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PROTOTYPE GAGES TO MEASURE PLATE SPACING
IN FLAT FUEL-PLATE SUBASSEMBLIES

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PROTOTYPE GAGES TO MEASURE PLATE SPACING IN FLAT FUEL-PLATE SUBASSEMBLIES

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The feasibility of two types of gages for measuring the plate separation in flat fuel-plate subassemblies was investigated with experimental model gages. One gage is based on a four-arm strain-gage bridge mounted on a flexible beryllium-copper beam. The deflection of the sensing beam as the gage traverses the channel is continuously recorded by a strain-gage analyzer. The second gage is a liquid-filled system consisting of a small flat plunger-and-cylinder arrangement. A rubber diaphragm between the piston and the cylinder serves as the seal. As the element is inserted in the space between the plates, the piston is forced into the cylinder. The liquid, distilled water, thus displaced expands an external bellows. The variable expansion during a scan is measured by a differential transformer and recorded.

The recorded output from either gage is directly proportional to the actual channel spacing and is reproducible to within 0.001 in. The general performances of the two gages are equivalent except that an error of about 0.001 in. is introduced into the calibration of the hydraulic gage for each 3 F change in ambient temperature. The strain-gage-type gage is temperature compensated.

INTRODUCTION

To insure the proper flow of coolant through the core of pressurized-water reactors, it is necessary to hold the water-channel spacing between the fuel plates within specified limits. To determine whether design specifications have been met during fabrication, a device is needed to measure, and also to record, the channel spacing in the completed subassemblies. The objective of this research program was to develop a suitably accurate and reliable prototype space-measuring gage within the scope of the following design and performance specifications established by the Bettis Plant of the Atomic Energy Commission:

- (1) The sensing elements must be designed to measure plate separations as small as 1/16 in.
- (2) A satisfactory method should measure the channel spacing to 0.0005 of an in.
- (3) The prototype gage must penetrate at least 48 in. into the channel.
- (4) The sensing element must be designed to approach within 1/4 in. of the edge of the channel so that in combination with two other gages the spacing along both edges and at the center of the channel can be determined simultaneously.

- (5) The surface of the sensing part of the gage contacting the channel walls should be less than 1/4 in. square and either made of or plated with a material compatible with the fuel plate.
- (6) The sensing element must be mechanically designed to permit easy insertion into the channel and to minimize damage by channel perforations or careless handling.
- (7) Readout and recording instrumentation should be specified.

Mock-up or breadboard models of the gages were to be constructed as necessary to demonstrate the feasibility of the method selected.

RESEARCH AND DEVELOPMENT PROGRAM

After considering various possibilities, two basically independent methods for measuring water-channel thickness appeared to be equally promising:

Method 1 was based on the use of strain gages on a deforming sensing member.

Method 2 was based on a hydraulic system incorporating a liquid-filled expandable sensing element.

Both systems were studied concurrently.

The Strain-Gage-Type Space Gage

The potential reliability and temperature independence of strain-gage systems and the general availability of commercial strain-gage data readout and recording systems were the principal reasons for the interest in this method. Space-gaging instruments of this type have been used at Bettis with fair success. The sensing unit in the Bettis instruments is essentially a pair of fingerlike spring feelers attached at one end to form a vee. Strain gages measure the deflection of the feelers as they follow the varying thickness of the channel. The problems with this system to date have been the nonlinearity of the response and the susceptibility of the sensing unit to damage caused by snagging in index or sample holes as it moves between the plates. In the present research, after considering many and testing several designs, an experimental prototype space gage similar to the one shown schematically in Figure 1 was developed which overcame these objections.

The deforming or sensing member is basically a triangular section in which the stresses at each point on the surface are nearly equal. This makes the placement of the strain gages less critical and duplicate gages can be made with similar characteristics. A right triangular shape was selected so that the device could scan close to the edge of the channel.

FIGURE 1. SCHEMATIC OF THE STRAIN-GAGE-TYPE SPACE GAGE FOR MEASURING WATER-CHANNEL SPACING IN FLAT FUEL-PLATE SUBASSEMBLIES

The deflecting beam and its surrounding support were made of 0.006-in. tempered beryllium-copper sheet, an alloy compatible with the channel material. The beam support was reinforced with 0.010-in. beryllium-copper sheet to cause practically all of the bending to take place in the triangular beam as the upper and lower contacts moved relative to each other. The pieces were tinned, clamped together, then joined while they were being tempered.

The active element was mounted in a recess milled into a stainless steel gage frame which carries it through the channels. Motion of the free end of the deflecting beam and its support is restrained by thin plates on the top and bottom of the leading edge of the gage frame. With this configuration all parts of the sensing unit, with the exception of the upper and lower contacts, are protected by the frame. Damage to the gage as it moves through the channel is unlikely.

To help insure the proper functioning of the gage, the bottom of the gage frame under the deflecting beam should be held snug against the channel surface during a scan. In the prototype gage, this was accomplished by slightly curving the frame just behind the sensing element. A leaf-type hold-down spring might be more satisfactory.

The lower contact and the gage frame position the beam root with respect to one side of the channel. The upper contact rides against the opposite side. The sharp bend was placed in the deflecting beam to provide a positive contact point which is always the same distance from the beam root. If the beam was straight or only slightly curved, the contact point would shift as the beam was deflected.

Four Baldwin-Lima-Hamilton SR4-A19 strain gages (1/16-in. gage length) were mounted two on each side of the deflecting beam as the components in a four-arm bridge.* This arrangement provides maximum signal and temperature compensation. They were attached with Duco cement. Good surface-bonding techniques and careful drying were required for accurate results. The 0.006-in. -diameter wire leads were joined directly behind the root of the deflecting beam to form the bridge. The four bridge leads were connected in turn to 30-gage enameled wire leads-out conductor laid in a groove milled the length of the gage frame.

The gage characteristics were statically determined by clamping the gage frame firmly on a flat plate and deflecting the beam with a micrometer screw head mounted perpendicular to the plate. The output of the strain-gage bridge was measured with a Baldwin-Lima-Hamilton strain-gage indicator. Figure 2 shows the output of the indicator as the beam was deflected. The data indicated that the output is directly proportional to the actual displacement of the upper contact point and is reproducible within 0.001 in. over a 0.040-in. range. Thus, it appears that changes in plate separation of 0.001 in. or less should be detectable. The device appeared quite stable in all respects. (The 0.006-in. -thick deflecting beam represents a compromise. Tests on beams of the same size and shape but of different thicknesses showed that thicker beams had better linearity but poorer reproducibility due to hysteresis effects. Thinner beams had better reproducibility but relatively poor linearity.)

*It was originally planned to use Tatnall Metalfilm etched-metal strain gages. These were thought to have some advantage over the SR4-A19 gages in that they (1) are smaller, (2) will take a somewhat higher stress, (3) have a higher electrical resistance, 120 ohms compared with 60 ohms for the SR4 gages, and (4) are easier to mount. However, poor delivery schedules prevented an adequate evaluation of these gages. If additional models of the strain-gage-type space gage are built, the Tatnall strain gages should be considered.

FIGURE 2. STRAIN-ANALYZER OUTPUT DATA VERSUS BEAM DEFLECTION FROM STATIC TESTS ON THE STRAIN-GAGE-TYPE SPACE GAGE FOR MEASURING WATER-CHANNEL SPACING IN FLAT FUEL PLATE SUBASSEMBLIES

The gage was dynamically tested between two 2-1/2 by 48-in. steel plates shimmed and clamped at 3-in. intervals to provide a variable separation. The plate separation at each station was checked with feeler gages with an estimated accuracy of ± 0.0005 in. The mocked-up channel was mounted on the tool carriage of a shop lathe. The sensing element was inserted between the plates and the gage frame held immobile while the tool carriage traversed back and forth. This, in effect, simulated an automatic scan of the plate by the gage. The output of the space gage was recorded on a Sanborn strain analyzer. Figure 3 shows the results of a typical scan of a section of the plates made in both directions. The scanning speed was 8-1/2 in. per min (maximum lathe speed). The results of the static tests were verified. A comparison of the recorded gage output and the plate spacings as determined by the feeler gages indicated that the instrument had a linear response. The reproducible data and their agreement with the feeler-gage measurements indicated an instrument accuracy of ± 0.001 in. This is less than the 0.0005-in. accuracy hoped for but is still considered good for the first prototype gage. A further indication of the sensitivity of the instrument was the detail with which the surface roughness of the plate was reproduced. Repeated passes through the channel produced no evidence of wear or damage to the gage.

The Hydraulic Space Gage

In principle, the hydraulic space gage consists of a small expandable element such as a bellows or capsule which is inserted between the fuel plates. The sensing element is connected by a tube or conduit to another expandable element outside the subassembly. The system is filled with a hydraulic fluid. By loading the system, the sensing element is expanded against the surface of both fuel plates. As the element penetrates the channel, an increase or decrease in the channel spacing will allow it to expand or cause it to be compressed accordingly. The displacement of the fluid within the sensing element will be transmitted hydraulically to the outside element. The corresponding contraction or expansion of the responding element can be measured and recorded by standard techniques. It was originally considered that this system might have a better chance of providing a linear response than the strain-gage-type gage.

The development of this method, however, posed several problems:

- (1) An expandable element which could be inserted into the small space between the fuel plates and which would be sensitive enough to follow accurately variations in channel spacing had to be designed and fabricated.
- (2) The entire hydraulic system had to be so designed that its resistance to fluid flow was low enough to permit it to respond without lagging at reasonable scanning speeds. This meant that the system had to be very clean by hydraulic standards and required a low-viscosity fluid.
- (3) The amount of fluid displaced by a 0.0005-in. compression or expansion of the sensing element would undoubtedly be very small. Therefore, compressibility effects in the liquid and thermal expansion of the liquid relative to the gage itself could be sources of excessive error.

FIGURE 3. RECORDED STRAIN-ANALYZES DATA VERSUS ACTUAL PLATE SEPARATION FROM A SCAN OF A WATER-CHANNEL MOCK-UP BY THE STRAIN-GAGE-TYPE SPACE GAGE

Several designs for bellows and capsules were considered and evaluated experimentally with varying degrees of success. The most promising element design is shown schematically in Figure 4. It consists essentially of a small flat piston-and-cylinder arrangement with a rubber diaphragm seal. In the normal position, the element is fully extended and will just touch both plates. As it enters the space between the plates, the piston is forced into the cylinder. The liquid (distilled water), thus displaced expands an external bellows. The expansion is measured by a differential-transformer system and recorded. The spring tension in the bellows and the rubber diaphragm tend to return the piston to its normal position.

Deaerated distilled water was selected as the hydraulic fluid because of its low viscosity, low compressibility, and relatively low thermal coefficient of expansion. To make the differential thermal coefficient of expansion between the fluid and the gage frame as small as possible, and thus minimize temperature effects, the frame was made of brass. (In a production gage the brass would have to be plated with a material compatible with the fuel plates.)

The cylinder of the expandable sensing element is oval shaped and as large as possible to provide the largest practical cross section. This maximizes the volumetric liquid displacement-to-piston displacement ratio upon which the sensitivity of the gage depends. The diaphragm of 0.008-in. rubber was bonded into a recess around the top of the piston with 3M-EC-1357 cement. The small brass piston was bonded directly on the diaphragm. The sides of the piston were beveled to prevent snagging on index and sample holes in the fuel plates.

The hydraulic connection between the piston and cylinder and the responding bronze bellows was a thin-walled 0.040-in. -ID stainless steel tube soldered into a groove milled in the gage frame. The system was evacuated and filled with the distilled water through an auxiliary tube which was then sealed off. In the experimental gage, the core of a differential transformer was attached to the responding bellows. The output signal from the transformer was fed into an Acotran position recorder.

The static characteristics of the prototype hydraulic space gage were determined in a manner similar to that used with the strain-gage-type instrument. However, since there was some question as to how much transient variations in ambient temperature would affect the accuracy of the hydraulic system, the work was done in a room where the temperature could be controlled. The results of typical tests are shown in Figure 5. At constant temperature the recorded output was directly proportional to the displacement of the piston and reproducibly indicated incremental changes of 0.001 in. or less. However, a definite temperature effect was observed. Between 62-1/2 F and 78 F the gage had a maximum temperature coefficient of 0.00045 in. per F.

Dynamic tests on the hydraulic space gage were made using the shimmed plates and equipment described previously. Figure 6 shows the results of a scan at 4-1/2 in. per min. The slower scan was necessary because of the relatively slow speed of the Acotran position recorder. Faster scans appear equally feasible. Again, as long as the ambient temperature remained fairly constant, the response of the instrument was linear, and indicated an apparent accuracy of ± 0.001 in. The hydraulic gage appears to be rugged enough for production gaging.

FIGURE 4. SCHEMATIC OF THE HYDRAULIC SPACE GAGE FOR MEASURING WATER-CHANNEL SPACING IN FLAT FUEL-PLATE SUBASSEMBLIES

FIGURE 5. POSITION-RECORDER OUTPUT VERSUS PISTON DISPLACEMENT IN STATIC TESTS ON THE HYDRAULIC SPACE GAGE FOR MEASURING WATER-CHANNEL SPACING IN FLAT FUEL PLATE SUBASSEMBLIES

Actual Spacing Between Shimmed Plates at 3-In. Intervals, in.

A-29870

FIGURE 6. POSITION-RECORDER DATA VERSUS ACTUAL PLATE SEPARATION FROM A SCAN OF A WATER-CHANNEL MOCK-UP BY THE HYDRAULIC SPACE GAGE

EVALUATION AND SUMMARY

The feasibility of water-channel space-measuring gages, based on either the strain gage or hydraulic method, has been successfully demonstrated with experimental model gages. There is no apparent reason why production-type gages could not be built which would meet all of the design and performance specifications, except that an accuracy of ± 0.0005 in. may not be obtainable. The experimental gages were only capable of reliably measuring channel spacing to 0.001 in. While further development of the gages into production instruments would probably result in a general improvement in performance, it appears doubtful if accuracies better than ± 0.001 in. would be obtained at reasonable scanning speeds.

Scanning speeds up to 8-1/2 in. per min were entirely feasible with the experimental gages. At this rate an 8-ft channel could be examined in approximately 10 min. The present limitation on the scanning speed, however, was imposed by the scanning mechanisms rather than by the gage itself. The observed performance of the model gages indicated that scanning speeds up to 60 in. per min would not be unreasonable for a production gage if a suitable actuator was devised.

Both systems can be readily developed into a three-element gage for measuring each side and the center of the channel. The gage frame can be made as long as necessary to measure an 8-ft-long channel from one end only.

More than ordinary care must be observed in fabricating the space gages. Dimensions must be held very close if the gage is to fit into and function properly in the narrow channels. The possibility of modifying the design to measure channels as small as 0.030 in. has been discussed. While perhaps not impossible, it would require some refinement of either design to produce a gage this small.

The Sanborn 150 strain analyzer is an excellent data readout and recording instrument for service with either gage. (Unfortunately one was not available for the evaluation tests on the hydraulic gage.) Other similar and readily available commercial instruments, however, could probably serve as well.

There is little to choose between the strain-gage-type space gage and the hydraulic gage as far as potential performance is concerned. The hydraulic gage suffers by comparison only because of the error which might be introduced into its calibration by ambient temperature changes. In a constant-temperature room or in an area where the ambient temperature would not change more than 2 or 3 F during a scan, the hydraulic gage would probably be satisfactory. If a production gage is developed, the strain gage system should probably be considered first.

The development of a production gage would be straightforward and would require relatively little effort since the experimental model gages in their present configuration meet nearly all of the requirements. Most of the work would be along the lines of determining the performance limits of the gage, optimum scanning speeds, instrument life, etc.

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