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INSPECTION OF CANDU NUCLEAR REACTOR FUEL CHANNELS

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SYNOPSIS

It is insufficient to apply conservative design codes to nuclear generating stations; the condition and integrity of materials, components and structures must be continually evaluated through the operational life of the plant. This evaluation is achieved largely through the application of nondestructive test procedures. Most of the piping and pressure vessels in a CANDU nuclear generating station are surprisingly accessible but inspection of the core components, primarily the many hundred horizontal fuel channels, each consisting of a pressure tube and a coaxial calandria tube, presents a formidable problem. The main components of the problem are: access; radiation field in terms of degradation of sensitive components, detection, characterization and sizing of flaws; and certain spatial measurements which must be precise but performed remotely and automatically.

The Channel Inspection and Gauging Apparatus for Reactors (CIGAR) is a fully automated, remotely operated inspection system designed to perform multi-channel, multi-task inspection of CANDU reactor fuel channels. Ultrasonic techniques are used for flaw detection, (with a sensitivity capable of detecting a 0.075 mm deep notch with a signal to noise ratio of 10 dB) and pressure tube wall thickness and diameter measurements. Eddy current systems are used to detect the presence of spacers between the coaxial pressure tube and calandria tube, as well as to measure their relative spacing. A servo-accelerometer is used to estimate the sag of the fuel channels.

This advanced inspection system was commissioned and declared in service in September 1985. The paper describes the inspection systems themselves and discusses the results achieved to-date.

1. INTRODUCTION

At the present, Ontario Hydro is either operating or constructing 20 nuclear generating units of the CANDU type. Although there are several CANDU plants outside of the Ontario Hydro system, both within Canada and elsewhere, Ontario Hydro currently has the largest investment in these units and, thus, is at the forefront of development of ancillary systems designed to enhance reliability and efficiency.

Rather than having a single pressure vessel, such as the PWR/BWR design, the CANDU reactor utilizes several hundred horizontal pressure tubes to contain the natural uranium fuel, figure 1. Heavy water, D_2O, flows through the pressure tubes to cool the fuel at a rate of about 18 kg/s, at a pressure of 9.6 MPa and at about 250-300°C. The pressure tube is of a zirconium-niobium material, 103 mm diameter, about 4.25 mm wall thickness, and 6 m in length. External and

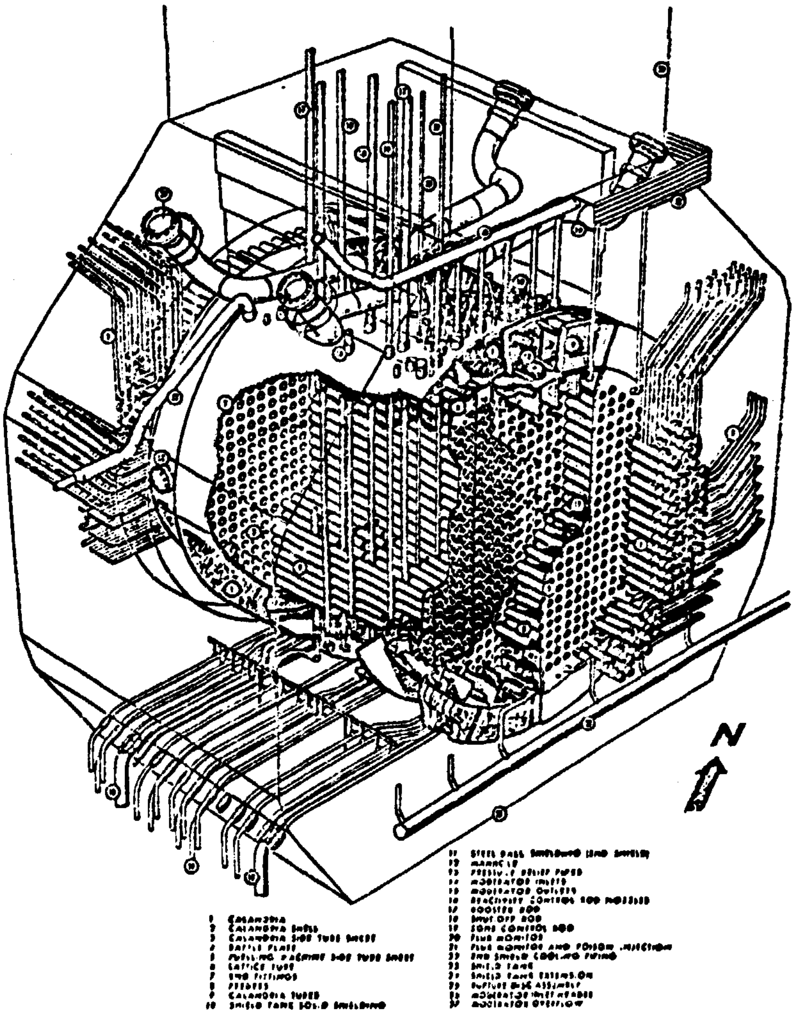


Fig. 1 Candu Reactor Assembly

concentric to the pressure tube is a calandria tube, also of zirconium-niobium, which is designed to separate the cool, low pressure heavy water moderator system from the primary heat transport system represented by the pressure tube. The annular space between pressure tube and calandria tube, approximately 8.5 mm, is filled with dry carbon dioxide gas, figure 2. As illustrated in figures 1 and 2, the calandria tube/pressure tube, or fuel channel, is terminated in stainless steel endfittings which are designed for fuelling, normally carried out with the reactor at full power.

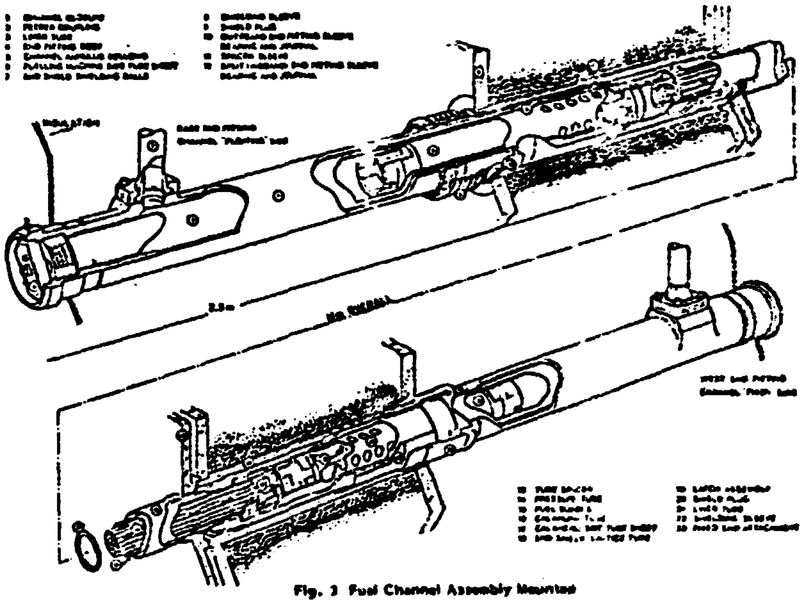


Fig. 1 Fuel Channel Assembly Mounted

The pressure tube, which forms part of the primary pressure boundary, is relatively inaccessible but procedures must be available to confirm its structural integrity, and to collect data related to long term materials performance under high neutron and gamma radiation which are required to predict maintenance needs and to assist designers. Such information may be gained from periodic removal of selected pressure tubes, but this process is time consuming, expensive, results in radiation exposure to personnel and can only yield data on a very meagre statistical base. A much more tenable approach is to derive the needed information through nondestructive evaluation techniques.

The information needed to give assurance of structural integrity and also to provide general materials performance data is quite extensive. Other primary considerations such as minimizing radiation exposure and optimization of cost versus time taken, conspire to dictate a highly automated, high speed inspection system based on several nondestructive evaluation methods (1). Further, it was recognized that needs could change and the system had to be flexible enough not only to be able to accommodate new inspection systems but also to encompass the design differences between reactors. The following paper describes this automated system, known as Channel Inspection and Gauging Apparatus for Reactors, - CIGAR.

2. INSPECTION NEEDS

2.1 Flaw Detection

It was decided that 100% volumetric inspection for defects was appropriate. This would be accomplished by using 45° shear waves augmented by a normal beam ultrasonic system. Definition of required sensitivity was not straightforward because there was limited information on the type of flaws that were expected plus the issue concerning what constituted an unacceptable defect was not completely resolved. However, there had been some history relating to the growth of delayed hydride cracks in the zone where a rolled joint is formed between the pressure tube and endfitting (2). These cracks were "penny shaped" and formed in an axial-radial orientation from the inside of the pressure tube. Another factor that was considered was that the primary manufacture's inspection used an ultrasonic system. The calibration standard for this called for a 70% full screen height (fsh) reflection from a notch 6 mm long by 0.075 mm deep on both inner and outer surfaces. Any reflector causing a signal greater than 20% fsh would need investigation.

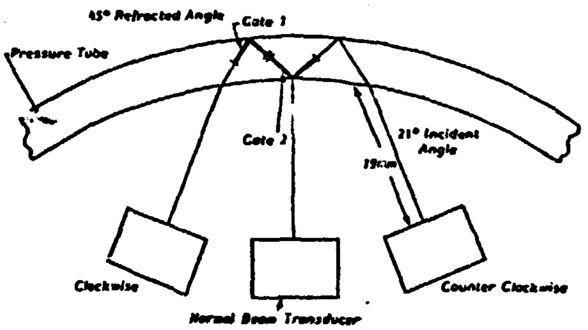
Essentially, this standard of performance was transferred to CIGAR but it only represented a formal statement of minimum achievement and considerable effort was expended to enhance sensitivity. This was achieved using 10 MHz, 10 mm diameter, 33 mm focal length transducers with a minimum beam diameter of about 1.5 mm. One advantage was that during inspection the pressure tube would be filled with heavy water, thus permitting the use of immersion testing philosophy.

Four angle beam transducers were used. Two facing toward each other in an axial direction and two facing toward each other in a circumferential direction. The transducers were positioned such that all of the beams passed through a common point on the inside surface of the pressure tube, the full-skip point, figure 3.

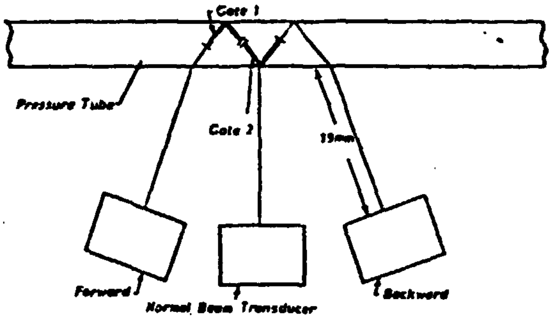
Yet another, and very significant, problem was that the inspection would be performed in a high gamma radiation field, estimated to be 10^6 R/hr. Gamma cell testing on "normal" transducers indicated that parameters could change rapidly and disasterously, figure 4, in such a radiation field. Most of this problem was associated with the swelling of the epoxy resin material used to provide damping of the crystal element. After prolonged effort a design was secured that could be guaranteed to function acceptably for a total radiation dose of 100×10^6R, that is 100 hours of actual inspection time.

2.2 Pressure Tube Gauging

It is known that both temperature and radiation flux cause dimensional changes in the zirconium-niobium material used in pressure tubes. Information was required about the wall thickness and profile of the pressure tubes such that these parameters could be mapped over the entire length and circumference,



a) CIRCUMFERENTIAL



b) AXIAL

FIGURE 3
CIGAR FLAW DETECTION SYSTEM TRANSDUCER CONFIGURATION
(a) CIRCUMFERENTIAL PROBES
(b) AXIAL PROBES

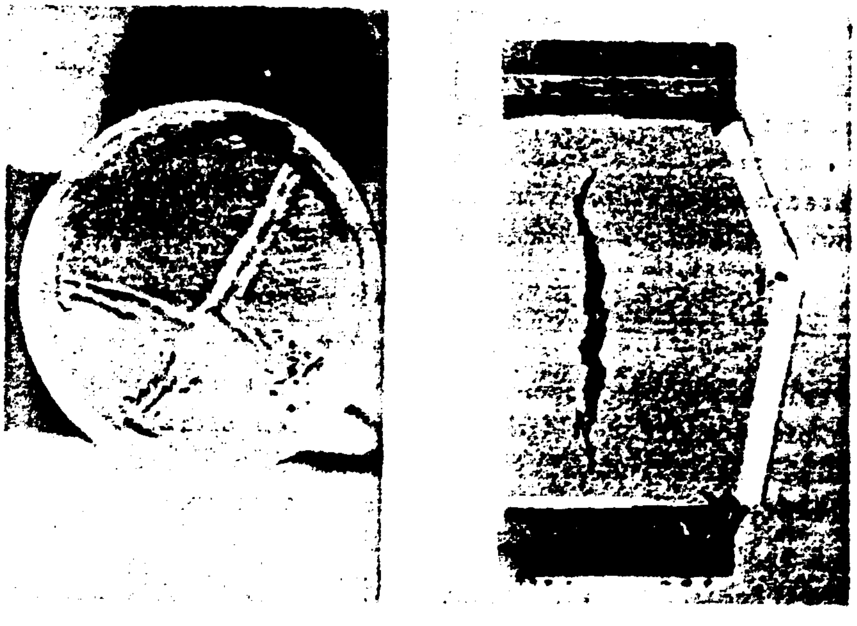


Fig 4.The Effect of Radiation on Transducers

As with the flaw detection system an ultrasonic system was envisaged. The precision required dictated compensation of readings for velocity change caused by temperature fluctuation. The diameter was measured using two back-to-back transducers aimed perpendicular to the pressure tube wall. One of these transducers was also used to measure wall thickness. A transducer aimed at a fixed target provided velocity change compensation. The transducers were activated by four commercial thickness gauges modified to operate in synchronism. These devices produced digital information at the rate of 4 sets of readings per second with a resolution of ± 0.01 mm.

2.3 Measurement of Pressure Tube Sag

During operation, the pressure tubes exhibit both diametral and axial creep. The designers have developed models of this behaviour but it is essential that the validity of these models be confirmed through measurement. The gauging system provides information on the diametral profile to about ± 0.02 mm but a system had to be designed to measure the sag of the pressure tube which results from the axial creep growth. An early version of this system consisted of a beam with fixed feet at its extremities, a third, moving, element mounted at the centre of the beam measured the mid-point displacement of the pressure tube surface. This technique provided inclination and displacement (sag) by an integration process.

Although this system has worked well, it was incompatible with the concept of a fully automated, high speed inspection system. The system eventually selected utilized a servo-accelerometer. This device is highly sensitive to its angular position with respect to an acceleration field (gravity in the absence of true acceleration), that is the output is dependent on orientation. However, this device although physically small (30 mm x 25 mm diameter) contains active electronic components and a lead shield was needed to achieve the required life in the existing radiation field.

The device itself is capable of detecting angular differences of as small as 0.1 seconds of arc but, in the inspection system a resolution of 15 seconds is adequate. The device produces absolute measurements of its tilt with respect to the earth's gravitational field which are integrated over the length of the pressure tube to provide the sag displacement profile.

2.4 Pressure Tube - Calandria Tube Spacing

During post-installation inspection, an eddy current technique is used to verify the condition of each pressure tube. This system operated at about 200 kHz, and, thus, was relatively insensitive to defects on the outer surface. It was thought that inclusion of an eddy current flaw detection/evaluation system within CIGAR was not essential, at least initially, in that it would largely provide duplicate information to that available from the ultrasonic flaw detection system. However, there was a requirement that the spacing between pressure tube and calandria tube be estimated and the only practical way to achieve this from within the pressure tube was through an eddy current technique, although one which is very different than that used for surface inspection.

The evolution of this facility is particularly interesting. Initially, a pancake probe was designed. This would be rotated through 360° at a fixed axial position and the X and Y channel response was recorded versus circumferential position of the probe. (The phase angle was adjusted to cause the X- signal to be predominantly lift-off). A two stage procedure was then developed using adaptive learning techniques. The first part separated those signals resulting from a relatively severely eccentric condition from those that indicated acceptable concentricity. The latter were not processed any further, but the former were manipulated to yield a numerical value of eccentricity.

Unfortunately, this information was less than that required. The critical measurement was the minimum gap between the two tubes. If the calandria tube had become oval, it would be possible to have zero gap in a perfectly concentric situation. The probe was improved to operate on the send-receive principle under constant current control and a method was devised whereby the largest interferring parameter, the Y-signal component dependent on wall thickness, could be eliminated by making use of the gauging measurements. The compensation needed was highly nonlinear, requiring either an iterative technique or an extensive computer-based look up table. The nonlinearity also meant that whilst spacings in the 1-4 mm range could be estimated with acceptable precision, above this, the error became large but still manageable as the prime concern was with small gaps rather than large ones (3).

It was known that other parameters not compensated for e.g. resistivity could adversely affect the system but, in the laboratory, these secondary influences had been relatively minor. By fortuitous accident the system showed surprisingly anomolous results when undergoing full scale trials. It so happened that the particular pressure tube used in the laboratory had an area of abnormal resistivity which caused the system to fail. This lead to the development of a third system.

Initial development of the third system occurred outside of the CIGAR project (4,5). It consists of an energizing coil with its axis coincident with the axis of the pressure tube and a diameter slightly less than the inside diameter of the pressure tube. This coil establishes the field at a frequency of 4 kHz. A small sensing coil located away from the energizing coil and close to the pressure tube inside surface responds to the field as a result of the proximity of the calandria tube to the pressure tube. Again, this system is sensitive to wall thickness variations but, as it can be made to have a linear relationship between eddy current signal, spacing and wall thickness, compensation is straightforward and can be achieved using a simple analog circuit.

2.5 Garter Spring Detection

Garter springs are the devices which are used to maintain the separation between pressure tube and calandria tube. Older reactors are equipped with two per channel, but newer units use four. These spacers consist of a helically wound coil through which is threaded a wire, the girdle wire, to maintain the torroidal shape of the spring, figure 5. The garter springs were designed to be a loose fit over the pressure tube and evidence shows that some have moved out of design position, probably due to vibration during construction and commissioning procedures. The movement of the garter springs can adversely affect the sagging process in that premature contact between pressure tube and calandria tube may occur. The displacement of the garter springs was not considered to be significant until late in the CIGAR design/construction. However, this need confirmed the advisability of the initial design criterion that the inspection system should be modular and able to accommodate new needs as they occur.

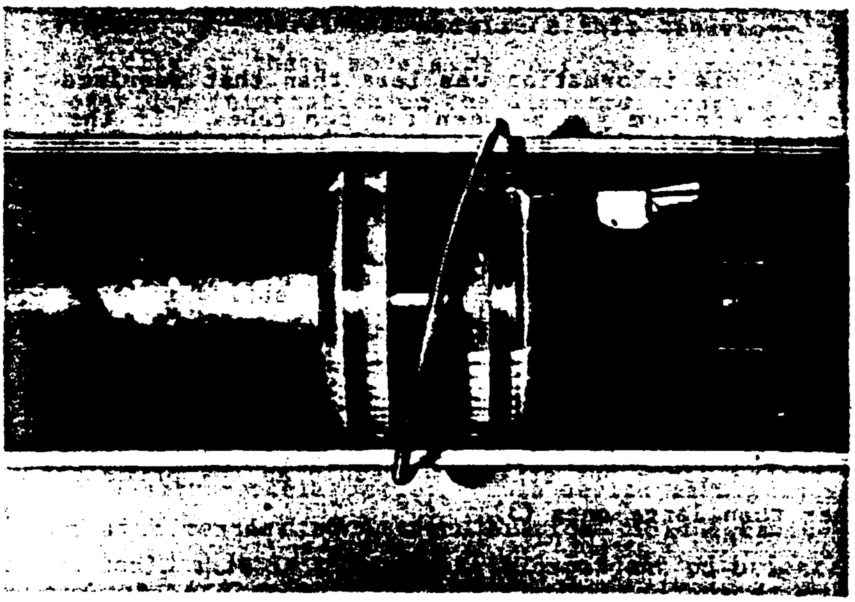


Fig. 5 Cross section of pressure tube with garter spring and eddy current probe

The garter spring detection system is based on an eddy current method using send-receive technology. A large diameter energizing, or send, coil induces eddy current flow in the girdle wire of the garter spring. Two detector, or receive, coils on either side of the send coil are connected in series-differential mode, figure 5. When the coil is passed through a garter spring position, a typical figure-eight type response is recorded in the impedance plane. The amplitude of the response is affected by the extent the garter spring is leaning away from the vertical plane. This is caused by the loose fit between garter spring and pressure tube.

3. THE INSPECTION HEAD

The sensors associated with the inspection systems are built into an inspection head, figure 6. This consists, in its usual form of an ultrasonics module, both flaw detection and gauging, a pressure tube-calandria tube spacing module and a sag/garter spring module. (The garter spring coils encircle the sag module). The modular assembly is supported within the pressure tube by two sets of spring loaded rollers, which also maintain the precise centering of the head. Various front, or nose pieces are added consistent with the requirements of the particular reactor. A head connector drive rod is attached to the assembly through a constant velocity joint. The connector rod carries 15 coaxial cables to the inspection modules.

4. THE DRIVE MECHANISM

The drive mdchanism, and the control consoles are shown in figures 7 and 8. CIGAR is completely controlled by a DEC 11/23 minicomputer. The drive mechanism has two principal roles, that is to connect/disconnect with the inspection head and to position the head at any location within the pressure tube either as part of the pre-programmed scanning mode or as a result of specific operator request.

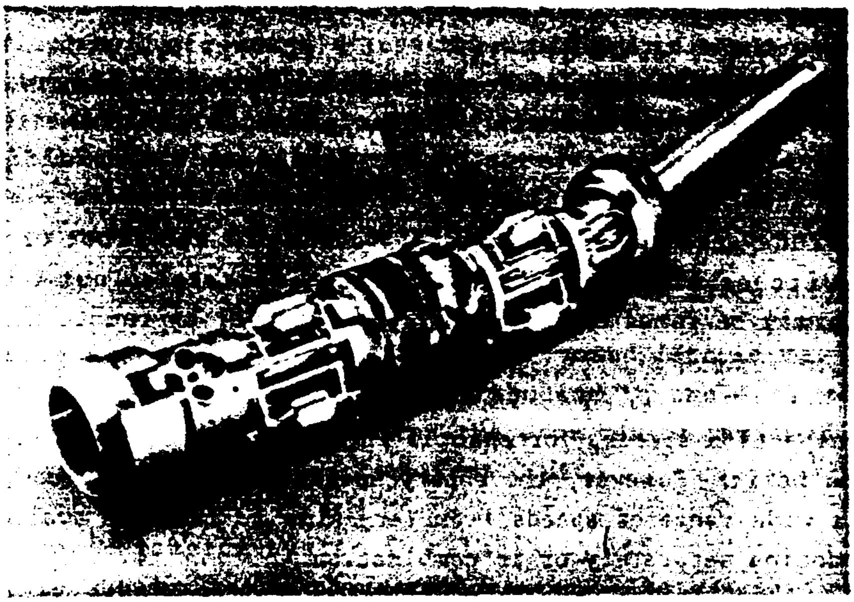


Fig. 6 In-channel inspection head

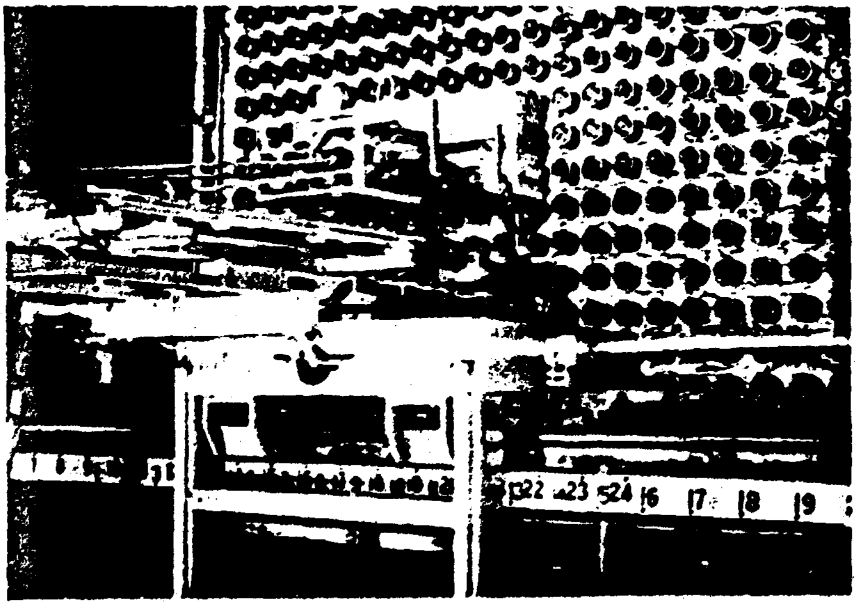


Fig. 7 CIGAR mounted on a Bruce GS Reactor

The inspection head is driven from the mechanism by a drive rod which also contains coaxial cables and mates with the head connector rod. Space restrictions do not allow the use of a single full reactor length drive rod. Thus, at approximately half way through a fuel channel, the drive mechanism separates from the drive rod, retracts, inserts and connects a second rod, and then returns to its scan sequence in the second half of the channel. This process, and the reverse is fully automatic.

Another feature is that the rod drive mechanism is on a subframe of the drive unit as a whole. Thus, the mechanism can be put into its approximate position and then the subframe can be driven in X and Y motion to finely align the mechanism with the channel to be inspected. This fine alignment is performed remotely by an operator using a television camera on the front of the drive.

The drive rods pass through a special bushing at the front of the mechanism. Microswitches attached to this bushing indicate an out of alignment condition which may be remedied either automatically or by remote manual intervention.

Typical inspection speeds, for example in a flaw detection pass, are 20 rpm on a 3 mm pitch helix. However, the rotary and axial drives are completely independent and a wide range of speeds from very slow to fast are available either on each drive motion separately or in combination.

5. DATA COLLECTION AND DISPLAY

The data collection systems are independent from the drive control except the data collection computer, another DEC 11/23, has extensive information exchange, especially position, with the drive system. The drive/data system consoles are shown in figure 8.

Fig. 8 Drive and Data Consoles

The flaw detection data consists of 8 analog channels of amplitude-in-gate data, two gates per angle beam transducer. The normal beam transducer is handled separately. This information, in addition to axial and circumferential coordinates, is stored on a 14 channel analog tape recorder. The operation of the tape recorder, including control settings, is dictated by the data computer. In addition to data storage, an on-line display of composite amplitude-in-gate data versus position is presented on a CRT terminal. A screen dump from the display to a hard copy device is available at any time.

The ultrasonic instrument, a KB6000 which is also controlled by the data system computer, presents the operator with the standard A-scan display of four channels simultaneously. In order to assist the operator, an alarm-print module provides a position and amplitude record should any signal exceed a present threshold. This allows the operator to identify selected areas of the pressure tube that may be revisited for more detailed inspection following completion of the general scan.

In addition to the on-line display, the stored data is reviewed in post test analysis through standard facilities embodied in the data computer when used in the play-back mode. If required the data can be reviewed by a similar computer/ tape recorder system separate from CIGAR.

The ultrasonic gauging system is relatively independent except that its microcomputer is supervised by the data computer. The gauging system data is displayed as digital information on four read-outs and is stored on the digital cassette tape system. This data is collected simultaneously with the flaw detection scan. Approximately 100,000 values, plus axial and circumferential position, are stored for each pressure tube. On-line presentation is not required but post test analysis and reporting is achieved using the data computer.

Sag data is collected separately from the flaw detection/gauging scan. The primary output is through a 4-1/2 digit digital voltmeter which, in turn, is interfaced to the digital cassette tape system used for gauging data. Again, this process is supervised by the data computer and only off-line results and analysis are required.

The X and Y channels of the "Defectomat F" eddy current instrument used for pressure tube-calandria tube spacing are recorded on the analog tape recorder. In post test analysis, the data computer retrieves the eddy current data from the analog tape recorder, retrieves the wall thickness data from the gauging system appropriate to the particular location, applies the compensation necessary and produces hard copy output in both graphical and tabular form.

The garter spring detection signal, also using the "Defectomat F", is stored on the analog tape recorder. Data presentation in post test analysis is in hard-copy graphical/tabular form. Interactive graphics displayed on the data computer CRT allow for operator confirmation of real-imaginary impedance plane displays, should that be required.

6. OPERATIONAL SEQUENCE

(i) The functions of the inspection head are checked and it is loaded into its carrier with special closure plug. This closure plug differs from the normal plug that terminates a fuel channel in that it has a sealed opening to allow passage of the drive rods.

(ii) The head is loaded into one of a pair of fuelling machines. Sometime after reactor shutdown the channel to be inspected is defuelled by the fuelling machine and the head inserted, including the special purpose closure plug. When a number of channels are to be inspected, either a head is loaded into each channel or a head will be 'shuffled' from one channel to the next. During the inspection the reactor is at low pressure and cool (< 50°).

(iii) The drive mechanism is bought into the reactor vault, lifted by crane to the fuelling machine bridge at the reactor face, and coarsely positioned. All cables are connected and personnel then leave the reactor area figure 9.

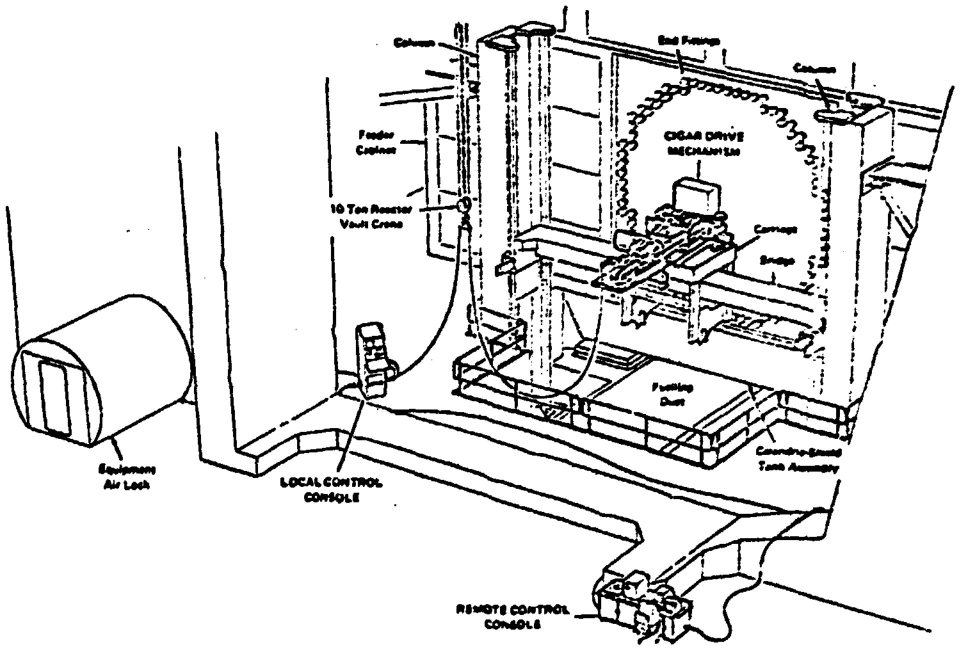


FIGURE 9
CIGAR SYSTEM AT A BRUCE GS REACTOR

(iv) Using the television alignment system, the drive is positioned in 'fine alignment mode', the first drive rod is advanced and automatically connected to the head connector rod which protrudes marginally from the endfitting.

(v) Certain functional checks are performed and the inspection commenced.

(vi) At the completion of the inspection, either the drive is removed or moved to the next channel to be inspected. Depending on which station is involved, personnel may be required to manually reposition the drive.

(vii) The fuelling machine removes the inspection head, refuels the channel and inserts the normal closure-plug.

(viii) The data computer is operated in the playback mode to produce the inspection reports.

7. CALIBRATION

Calibration is almost universally a critical part of any NDE procedure. It provides the means whereby results may be compared against a constant standard and it allows comparisons of one test result against another. This is especially important in periodic inspection procedures where it may be essential to compare the results from one inspection with those obtained previously. However, calibration has to be considered for what it is, no more than that. It rarely provides the means by which the response of an inspection system to a certain type and size defect can be compared with the response from a different size and type defect. The CIGAR calibration procedures most definitely provide a repeatable standard.

7.1 Flaw Detection

As stated previously, the manufacturer's inspection standard for ultrasonic inspection of pressure tubes requires the reflected signal from an outer or inner surface notch, 6 mm long by 0.075 mm deep, be adjusted to 70% of full screen height and that any signal from a reflector greater than 20% full screen height requires investigation. The basic philosophy was that the periodic inspection capability should be equal to, or even exceed, the sensitivity of the manufacturer's inspection. This was achieved by the design of the CIGAR flaw detection system as a whole but, space limitations within the fuel channel essentially precluded the inclusion of a meaningful calibration piece, that is the reduced space would dictate a calibration piece smaller in diameter and with a different spacial relationship to the flaw detection transducers. These factors cause, for example, shear waves to be set up in such a sample with angles markedly different than in the actual pressure tube. Also, the sensors are focussed and, again, the sound beam in a reduced diameter and thickness calibration piece would be significantly changed.

CIGAR is not immune from the necessity of both insuring detection sensitivity and repeatability both within the five flaw detection transducers on each individual head and from inspection to inspection. Further, it was highly desirable that the individual characteristics of each pressure tube be incorporated into the calibration process, just as it is, for example, when a "transfer value" is measured when inspecting a weld.

The design of the inspection head is such that beams from all flaw detection transducers pass through a common point on the inside surface of the pressure tube, figure 3. Thus, a method of calibration was devised such that one transducer of a pair is used to pulse and the other used to receive. The gain on the ultrasonic instrument is then adjusted to give a predetermined, calibrated response. This is known as the "power check level". The advantage the calibration process. During operation the gain on the ultrasonic instrument is then increased until the full skip (inside surface) response is a preset level on each channel to establish the required sensitivity.

Experiments were performed to demonstrate the appropriateness of this "power check" calibration scheme against more typical schemes, including a 0.075 x 6 mm notch. The results are illustrated in figure 10.

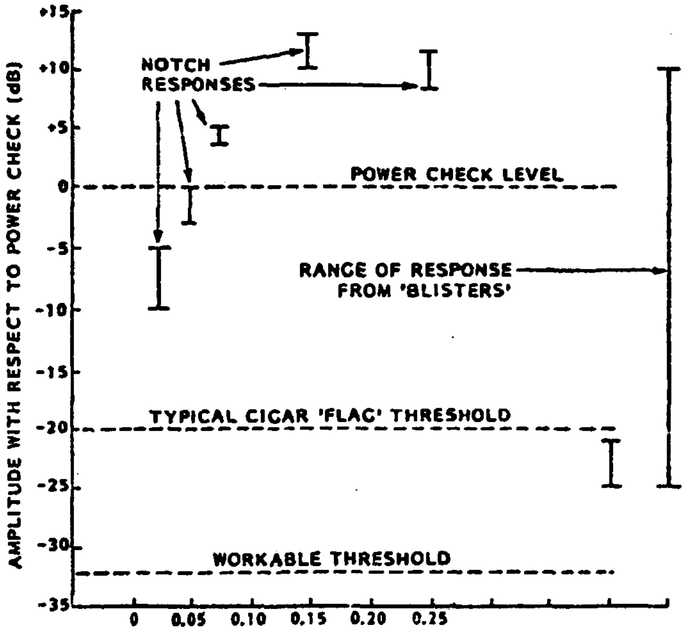


FIGURE 10
COMPARISON OF CALIBRATION ON STANDARD NOTCHES AND THE POWER CHECK APPROACH

7.2 Gauging System

The gauging system uses normal beam transducers which are less disturbed than their flaw detection counterparts when a reduced diameter and thickness calibration piece is used. This calibration piece is a brass extension to the carrier, that is the ultrasonic module is surrounded by a precisely machined brass cylinder when it is in position within the fuel channel prior to commencement of the inspection. Calibration is in two stages. Firstly, out-reactor, the relative spacing between the velocity compensation transducer, and the reference surface is precisely measured. Secondly, the wall thickness and diameter of the calibration piece, as indicated by the ultrasonic system, are recorded. These dimensions are precisely known. Actual gauging measurements taken during an inspection are then adjusted to conform with the initial calibration measurements. Although the operator has the facility of adjusting the thickness measuring system to exactly comply with the true physical measurements of the calibration piece, this is not necessary as the compensation is in-built into the data processing algorithm.

7.3 SAG System

The sag system performs absolute measurements. Before the inspection head is carried to the fuel channel to be inspected, performance checks are under-taken. In the strictest sense of the word, these checks are not calibration procedures but more of a functional nature. Whenever possible, these checks are reperformed after the inspection but this is not always feasible due to radioactive contamination. Experience has shown that degradation of the servo accelerometer unit, usually due to radiation induced damage, produces easily recognizable, erratic readings, often going off-scale.

It is inevitable that the sag unit will be biased due to slight mechanical misalignment. To compensate for this at the beginning and end of the slope measuring pass, and at each end of the fuel channel, the inspection head is rotated through 180° and slope measurements compared. The measured difference is then used to correct the slope measurements prior to integration to obtain the sag profile. It is possible that other errors, e.g. integration errors, will produce a constant slope bias superimposed on the sag profile. This type of error is removed within the computer processing algorithm.

7.4 Garter Spring Detection

The calibration of the two eddy current systems present particular difficulties. For example, it is not practical to incorporate reasonable facsimilies of garter springs into the head carrier, let alone a simulation of pressure tube-calandria tube for the spacing system. Also, the carrier, when in position, is surrounded by the mass of the endfitting which is manufactured from ferromagnetic stainless steel (type 416). The presence of the endfitting overwhelms the eddy current systems.

The garter spring function, fortunately, requires little calibration as it is a detection, rather than measurement, system. It is sufficient to confirm the operation of the system prior to loading the inspection head into the fuelling machine and then to rely on predetermined instrument settings. During the inspection, the variation in diametral creep at each 0.5 m due to the reduced flux at the ends of each fuel bundle, produces quite a significant response. Instrument settings are adjusted to cause this disturbance to lie as much as possible on the X-axis. The frequency, typically 3.5 - 5 kHz will be adjusted to maintain 90° separation between the garter spring signal and that due to the diametral creep variations.

7.5 Gap System

This system presents the most significant problems in terms of calibration in that it is designed to perform absolute measurements yet cannot be provided with a calibration facility. This problem is not fully resolved at this time. The present calibration essentially consists of passing the inspection head through a calibration piece prior to loading into the fuelling machine. The calibration piece consists of a length of pressure tube surrounded by three lengths of calandria tube. Of these three lengths, one is concentric whilst the other two are full eccentric. This allows the operator to adjust and record instrument settings.

Within the channel there are a number of functional checks, for example the eccentricity is mild towards the extremities of the fuel channel. Another check of performance is the degree of correlation between the sag results and the gap measurements. Both of these should be consistent with garter spring positions and dimensions.

The precision claimed for the pressure tube to calandria tube space estimating system is ± 1 mm. It is felt that better can be achieved but there is a certain reluctance to claim better performance without insitu calibration.

In general terms, it would be expected that the eddy current probes would suffer degradation due to radiation to a far lesser extent than ultrasonic transducers. Thus, there can be some confidence that although out-reactor calibration would be inappropriate for the ultrasonic systems, it is entirely acceptable for the eddy current systems.

8.0 OPERATIONAL RESULTS

8.1 The CIGAR System

The CIGAR system has been operational since mid 1985. During its first year of operation full inspection, using all systems described above except gap measurement*, have been performed on 60 fuel channels in 4 reactors.

Also, limited ultrasonic inspections of a large number of other fuel channels have been performed.

Typical performance of the system is illustrated by the first inspection of an active reactor by CIGAR. Twenty fuel channels were inspected in 12 days. Approximately half this time was required for fuel handling and inspection head movement. The other half was required by CIGAR for alignment and connection of the drive with the inspection head and to perform the inspections. The total radiation dose accumulated by personnel involved in all aspects of the work was only 1.2 man Rem.

All parts of the system have worked very well with only infrequent minor maintenance being required.

Typical results from each inspection system are presented below.

8.2 Ultrasonic Flaw Detection

During the general helical flaw detection scan, the eight channels of data from the four transverse wave transducers are recorded on the analog tape recorder. The playback computer can simultaneously produce two "isometric C-scan" plots of this stored data. Header and position information is presented on the

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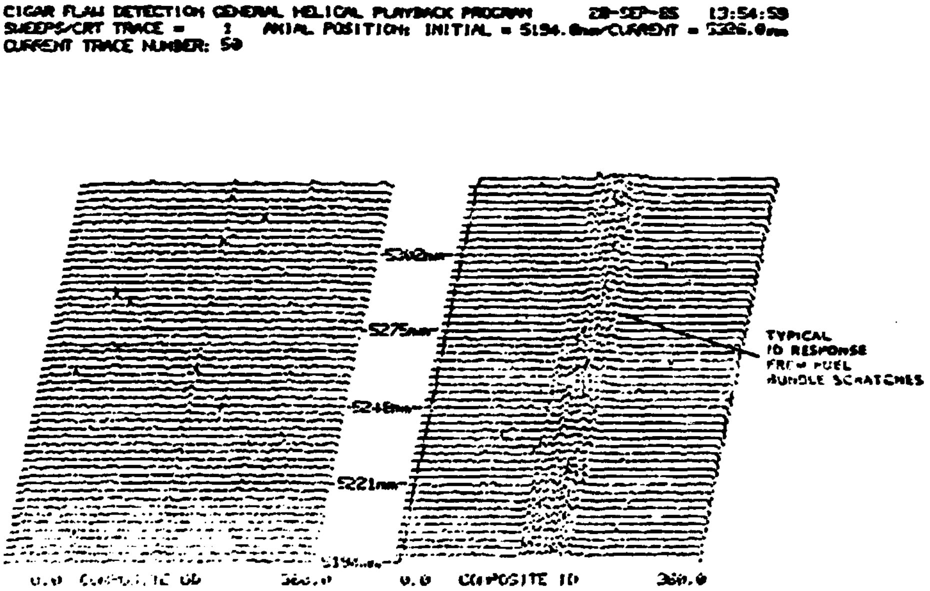
*Currently being added.

plot and each plot may represent the composite data of a number of transducer rotational scans. The plots may also be the composite of all four inside surface gate signals and all four outside surface gate signals. The data playback may be performed on-line during the inspection or off-line after the inspection. If done on-line, only the data from every second rotational scan line is displayed. However, all inspection data is recorded on the tape recorder and may be displayed during subsequent off-line playback. Figure 11 illustrates a detection scan composite playback from a typical tube. The inside surface indications in the middle of the right hand plot are the response from fuel bundle scatching on the bottom of the tubes inside surface. The amplitudes of these indications are typically 20 to 30 dB below that from a 0.075 mm deep reference notch.



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CIGAR FLAW DETECTION GENERAL HELICAL PLAYBACK PROGRAM      28-SEP-85   13:54:59
SWEEPS/CRT TRACE =   1   AXIAL POSITION: INITIAL = 5194.0mm/CURRENT = 5326.0mm
CURRENT TRACE NUMBER: 50
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FIGURE 11

CIGAR - FLAW DETECTION - TYPICAL COMPOSITE SCAN OUTPUT

If an indication is found during the detection scan, detailed inspection scans consisting of short, closely spaced axial or circumferential movements may be performed. The inspection transducers may be configured to provide either pulse echo or pitch catch inspections. Header information specifying the location, type and range of scan are entered via the control computer. Data collected during these scans is stored on the tape recorder and on-line or off-line playback of the collected information in "isometric C-scan" format may then be produced. A typical detailed axial scan of a small inside surface indication is shown in figure 12.

8.3 Wall Thickness and Diameter Gauging

As described above, these measurements are also performed during the general helical scan, with data being stored on a digital cassette tape. After the inspection, the cassette tape is read under control of the playback computer. Tables and graphical results of minimum, maximum and average wall thickness and diameter, along with the rotational orientation at which they occur are produced. Typical results are shown in figures 13 and 14.

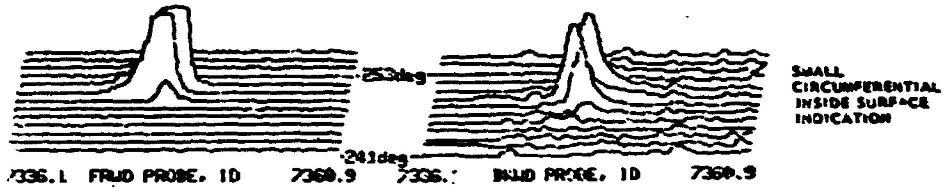

FIGURE 12
CIGAR - FLAW INSPECTION - DETAILED AXIAL SCAN

Figure 13 shows that the average wall thickness at any point is quite uniform but there are periodic variations that are believed to be due to the manufacturing process. The minima are at approximately 0 or 180° and the maxima at approximately 90 or 270° showing a two lobed pattern characteristic of tube extrusion processes.

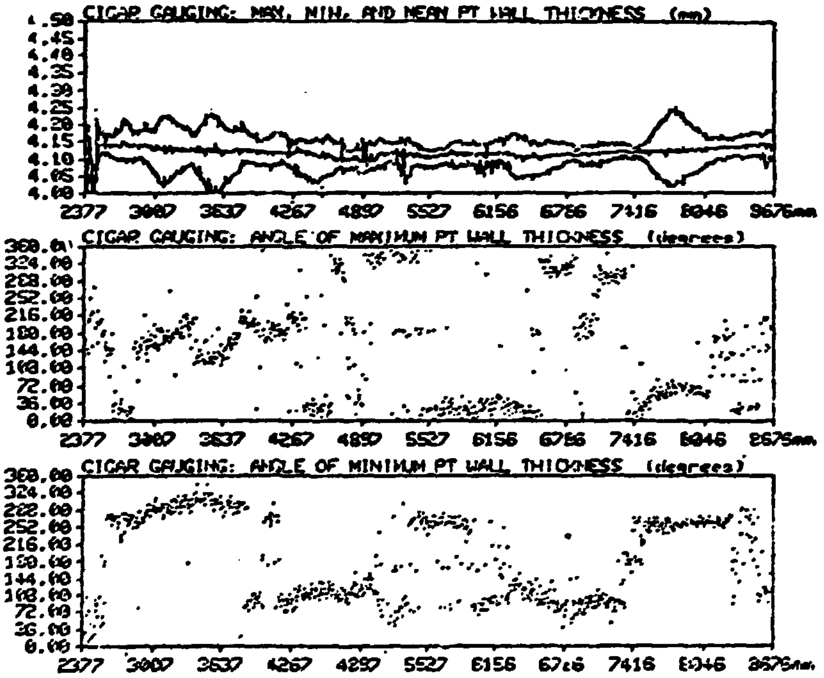

FIGURE 13
CIGAR - GAUGING SYSTEM - WALL THICKNESS MEASUREMENT

The diameter plots in figure 14 show an increase in diameter in the central area of the tube with the maximum closer to the hotter outlet end of the fuel channel. There is very little circumferential variation but because of sag, there is a slight ovality with the maximum diameter in the horizontal plane (90°) and the minimum in the vertical plane (0° and 180°).

It is interesting to note that calculation shows that the small measured reduction in wall thickness corresponds well with the increase in diameter if a conservation of material volume rule is applied as would be expected with traditional creep mechanisms.

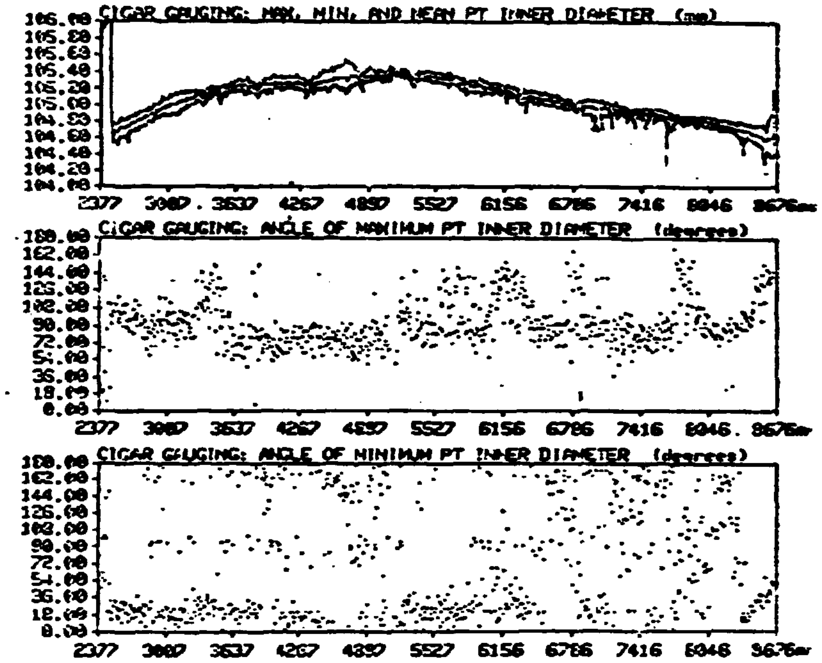

FIGURE 14

CIGAR - GAUGING SYSTEM - DIAMETER MEASUREMENT

8.4 Sag Measurements

Slope measurements used to generate sag data are made at 25 mm intervals as the head is traversed axially down the full length of the channel. The playback computer calculates the vertical deflection and local curvature of the tube by integrating and differentiating the data respectively. Typical results are presented graphically as shown in figure 15 and tabularly with the value and axial position of maximum sag defined.

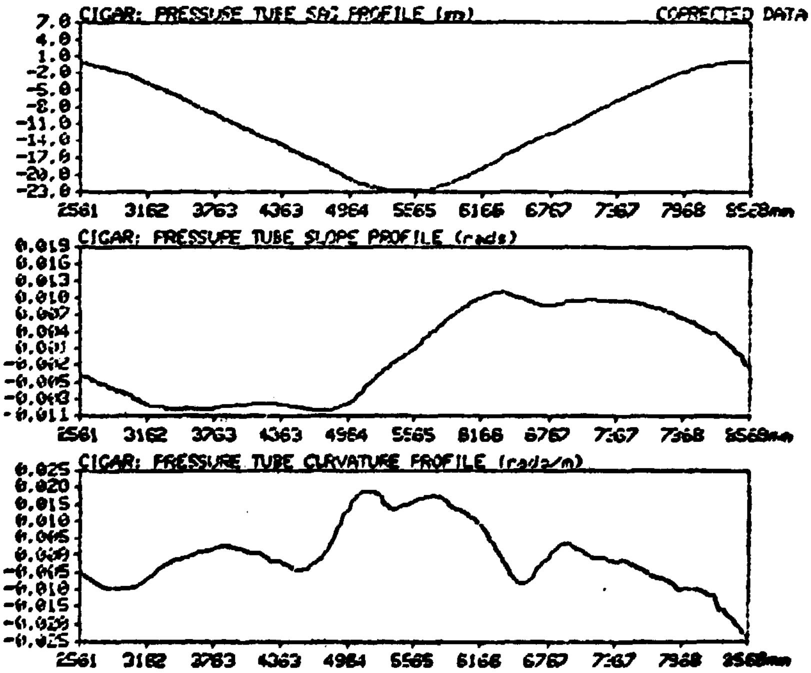

FIGURE 15

CIGAR - PRESSURE TUBE SAG PROFILE MEASUREMENT

The sag profile shown is quite typical of those in reactors with only two garter spring spacers. The spacer positions can be inferred by the two dips in the tube curvature curve on either side of centre.

8.5 Spacer Location Measurement

Typical spacer location results are presented as shown in figure 16. As described above, the inspection is configured so that the presence of spacers causes a change predominantly in the Y component. Other features such as diameter variations between fuel bundles cause changes predominantly in the X component as illustrated by figure 11. The operator can examine signals, selected by moving a cursor, as a Lissajous figure which aids in distinguishing spacer responses from spurious ones. The results shown in figure 11 were from a channel constructed with only 2 spacers which are clearly evident on the Y trace at the two vertical line cursor positions.

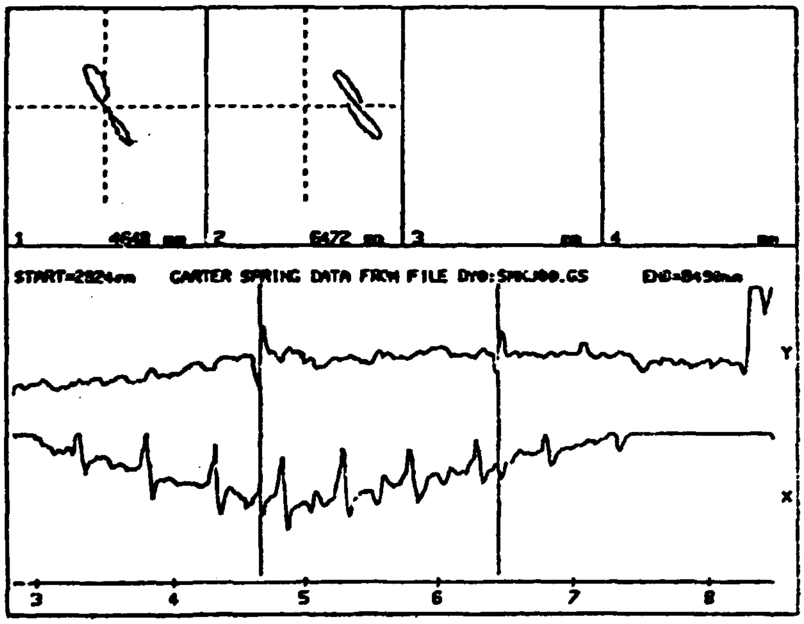

FIGURE 16

CIGAR - GARTER SPRING LOCATION DETERMINATION

9.0 FUTURE DEVELOPMENTS

The primary limiting factor in terms of additional systems to be added to CIGAR is the cable capacity of the drive rods. This stands at 15 coaxial cables at maximum packing density. This has already presented some problem in that it was not possible to add the garter spring detection system without dropping another system (the gap measurement). Thus, an in-channel multiplexer has been designed and is currently under test. This device enables switching of a set of three signal lines to six separate on-head systems, each utilizing three coaxial cables. The multiplexer utilizes three control lines, leaving nine lines for direct connection to on-head functions. It is anticipated that this will be incorporated into CIGAR by the end of 1986.

In addition to the incorporation of the gap measurement system, the multiplexer will enable the addition of surface defect eddy current systems, for example, to measure the dimensions of crevice corrosion attack at the positions corresponding to the fuel bundle wear pads. Such a system has been devised (5) but not used in reactor. Yet another eddy current system under consideration is one designed to measure the thickness of oxide on the inside surface of the pressure tube.

Recent experience has shown that some defects of concern may be at a very shallow angle and close to the pressure tube surface. In one instance, full mapping of such a defect was achieved using 100 MHz ultrasound. Again, the multiplexer system would permit the installation of such systems, although not proven in terms of necessity.

It is foreseen that yet another role exists for CIGAR, namely in visual inspection of pressure tubes. In this situation a miniature, radiation resistant tv camera would be used. This would not be incorporated into the normal inspection head but would be a specially designed head driven and controlled by the CIGAR system. It would be possible to provide lighting for underwater use plus the facility to use a steerable mirror in front of the camera.

The philosophy and some of the functions embodied in CIGAR are being used to provide an inspection facility for the CIRENE reactor in Italy.

10. CONCLUSIONS

A highly automated inspection system has been designed, fabricated and used to inspect fuel channels in Candu reactors.

The system comprises an in-channel inspection head, drive mechanism, computer controls and full data collection, processing and playback facility.

CIGAR currently uses a 5-probe ultrasonic flaw detection system, a three probe/four channel ultrasonic gauging system, an eddy current technique for detection of garter springs, a combined eddy current and ultrasonic system for estimating the spacing between pressure tube and calandria tube and a servo accelerometer to measure pressure tube sag. Future developments will realize additional capabilities, including comprehensive visual inspection through a special purpose television camera.

The results obtained, a sample of which are described in section 8, are fully consistent with design expectations.

REFERENCES

(1) Baron, J.A., Erven, J.H., Dolbey, M.P., Booth, J.H. and Murray, D.W., "Automated Inspection and Gauging of Fuel Channels in Candu Reactors", Proc. I Mech E Conf. Periodic Inspection of Pressurized Components, I Mech E 1982-9.

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