpendicularity, the diameter indication will be in error by at least 225×10^{-6} in.

Fig. 1. Error Associated with Deviation from Perpendicularity

In designing the HFEF profilometer, one important decision was whether to employ two opposed LVDT's or a single LVDT with a fixed reference anvil. The latter was first considered. Because of the wide variety of capsule sizes, however, the reference anvil would have to be adjustable. Because of the difficulty of remotely adjusting the anvil to accommodate various capsule sizes and because there is no acceptable method to ensure contact with the fixed anvil, it was decided to use two opposed LVDT's in an additive mode.

Another basic decision was the selection of cylindrical contact probes. Three types of contact were considered: flat-faced contacts, spherical contacts, and cylindrical contacts at right angles to the capsule. (See Fig. 2.)

Fig. 2. Types of Contact

Flat contact probes have the advantage of reducing the contact stress, but they were rejected because they lack the ability to resolve small surface irregularities.

Both the spherical and the cylindrical contacts give point contact with the capsule and a high contact stress. No evidence of any damage to capsules has been observed as a result of using the cylindrical contact probes.

Spherical contacts were rejected because of the difficulty in ensuring that the diameter measurement is being made instead of the length of a cord. (See Appendix B, Section 2, for the error contributed by this source.)

Cylindrical contacts were selected, and as a result, the problem of parallel alignment of the contact probes had to be solved. To meet the

design requirement for uncertainty, the contact probes had to be maintained parallel to one another with a deviation of less than $\pm 50 \times 10^{-6}$ in. No sufficiently accurate instrument was available to check the alignment of the contact probes in the assembled sensing head. To facilitate the alignment and stability of a contact probe, it was mounted on the ram of a linear air bearing, with their respective axes mutually perpendicular (see diagram at bottom of Fig. 3). A tolerance of $\pm 50 \times 10^{-6}$ in. is equivalent to a 0.023° rotation of the 0.25-in.-long contact probe. This 0.023° rotation of the air-bearing ram is equivalent to a 0.0013-in. displacement of one end of the ram (see Fig. 4).

Fig. 4. Maximum Allowable Misalignment of Contact Probes

Alignment was achieved as follows:

The rams were removed from the air bearings and placed against a precision parallel bar on an optical comparator. The end of one ram was shimmed until there was no light gap between the contact probes. The amount of shim required determined the required deviation between the rams to obtain parallelism of the contact probes. By "amplifying" the motion in this manner, it was possible to adjust the parallel alignment of the probes by checking the rams with a dial indicator.

Stability of the alignment is maintained by the air bearings. The clearance between the air-bearing wrapper and the ram is 0.0014 in., which would allow 0.08° rotation of the ram if no air were supplied to the air bearing. This is greater than the allowable design requirements; but because of the centering effect of the air flowing through the air bearing, the actual rotation is within the acceptable limits.

D. Electronics

The LVDT's* and associated signal-conditioning equipment** have an output signal of 0 to 50 mV and a sensitivity of 1 mV per 0.001 in.

The recorder*** has an accuracy of $\pm 0.25\%$ of span. When operating on the 10-mV scale, this introduces an uncertainty of $\pm 25 \times 10^{-6}$ in.

E. Positioning Stage

The positioning stage holds the capsule in a vertical position, and the sensing head is moved downward with respect to the capsule. It is desirable to restrain the capsule in the X and Y directions to remove bow during profilometry. The combination of air chuck and roller guides gives this restraint. The sensing head moves along the capsule rather than the capsule moving through the sensing head because of a space limitation in the hot cells. (With a moving capsule the stage would have to be twice as long as the capsule.) The head is traversed downward because it is convenient to have the sensing head in the up position after each run to check the zero standard. The sensing head is mounted on and travels with two linear ball bushings (see Fig. 5).

The concept for the stage is based upon a design developed by others.³

* Daytronics Model DS-200.

** Daytronics Model 300D72.

*** Texas Instruments Model FL03W6D.

Fig. 5. Overall View of Profilometer

F. Adjustability

Since the error of an LVDT is proportional to the calibrated range, low-range LVDT's were used (calibrated range ± 0.020 in.). This made it necessary to mount the LVDT's on precision dove-tailed slides to make the unit adjustable for various sizes of capsules.

G. Error Analysis

After the system was defined, it had to be analyzed to determine the principal sources of uncertainty so that realistic design limits could be assigned to each source.

Practical limits for each source of error were determined prior to the start of detailed design; see Appendix B. In summary, these sources are as follows:

(1)	Lack of perpendicularity between sensor and capsule (capsule bow)	$\pm 75 \times 10^{-6}$ in.
(2)	Transducer error	$\pm 30 \times 10^{-6}$ in.
(3)	Lack of parallelism between contact probes	$\pm 50 \times 10^{-6}$ in.
(4)	Recorder error	$\pm 50 \times 10^{-6}$ in.
		<hr/>
		$\pm 205 \times 10^{-6}$ in.

With a completely random distribution on the sign of any individual error, the achievable accuracy should have an uncertainty of less than 200×10^{-6} in.

Other sources of error that are recognized but not quantified are (a) contact-probe wear, and (b) lack of correlation of measuring positions for preirradiation and postirradiation data.

The largest error source when comparing pre- and postirradiation data is that associated with azimuthal positioning. The operator attempts to position the capsule so that the wire wrap is facing him at the level of the probes. Because the wire is cutting across this point at an angle, it is difficult to position the capsule the same way each time. For a capsule whose major diameter is 0.001 in. greater than its minor diameter, a 5°

azimuthal misplacement introduces an error as high as $\pm 88 \times 10^{-6}$ in. Many general and some unique design features have been incorporated to minimize these sources of error. These design features are briefly described in Sections III and IV.

III. GENERAL DESIGN FEATURES

A. Capsule Orientation

The capsule (or element) is held in a vertical position by an air-operated chuck* (see Fig. 5). Unlike conventional Jacobs chucks, this chuck has only radial movement of the jaws. Repeatability of the axial location of the measurement is ensured by seating the capsule against a stop in the chuck. The chuck does not impart any axial motion to the capsule as it closes, so the axial repeatability is not lost. When a capsule is inserted in the chuck and the sensing head is in the full-up position, the probes are then 4.906 in. from the end of the capsule. A cam-actuated switch mounted on the ball screw gives a position indication on the chart paper every 0.2 in., corresponding to the lead of the screw. With the capsule against the stop in the chuck, the estimated accuracy of axial placement is ± 0.05 in.

B. Framework

The framework or structural support of the unit is composed of two vertical, parallel linear ball shafts.³ The sensing head is mounted on a 4-in.-dia split-ball bushing. Adjustment of the ball bushing provides axial stability for the sensing head, and the 2-in. parallel ball shaft provides azimuthal stability for the sensing head.

C. Drive Mechanism

The capsule is held stationary and the sensing head is driven downward with respect to the capsule during gauging. A precision ball screw

*The air-operated chuck was designed by J. Pilger of Battelle Memorial Institute, Pacific Northwest Laboratory.

drives a ball nut attached to the sensing head. The unit was originally constructed with a lead screw, which proved unsatisfactory because of excessive wear of the follower nut.

IV. UNIQUE DESIGN FEATURES

The following is a discussion of some of the error sources and the unique design features that were incorporated to minimize them.

A. Capsule Bow (Roller Guides)

To maintain the system uncertainty at less than $\pm 200 \times 10^{-6}$ in., it is necessary to keep the capsule perpendicular to the sensor axis within $\pm 1.0^\circ$. (One degree causes an error of 75×10^{-6} in., and 2° causes an error of 225×10^{-6} in.) Because most capsules and elements are quite slender and susceptible to bow, roller guides were provided to reduce the bow. The bottom diagram of Fig. 3 shows the spring-loaded roller guides that were incorporated for this purpose.

B. Transducer Error (Roller Guides)

To maintain a transducer error of less than $\pm 30 \times 10^{-6}$ in., a low-range LVDT was specified. The uncertainty of an LVDT is of the order of 0.15% of the calibrated span, so a usable range of ± 0.020 in. was selected. The capsule must be centered between the LVDT's within this range, and the above-mentioned roller guides provide this necessary function. Statistical observation of the completed unit indicates that the spring-loaded roller guides center a capsule within ± 0.005 in.

The transducers must also be movable to make the unit adjustable for the full range of capsule sizes. This adjustment is achieved by mounting the LVDT's on precision dovetailed slides.

C. Contact-probe Wear (Air Bearings)

Because the air-bearing ram can be removed from the wrapper without disturbing the alignment of the sensing head, it is very easy to monitor the the contact probes for wear. The rams are removed and checked on an optical comparator.

An air cylinder is connected to the back end of the air-bearing ram to make it retractable. The contact probes are retracted when a capsule is being inserted or removed from the sensing head and when the sensing head is being returned to its starting position.

To further reduce contact-probe wear, it was decided to use sapphire for the contact probes. Sapphire is the hardest homogeneous material available except for diamond. (Because sapphire was not available at the time the machine was assembled, tungsten carbide was substituted; however, sapphire was used on the second unit built.)

D. Correlation of Pre- and Postirradiation Data (Spiral Cams)

To profile a capsule with a spirally wrapped spacer wire, it is necessary to rotate the capsule azimuthally as the sensing head moves axially along the capsule. In order to correlate pre- and postirradiation data, the relative motions of head and capsule must be highly repeatable. The capsule is held by an air-operated chuck, which is rotated as the sensing head moves down the capsule. Our experience shows that speed regulation on variable-speed motors varies enough with load and operating conditions that two variable-speed motors cannot be "synchronized" to produce a uniform and repeatable spiral pitch. A servo-feedback control system might have provided "synchronization," but it was felt that a direct mechanical linkage between capsule rotation and sensing-head travel would be sufficiently accurate and considerably more reliable. To maintain a precise relationship between azimuthal and axial displacement, a cam and cam follower were incorporated (see Fig. 5). The cam follower is mounted on the sensing head. As the sensing head moves axially along the capsule, the cam follower engages the cam, which in turn drives the chuck that holds the

capsule. Two cams, one a 6-in.-pitch and the other a 12-in.-pitch, are available.

To correlate pre- and postirradiation data, the azimuthal position of the capsule for the two measurements must be nearly the same. As an example, a capsule whose major diameter is 0.001 in. greater than its minor diameter would record a measurement error of about 10×10^{-6} in. for a 1° displacement between azimuthal positions (Appendix B, Section 3). An initial positioning error would cause only a small error in the data. With a cam drive, this error would remain constant over the length of the capsule. However, if the error were able to change by $\pm 2^\circ$ per revolution, a cumulative error of $\pm 20^\circ$ over the length of a capsule would result in a diameter error of $\pm 120 \times 10^{-6}$ in.

An auxiliary variable-speed drive motor is provided to turn the chuck to accommodate a variety of nonstandard wire-wrap pitches. This drive motor can also be used to run capsules with a nonuniform wire wrap by manually adjusting the speed. It also allows running of eccentric standards by rotating the chuck without moving the sensing head.

For capsules that are not wire wrapped, measurements have normally been made at 0° and 90° with respect to the spade. Recently, measurements have been made with the capsule rotating azimuthally while the sensing head traverses the length of the capsule. If the capsule is not round, then the capability exists to determine the major and minor diameters of the capsule several times during each inch of sensing-head travel. This method also obviates the need for precise azimuthal positioning.

V. RESULTS OF ACCEPTANCE TESTING

A. Zero Shift.

Based on statistical observations of more than 200 events, the unit has a random zero shift of less than $\pm 40 \times 10^{-6}$ in.

B. Linearity.

Linearity of the completed unit was checked with a commercial precision-

stepped standard. Each step was measured to be the specified dimension within $\pm 20 \times 10^{-6}$ in. The smallest minor division on the linearity trace was 0.10 in. of chart paper for 200×10^{-6} in. displacement of the transducer. On the assumption that it is unwise to interpolate any scale to a value of less than half the smallest division, it is safe to say that the profilometer will measure round, straight rods with an uncertainty of less than $\pm 100 \times 10^{-6}$ in.

C. Repeatability.

Since most of the capsules to be gauged are neither perfectly round nor straight, it was felt that additional acceptance testing was necessary.

An unirradiated, spirally wrapped capsule containing depleted uranium was obtained. It had been thermally cycled at reactor operating temperatures. It was first measured with the DR-25 optical gauge,² and then run five times in the profilometer. Fifty-five points were compared; the average deviation was less than 55×10^{-6} in.

Adding the uncertainty of the DR-25 ($\pm 40 \times 10^{-6}$ in.) and the zero shift, the repeatability of the profilometer in normal operating conditions is within $\pm 135 \times 10^{-6}$ in.

To increase the throughput of the unit, the allowable zero shift was increased to $\pm 100 \times 10^{-6}$ in. A zero standard is checked before and after each capsule is gauged. If the zero shift is greater than 100×10^{-6} in., the run is considered invalid. The zero shift is recorded at the end of each run. Even with 100×10^{-6} in. of zero shift, the repeatability is within $\pm 195 \times 10^{-6}$ in. and the confidence level is high.

VI. OPERATIONAL EXPERIENCE

During the first year of operation of the first profilometer (unit 1), it gauged over 490 capsules, equivalent to about 2150 lineal feet of profilometry. The zero shift for this period averaged $\pm 45 \times 10^{-6}$ in. The maximum rate of operation was 23 capsules in an 8-hr shift, and the average was about nine capsules in an 8-hr shift. Figure 6 shows a typical profilometer trace.

Fig. 6. Typical Profilometer Trace

Unit 1 was removed from the cell for inspection after five months of operation. The lead screw that drove the sensing head was replaced with a precision ball screw. The natural-rubber tubing that supplied air to the air bearings was replaced, having deteriorated from exposure to radiation. The contact probes were inspected on an optical comparator and no wear was noticeable.

Unit 1 was in the cell for a total of 27 months. During the last six months it gauged 311 capsules, and its zero shift for that period averaged $\pm 44 \times 10^{-6}$ in.

Unit 2 is now in-cell and has operated for six months. It has gauged 758 capsules, and its zero shift has averaged $\pm 38 \times 10^{-6}$ in.

VII. IMPROVEMENTS

Two additional profilometers of a similar type were constructed. Based on operating experience with the first unit, the following improvements were made:

- (1) Precision dovetailed slides with antibacklash nuts were used to reduce the zero shift.
- (2) The diametral capacity was increased from 0.500 to 0.805 in. by increasing the throw of the roller-guide arms to allow acceptance of larger-diameter capsules. Because the profilometer chuck only accepts capsules up to 0.500 in. in diameter, a collet-type chuck was designed and fabricated to accept 0.805-in.-dia capsules; the upper end of the collet-type chuck can be inserted into the profilometer chuck.

The following additional improvements were planned but not carried out because of budgetary problems:

- (3) Analog data including azimuthal position, axial position, and diameter were to be digitized for input to a Datacraft 6024-3 computer. A remote teletype station was to be provided to allow additional information such as burnup and flux density to be stored.
- (4) Data were to be displayed on a graphic-display terminal. The terminal was to produce printed copies of the diameter profile

in an 8½ x 11-in. format.

A future aim at the HFEF is to investigate the use of an optical non-contact profilometer. Its principal advantage is that most of its components can be located out-of-cell in an uncontaminated area.

APPENDIX A

Evaluation of Sensing Systems

1. Proximity Gauges - Pneumatic and Capacitance

These gauges are characterized by being very accurate over a narrow measurement range. As the measurement range is increased, the accuracy drops off. To get the accuracy that is required, these gauges would have a measuring range of only about ± 0.001 in. Some of the capsules that we measure have diameter changes of 0.010 in. or more, so these gauges were considered inadequate for our application. Capacitance gauges also depend on a uniform dielectric, which a fuel pin would not have.

2. Photo-optical Sensors

The art of gauging with photo-optical sensors is advancing rapidly. In general, the capsule to be measured is placed between a source of parallel light rays and a photodetector tube. The diametral signal is proportional to either the amount of light incident upon the tube or the time required to sweep between the light/dark interfaces on each side of the capsule.

References 1, and 4 give additional information about the photo-optical systems considered. None were considered to be sufficiently advanced at the time this unit was being designed.

3. Laser Interferometry

Laser interferometry systems are extremely accurate and have a more than adequate linear range. Investigations were made of the feasibility of using the capsule surface as a reflector to avoid the need for a corner cube reflector mounted on a contact probe. None of the laser-system vendors contacted felt that it was feasible to operate the system without the corner cube reflector.

At the time LVDT's were selected, it was felt that mounting a corner

cube reflector on a contact probe would introduce too much error into the system to allow taking advantage of the extreme accuracy of a laser interferometry system. The experience with the present system indicates that this initial premise may not be valid.

4. Optical Relay

The Bausch & Lomb DR-25B optical gauge² is an optical amplifier. Images of the main scale (which is on the same axis as the measuring spindle) and a vernier scale are projected and magnified with lenses and optical levers onto a ground-glass screen. The HFEF has been using these gauges in-cell for several years. Our experience shows that with careful use, it is accurate to within $\pm 40 \times 10^{-6}$ in. Its chief drawback is that it will not make continuous measurements, and consequently, it is a costly and time-consuming tool to operate, particularly for a remote operation.

5. LVDT's

An LVDT (linear variable differential transformer) is an electro-mechanical transducer that produces an electrical output proportional to the movement of an iron core in a magnetic flux (see Fig. 7). A constant

Fig. 7. Diagram of LVDT

voltage is put on the primary coil, and when the secondary coils are connected to give a differential output, this output will vary linearly with

the position of the core. At a position where the core is centered and the resultant voltage in each secondary coil is the same, the differential voltage will be zero and the LVDT is nulled. Movement of the core in one direction will produce a positive voltage and in the other direction a negative voltage. The output is resolvable to within 0.1% of full-range output. LVDT's are simple, reliable, and rugged. They are stable over a wide temperature range and are inherently stable in a radiation environment.

APPENDIX B

General Sources of Error

1. Use of Cylindrical Contact Probes

If the probes are right circular cylinders with their axes mounted at 90° to the axis of the capsule, the probes must be parallel to each other; e.g., if contact probe A is not parallel to contact probe B, then movement

of the capsule in the Y direction will cause an error equal to the deviation from parallelism. A supplier of sapphire rods has been found who will supply rods with a cylindrical tolerance of 50×10^{-6} in. (This tolerance means that the surface of the rod must lie between two concentric cylinders, one having a radius 50×10^{-6} in. greater than the other).

Two cylinders mounted parallel to each other cannot have a tolerance zone less than the sum of the tolerances of both of the cylinders.

With the best techniques known at present, two cylindrical contact probes will introduce an error of at most 100×10^{-6} in. All error calculations are based on a capsule diameter of 0.375 in.

2. Use of Spherical Contact Probes

If two spherical contact probes are used, error can be introduced by measuring a chord of a circle instead of the diameter, unless the axes of both probes line up with each other and the centerline of the capsule.

The error introduced as a function of deviation from the theoretical centerline is tabulated below.

<u>Deviation, 10^{-3} in.</u>	<u>Error, 10^{-6} in.</u>
1	5
2	22
3	48
4	65
5	133

3. Capsule Orientation (Azimuthal Coordinate)

If a capsule has an ellipsoidal configuration, it is essential that the postirradiation measurement be made as close to the azimuthal coordinate of the preirradiation measurement as possible. The maximum error introduced per degree of misalignment occurs at an azimuthal coordinate midway between the major and minor diameters.

For a capsule with a 0.001-in. difference between the major and minor diameters, the difference between d_0 and d_1 per degree of angular misalignment at $\alpha = 45^\circ$ would be about 10×10^{-6} in.

Consequently, it is necessary that azimuthal orientation be repeatable to within $\pm 2^\circ$. It is not felt that visual positioning through a 5-ft-thick shielding window or a periscope will allow azimuthal control to within $\pm 1^\circ$.

4. Angular Misalignment of Contact Probe in X - Y Plane

If the horizontal axes of the transducers are misaligned, an increase in capsule diameter in the X direction will cause a component of movement along the transducer axis X' that will be larger than X. The error introduced for a 5° misalignment will cause an error of 3×10^{-6} in. per mil of capsule diameter increase. For a capsule with a 10-mil growth, this error would then be 30×10^{-6} in.

5. Lack of Perpendicularity Between Transducer and Capsule

For a 1° divergence from perpendicularity between the transducer axis and the capsule axis, an error of 75×10^{-6} in. will be introduced. Error as a function of angular misalignment is tabulated below.

<u>Degrees</u>	<u>Error, 10^{-6} in.</u>
1	75
2	225
3	525
4	902
5	1403

6. Recorder

The best recorder that has been identified to date has an accuracy of approximately $\pm 0.25\%$ of span. Assuming a 20-mil span, the error introduced would be $\pm 50 \times 10^{-6}$ in. (100×10^{-6} in. total).

7. LVDT

The best accuracy quoted for an LVDT without linearity compensation is 0.15% of span. Assuming a 10-mil span on each side of the null point, the error introduced by an LVDT would be $\pm 30 \times 10^{-6}$ in.

8. Summary of Error Sources for Cylindrical Contact Probes

Parallelism of contacts	$\pm 50 \times 10^{-6}$ in.
Capsule orientation	$\pm 20 \times 10^{-6}$ in.
Angular misalignment in X-Y Plane	$\pm 30 \times 10^{-6}$ in.
Perpendicularity of capsule and transducers	$\pm 75 \times 10^{-6}$ in.
Recorder	$\pm 50 \times 10^{-6}$ in.
LVDT	$\pm 30 \times 10^{-6}$ in.
Total	$\pm 255 \times 10^{-6}$ in.

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