REFERENCE

CORE RADIAL DISPLACEMENT TRANSDUCER

DESIGN EVALUATION REPORT

WANL-TMI-1845

October 25, 1967

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FOREWORD

This report, WANL-TMI-1845, describes a strain gage displacement transducer designed and tested by the Westinghouse Astronuclear Laboratory for use on NRX-A6.

The project was initiated February 4, 1966 with the establishment of the displacement measurement as a requirement for NRX-A6 Instrumentation. Evaluation of the final design was completed August 1, 1967 .

ABSTRACT

The purpose of this report is to document the evolution and capabilities of the Core Radial Displacement Transducer. Pertinent details of the transducer history (Measurement Definition, Basic Design Equations and Evaluation Program) are included to substantiate the evolution.

SUMMARY

The solution to several design problems was required for a successful transducer. The first requirement, high radiation environment, was met with the use of Inconel (transducer structure) and the weldable strain gage sensor. Both of these items were considered qualified to the environment by successful usage on previous reactors. Similarly, both were considered qualified for the temperature variations of the environment.

With the acceptance of these two items, the mechanical configuration of the transducer was evolved. Successful qualification of the final transducer design to all non-radiation requirements was accomplished through the facilities of the Instrumentation Laboratory and the Engineering Mechanics Laboratory. The transducer was included in the Engineering Mechanics Vibration Test Program of the Partial Core. Additional testing of the transducer was undertaken by Engineering Mechanics and is documented in Reference Item Five.

INTRODUCTION

The measurement, Radial Displacement of the Core, was requested by Reactor Design. The working environment, however, was not completely defined at that time but was slowly resolved during the transducer program. Reactor Design used NRX-A5 as the primary source for the operation environment definition.

OPERATIONAL ENVIRONMENT

Radiation Level: As anticipated for the Reflector Outlet Plenum

Temperature: 200° to 540°R

Vibration: 2.5 G at 240 cps

DESIGN REQUIREMENTS

Parameter: Mechanical Displacement of 0.600 inch

Accuracy: $\pm 2.5\%$ of full scale

Configuration Envelope: The sensor pickup shall follow the motion of a plunger. As defined in layout drawing 938J290, the maximum allowable dimension in the path of motion is 1.000 inch. One direction only (at right angles to the path of motion) shall be available for the body of the transducer.

Spring Loading: To provide a plunger force of 1.0 pound minimum, 10.0 pounds maximum over the displacement range.

DISCUSSION

The Introduction describes the need for a transducer that could measure a ± 0.300 inch movement accurately, be relatively unaffected by the environment and fit within a rather restricted configuration.

The cantilever beam was regarded as ideal for this measurement. The strain gage was already qualified for the environment and a preformed cantilever beam would allow the transducer to fit within the configuration requirements. The preformed beam would, in addition, supply its own spring loading and by proper design (See Reference No. 1) permit maximum output from the strain gage and optimum linearity characteristics.

The first designed transducers were a combination of two basic types of cantilever beams as suggested in the referenced document. Six transducers, fabricated according to this design were evaluated. Several variations in fabrication were attempted; however, each transducer when flexed over the designed range of 0.65 inches, failed. The data indicated that the transducers were never excursed past their design limit of 6000 microstrains in either tension or compression. Two possibilities appeared as causes for the failures; (1) Strain levels of ± 6000 microstrains were beyond the capability of the sensor, or (2) a critical level of strain was being placed on the sensor at some point other than the strain element.

With these points in mind, the transducer was redesigned. The upper limit for the gage over its full scale excursion of minus 0.30 inches to plus 0.30 inches was set at 3500 microstrains. The basic design of the original beam was accepted requiring only dimensional changes to allow full-scale excursion at a lower strain level. The End Cap was lengthened to allow for a cable strain relief if necessary. Several additional factors were included in the calculations for the beam curvature and deflection:

- (1) If evaluation of the new design indicates that higher strain levels (i.e. higher output) can be attained without failure, the beam should have the capability of being easily modified. Specifically, the beam must have sufficient displacement from horizontal initially to allow a shorter beam to have a relaxed displacement of at least 0.350 inches below horizontal. (This position is referred to as minus 0.350 inches)
- (2) Spring loading over the full scale excursion should be greater than one pound but less than ten pounds.
- (3) Since the addition of the strain gage to the beam changes the natural displacement of the beam, allowance should be made in the original curvature.

Equations were established by the expedient of loading diagrams and new dimensions were then calculated.

The equations (See Appendix for symbol definition)

$$d = \frac{5.82 PL^3}{Eb_o h^3}$$

$$e_{\text{beam}} = (2.300) (10^{-3}) d$$

$$e_{\text{gage}} = (3.998) (10^{-3}) d$$

were derived to describe the deflection and strain levels of our specific beam and gage.

During fabrication of the detail parts per the new dimensions, nearly all of the beams were found to deviate from the drawings. The beams were carefully checked and each beam was found to have various radii of curvature along its length. Any deviation from a constant radius of curvature would cause a certain amount of non-linearity; however, it would have been unreasonable to attempt to calculate the degree of non linearity for each transducer. In addition, schedules did not permit sufficient time to have the beams recurved and heat treated. The choice was to make the transducers and evaluate their performance or have no transducers at all. The beams were accepted on that premise.

During testing, the third unit, fabricated according to the new design, failed after only 200 cycles over the range minus 0.620 inches to plus 0.356 inches. This corresponded to a strain range of approximately 3000 microstrains tension and 1900 microstrains in compression. Over a range minus 0.300 to plus 0.300 inches, the beam had an excursion of approximately 3000 microstrains. The realization here was that the beam not only could not be shortened but must be further restricted in allowable travel.

Accordingly, the transducer hardware was modified with the addition of a pin which would limit the deflection of the beam. Strain excursion in tension was thus limited to approximately 2500 microstrains maximum.

The remaining evaluation transducers were successfully tested and found to have an average error band (including linearity, repeatability and hysteresis) of $\pm 1.5\%$ of full scale. The worst case was $\pm 3.3\%$ of full scale.

Later the evaluation transducers were recalibrated in terms of output voltage (instead of microstrains) and given to Engineering Mechanics for inclusion in their testing program involving the Partial Core. Throughout the static tests, the correspondence between the transducers and the dial position indicators was checked. During portions of the dynamic tests, the transducers indicated oscillatory motion. At first, this was believed to be due to resonance of the transducer beam. Subsequent testing and data analysis resolved the resonance to exist in the test fixture producing an actual (low amplitude) motion of the core relative to the reflector.

Additional testing to determine the resonance frequencies of the transducer was also accomplished by Engineering Mechanics. Their results indicated a fundamental resonant frequency existing in the frequency band 360 cps to 400 cps. Significantly, calculations by Sensor Application Engineering anticipated this result.

The equation assumed is standard for a uniform cantilever beam. The equation constant is for the condition: Beam fixed on one end and simply supported on the other.

$$f = c \sqrt{\frac{E I}{\omega L^4}}$$

$$\begin{aligned} \text{where } c &= 2.45 \\ g &= 386 \text{ in/sec.}^2 \\ E &= 30 (10^6) \text{ pounds/in}^2 \\ L^4 &= 256 \text{ in}^4 \\ *I &= 6.18 (10^{-6}) \text{ in}^4 \\ *\omega &= 0.0128 \text{ pounds/in} \\ \text{and } f &= 368 \text{ cycles/sec.} \end{aligned}$$

* Although the moment of inertia varies along the length of the beam, the weight per unit length also varies such that the ratio remains constant. The I and ω selected were at the base of the beam.

Evaluation of the data revealed large deviations from the anticipated results. The strain levels actually achieved by the gages varied from 9.0% below to 15.0% above the predicted values. It is believed that the beams with their inconstant radius of curvature could be responsible for the variation in the readings.

All beams experienced an increase in the absolute strain level and in the differential strain readings when the strain gage cables were brazed in place. The greatest change was 18.5% above the prebrazing readings. The only possible source for this increased strain is the strain gage assuming a portion of the cable strain. As the cable cools from brazing it places a strain on both attachment points. Similarly, as motion of the beam increases angular distance between the two attachment points, the cable strain will increase. Even with this variation in individual strain characteristics, the actual signal error band (including linearity, hysteresis and repeatability) for every reactor designated transducer was less than 2.024% of full scale. The worst case was on one evaluation transducer that had an error band of 3.3% of full scale.

CONCLUSION

The transducer has been evaluated on the basis of meeting the original design requirements including environmental conditions. The test program has subjected the transducers to conditions exceeding the requirements. The transducers successfully passed all criteria for the measurement requirements; therefore, the transducer is considered adequate for the measurement.

APPENDIX I

To arrive at the final equations for the transducer beam, we started with the basic equations for a beam of constant cross section and a beam of variable cross section, where:

b	=	Width of the beam at any point
b _o	=	Width of the beam at the base
d	=	Deflection of the beam from horizontal
e	=	Strain
e _b	=	Beam Strain
e _g	=	Gage Strain
E	=	Modulus of elasticity
h	=	Beam Thickness
I	=	Moment of Inertia
L	=	Length of Beam
M	=	Loading Moment
P	=	Pressure applied Vertically
S	=	Stress

By definition:

$$(1) \quad S = Ee = \frac{M(h)}{I(2)}$$

$$(2) \quad M = PL$$

$$(3) \quad I = \frac{bh^3}{12} \text{ (Rectangular moment about center axis)}$$

APPENDIX II

STABILIZATION PROGRAM

The following program was found to be necessary to stabilize the operation of the Strain Gage and Beam. The sequence of events and cycling parameters were determined with the evaluation units. As determined, the program was implemented on all units designated for NRX-A6 Test.

1. Install Strain Gage.
2. Mechanically cycle the beam for fifty cycles.
3. Heat soak the transducer for two hours at 600°F.
4. Mechanically cycle the beam for fifty cycles.
5. Temperature cycle the transducer (two cycles) ambient to -320°F to + 200°F to ambient.
6. Mechanically cycle the beam for fifty cycles.
7. Calibrate the transducer.

FIGURE NO. 1 WELDING OPERATION

FIGURE NO. 2 STRAIN GAGE WELDED TO BEAM

FIGURE NO. 3 TRANSDUCER IN CALIBRATION HOLDING FIXTURE

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FIGURE NO. 4 TEMPERATURE CYCLING

FIGURE NO. 5 CALIBRATION

REFERENCES

1. Memo J. Soo to R. R. Swope dated April 11, 1966
2. Memo D. C. Thompson to R. R. Swope dated March 24, 1966
3. WANL TME 1615 dated May, 1967
4. WANL TME 1636 dated June, 1967
5. WANL TMI 1816 dated August 1, 1967