OPTICAL TECHNOLOGIES FOR MEASUREMENT AND INSPECTION

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Ontario Hydro has benefitted from specialized optical measurement techniques such as FRILS (fret replica inspection laser system), which permits in-house inspections of pressure tube replicas and has been estimated to save $2M per year. This paper presents a brief overview of (1) FRILS, (2) OPIT (*in-reactor* Optical Profilometry Inspection Tool), (3) miniature optical probe for steam generator tubes, (4) laser vibrometer used for end-fitting vibration, and (5) computer vision to recognize the ends of fuel bundles and automatically measure their lengths.

We describe certain items of specialized optical inspection equipment developed by OHT (Ontario Hydro Technologies) and NTS (Nuclear Technology Services) for use by OHN (Ontario Hydro Nuclear). Persons who have contributed to the work described in this paper include: (at OHT) M.J. Tinkler, D.L. Mader, S.C. McNabb, S.B. Peralta, E.G. de Buda, J.C. Kuurstra, E. Di Blasio, H.E. Whitmell, R. Scheer, J.A. O'Neill, R. Gnoyke, M.P. Eygenraam; (at OHN) K.S. Mahil, G.N. Jarvis, E.O. Cornblum, M.G. Grabish, J.M. Hewer, D. McKinney; (and outside OH) M. Grossman (PLV Systems); T.G. Onderwater and others at GE Canada.

The examples in this paper illustrate the benefits of optical instrumentation to utilities; and appreciation of these benefits should lead to development of further applications.

3D Shape Measurement can be performed with optical triangulation. The form used in FRILS and OPIT is "light sectioning" with a sheet of light produced by a line projector. On the other hand, the miniature optical probe for steam generator tubes has a point projector and a 1D light sensor. With suitable scanning mechanisms, the results can be assembled into the shape of the surface of the target, a process herein called *optical profilometry*.

The principle of operation of light sectioning is illustrated in Figure 1 where the sample is "sectioned" by a sheet of light transverse to the flaw axis. The resultant stripe of light is viewed at a different angle by a video camera coupled to a computer, which traces the centreline of the stripe of light, in order to arrive at a single surface profile. Calibration of the system on wires and machined steps is done to convert pixels in the image to actual dimensions. When the sample is scanned along its axis under the optical head, a large number of individual profiles can be obtained and can be assembled into the 3D shape of the sample.

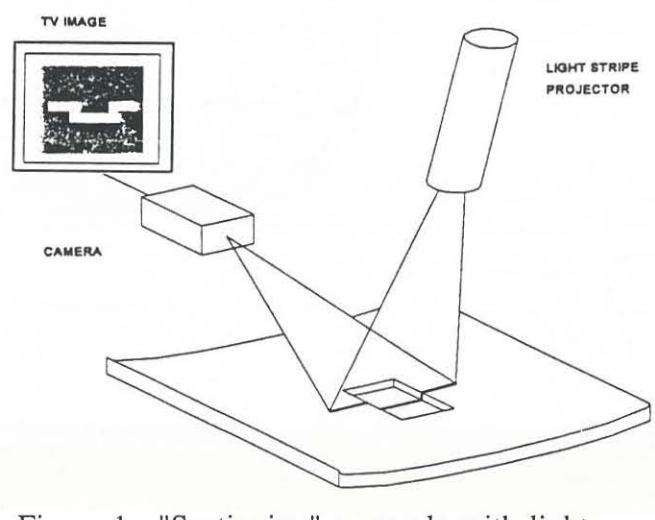

Figure 1. "Sectioning" a sample with light

The data acquisition computer digitizes the video signal and the OPIT/FRILS software developed by OHT and SSD (Simulator Services Dept) extracts the surface profile of the pressure tube. Surface profiles can be segmented, and circles can be fitted manually or automatically to high stress locations.

A particular niche for optical profilometry is its non-contact capability to take root-radius measurements for flaw assessment, since "sharp" flaws are assessed differently from "blunt" flaws. Both FRILS and OPIT were designed to profile a type of pressure tube flaw called bearing pad fret marks, caused by contact of the bearing pads on nuclear fuel bundles with the inside surface of the fuel channels (pressure tubes). These flaws among others are first detected with ultrasonic probes, which identify those flaws that require further characterization. A rubber replica will be made of the flaw inside the reactor, and it is removed for flaw measurements outside the reactor. FRILS takes flaw measurements on replicas, including root-radius measurements down to a root radius of 40 μm. FRILS is used by OHN and OHT on a routine basis. OPIT is still under development to measure bearing pad fret marks directly in the reactor without the need to take replicas.

The FRILS apparatus, shown in Figure 2, consists of a large turntable underlying the inclined brackets that hold the sample scanning linear table and replica holder. A separate part holds the optical head, which positions a commercial laser line projector horizontally, and a machine vision video camera and zoom lens inclined at a steep angle. The various angles result in suitable angles of projection and view to carry out optical triangulation. The large turntable is used to change the aspect of the sample with respect to the optical head, in order to acquire left and right rootviews. The operator manually adjusts the zoom factor of the lens to high magnification to measure root-radius values. This system was designed to measure the geometry of bearing pad fret marks as retrieved from fuel channels via rubber replicas. These flaws are oriented axially in the pressure tubes. FRILS is also pressed into service to measure debris flaws, which may have any arbitrary orientation.

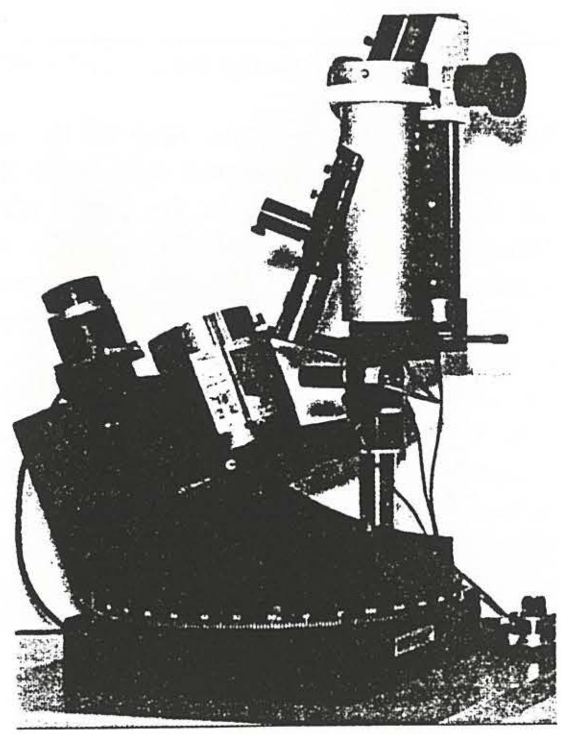

Figure 2. FRILS apparatus

Flaw shape *in-reactor* is obtained by OPIT (Optical Profilometry Inspection Tool). This tool works under the following constraints: tool head must fit in fuelling machine (40 inches long by 4 inches diameter), the tool delivery system supplies only 15 electrical cables, the channel is flooded, and the gamma radiation is about 0.5 MegaRad per hour. Since movement of the optical head relative to the flaws (as is done in FRILS) is not feasible, three separate optical systems are used to collect the overview, right rootview, and left rootview. The systems were designed to focus with water as part of the optical path, and to focus on a common plane, where the sensor of a rad-tolerant video camera is positioned. Each system consists of custom focusing optics for the camera, and projectors that generate a thin stripe of light to "section" the flaw.

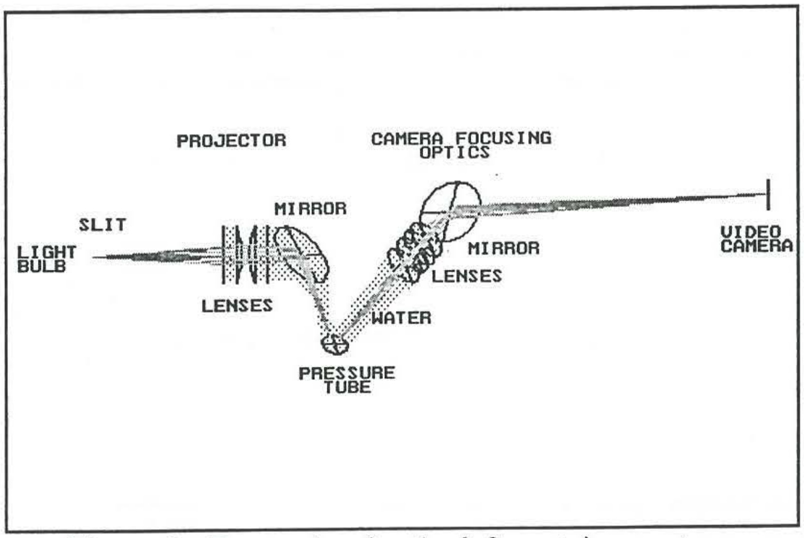

Figure 3. Raytracing for the left rootview system.

Optical design was done with ray-tracing software to ensure that the three optical systems would be in focus on the sensor surface of the video camera. A sample of the design output is shown in Figure 3, which shows a composite of the rootview projector design and focusing optics for the video camera. (This figure fooled the ray-tracing software into producing a bundle of rays off of the target by placing a mirror at the pressure tube location).

Figure 4 shows the active area of the optical head for OPIT. The camera side is on the left and the projectors are on the right, with the global lights for general illumination in the middle. On the right, the mirror mounts are seen for the rootview projectors, with the output lens of the overview projector between them. The rootview objectives are in focusable carriers, while the overview lens between them is fixed. In optical alignment, the overview camera is focused using the internal focus capability of the video camera, and then the root views are focused by adjusting their objectives. Figure 5 shows the tool configuration for the Darlington NGS.

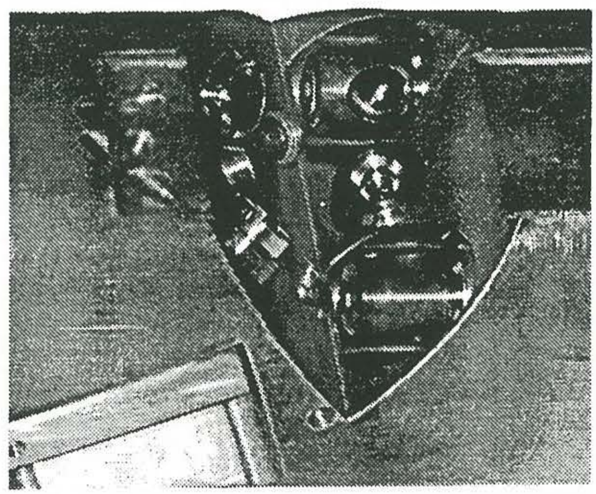

Figure 4. Optical head for OPIT

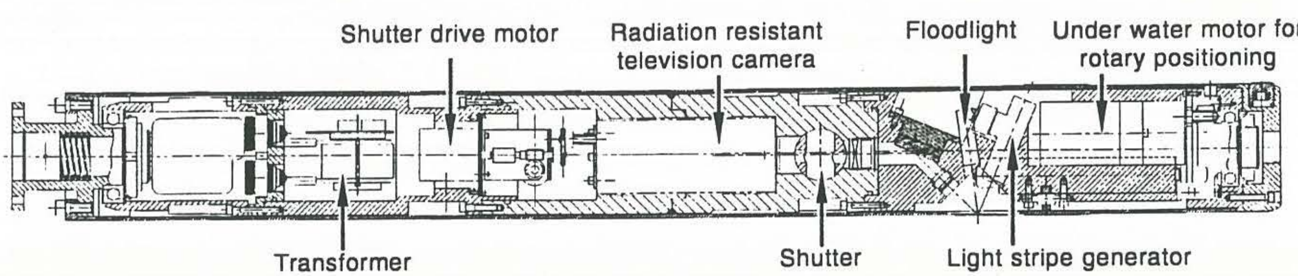

Figure 5. Tool configuration for Darlington use

For a qualitative look at the pressure tube ID (inside diameter), the global lights can be operated along with one of the projectors. The appearance of the surface can often be deceptive, inasmuch as a stain can resemble a flaw. However, the stripe of light from the line projector can distinguish between these two possibilities. If the stripe is distorted as shown in Figure 6, there is a flaw. Figure 6 was retrieved from a video tape of camera output with the overview system and the global lights turned on, during trials of OPIT at Darlington in 1995.

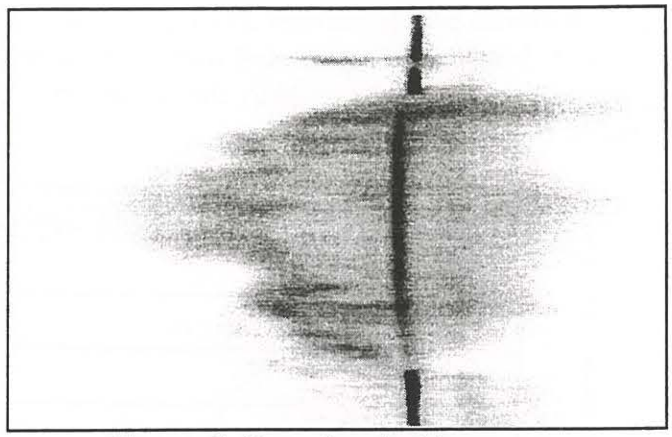

Figure 6. Overview inside reactor

A replica of the fret mark seen in Figure 6 was obtained and was examined with FRILS. An isometric plot of a large number of profiles taken in a FRILS scan of the flaw is given below in Figure 7.

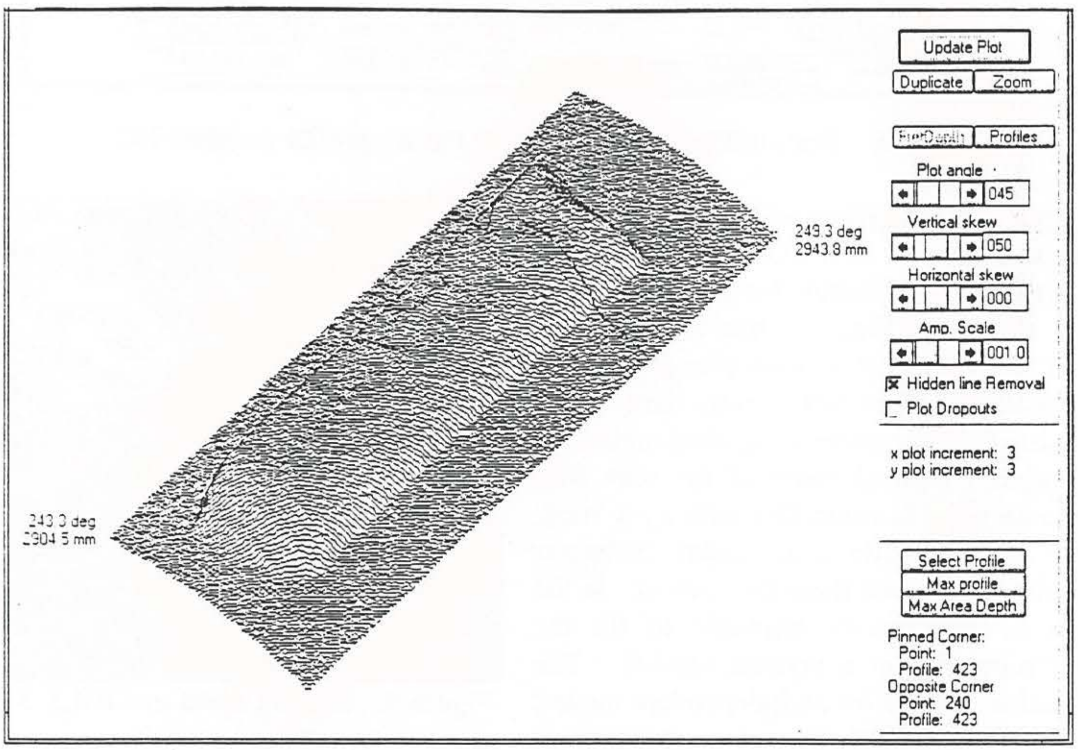

Figure 7. Isometric plot of profiles taken on a replica in D4.

The software developed for FRILS and OPIT can obtain flaw parameters such as length, width, and depth from overview data. In addition, individual profiles can be examined for their maximum depth, for example, or their radius of curvature in any selected region. In Figure 7, profile number 423 is highlighted in the top half of the plot.

Figure 8 shows profile number 391 from the above data file being analyzed for maximum depth (shown as height in the plot) and root-radius at the left side. In this case, the circle seen in the figure was set manually to skirt the inside edge of the data points and obtain a lower-bound estimate of the actual radius.

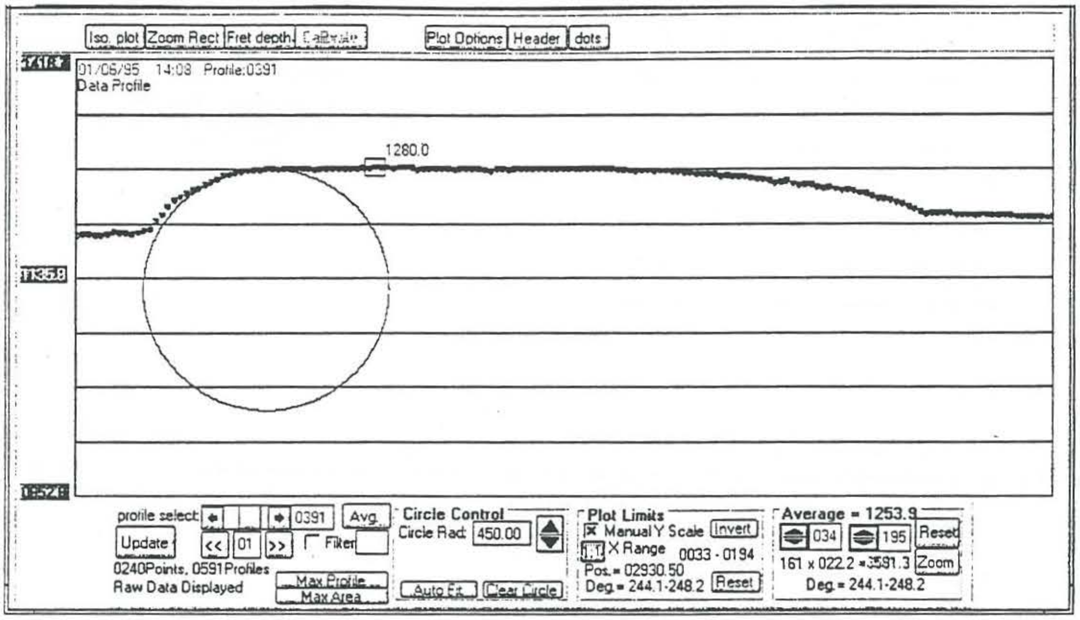

Figure 8. Root-radius estimate of 450 μm on profile number 391

Custom scanning equipment was demonstrated on pressure tube replicas in a COG-funded project. A new hardware apparatus for FRILS (called FRILS-3) shown in Figure 9 has been built to perform a scan of a debris flaw along its major axis, at whatever orientation it may have. This apparatus has four computer-controlled motorized motion stages. Manual setup of the scan start point and end point is controlled with a joy stick; and then an automatic scan under computer control is done between these two points. In the apparatus, a large rotary turntable to tilt the sample is mounted on a vertical bracket. The optical head is located on an independent mount; and the stripe of light from the projector is always horizontal. The tilt turntable is used to rotate the axis of the flaw perpendicular to the stripe of light.

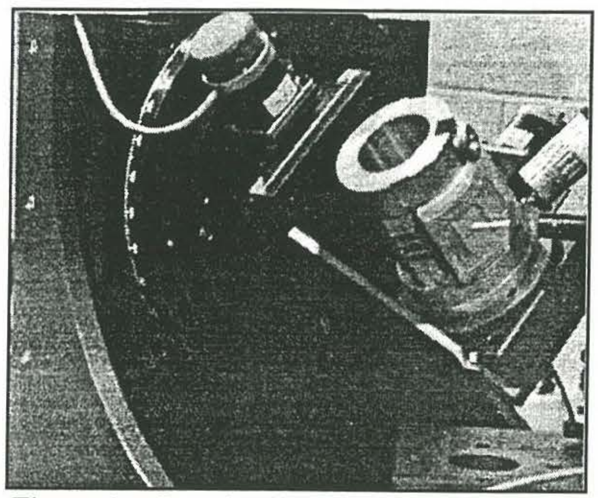

Figure 9. Sample tilted in FRILS-3 at 45°

A picture and an isometric plot of a replica of a debris flaw is given in Figure 10 below. The picture includes a ruler with 1 mm gradations. This flaw has a complex shape and needs to be scanned in several orientations to obtain cross sections of interest. The pressure tube axial direction is horizontal in the figure.

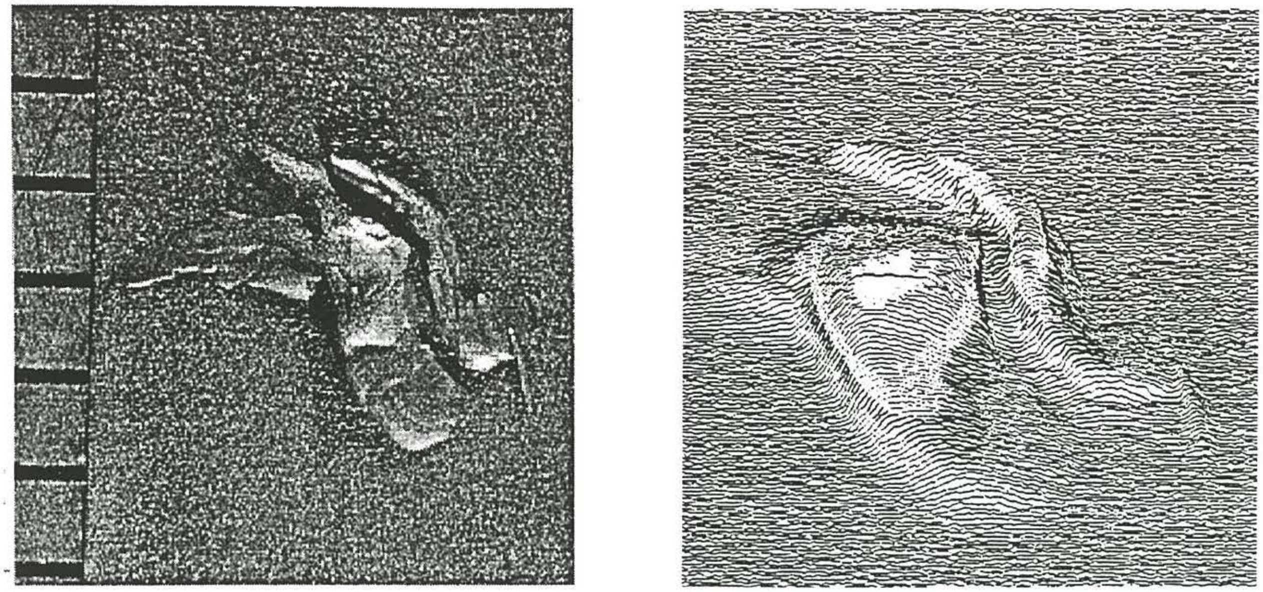

Figure 10. Debris flaw. Left - picture, Right - isometric plot of surface profiles

A rootview scan taken with the flaw tilted to profile a high stress area provided profile #98 for detailed analysis in Figure 11. The region of interest was set as horizontal locations 201 to 232; and a circle was automatically fitted to the data in this region, yielding a root-radius value of 78 micrometres. The algorithm for analysis of error gave an expected uncertainty in this value of 4 micrometres.

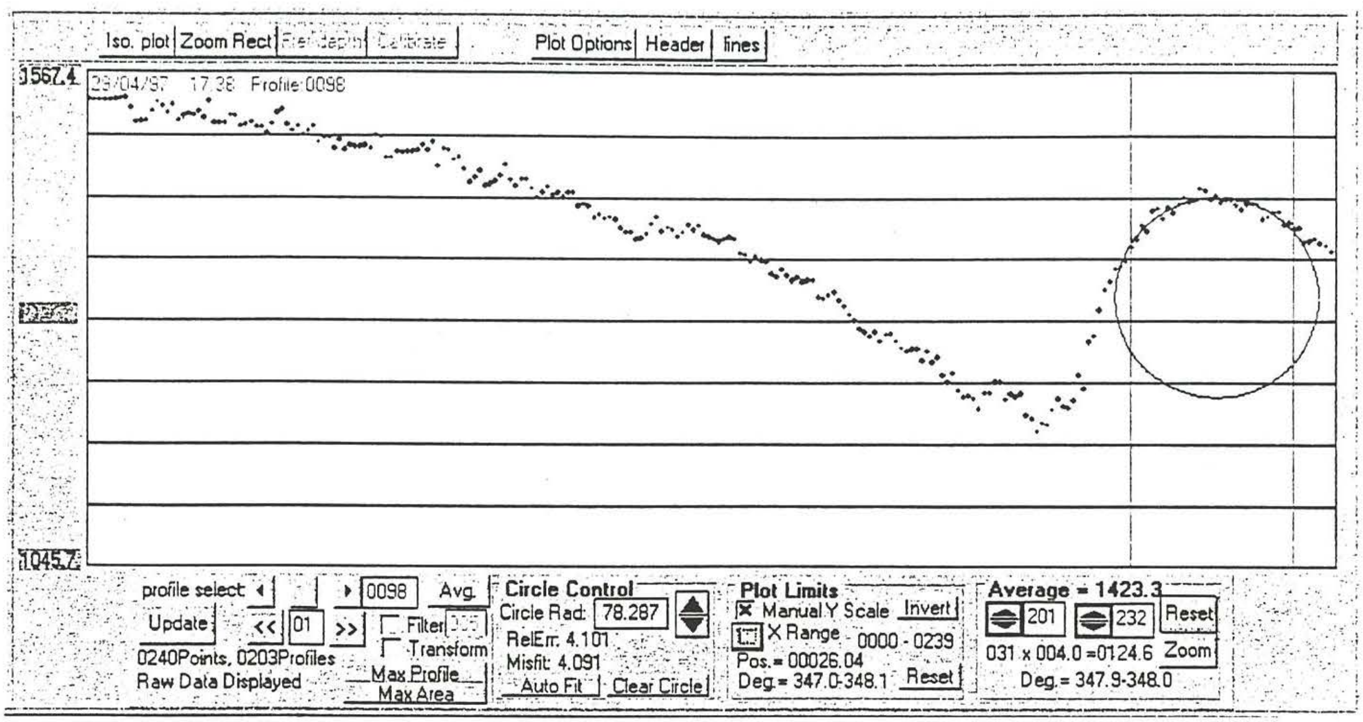

Figure 11. Circle fitting to root data gives radius of 78 μm.

Steam generator tubes can be scanned by a miniature optical profilometry tool that scans a point of light over the inside surface in a helical scan. This probe uses a point of light rather than a line of light as in FRILS and OPIT. The probe is delivered with the TRUSTIE motion system.

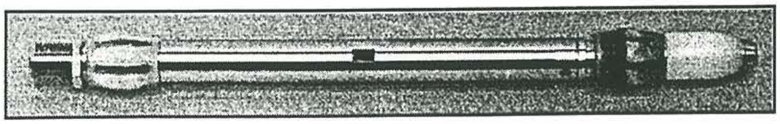

Figure 12. Steam generator probe, 0.275 inches diameter by 3.5 inches long

On one side of the window seen in Figure 12, there is an infrared laser with a focusing lens and a prism to direct the beam of light into a spot of light on the inside surface of the steam generator tube. On the other side of the window, there is a second prism to receive light scattered from the tube's surface and direct it horizontally to a focusing lens. This second lens images the spot of light onto a sensor which is inclined at an angle from the vertical such that the spot of light is in focus even on dents or pits, which occur at various depths. A miniature amplifier circuit is also included inside the probe, whose outside diameter is a mere 7 mm.

Figure 13 is a monochrome rendition of a pseudo-colour display of deformation due to a dent in a steam generator's inside surface. The dent is about 1.5 mm long (vertical dimension in the figure) and covers about 20 degrees circumferentially (horizontal dimension in the figure).

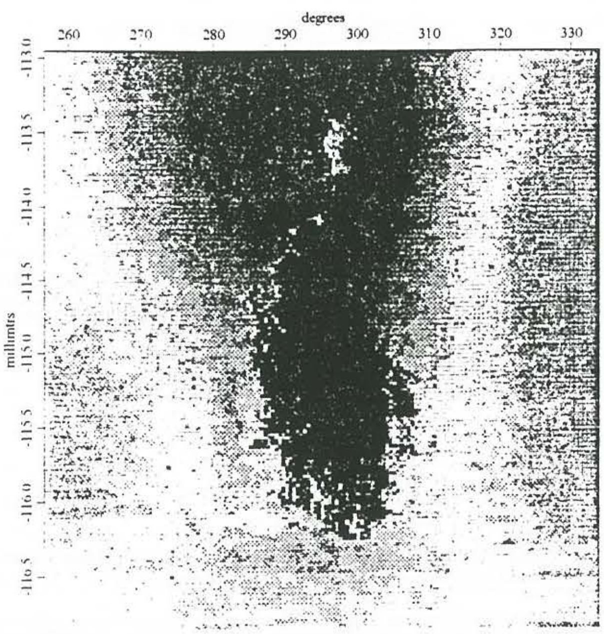

Figure 13. Dent in steam generator tube

Laser vibrometry was used at Darlington in 1992. The original 5-vane impellers for Heat Transport flow were causing excessive vibration. (This vibration lead to cracking of the end-plates of a small number of fuel bundles, and also to excessive fretting of fuel-bundle bearing pads on the inside surface of the pressure tubes). To support the proposed 7-vane solution, data were needed on fuel channel vibration. OHT developed a non-contact laser system to measure the vibration of end fittings. This system could tilt and pan the laser probe beam from one channel to the next, and acquire channel vibration amplitudes for a complete reactor face in 24 hours. With lead shielding for the vibrometer (seen in Figure 14) the in-vault system took data right up to full power operation.

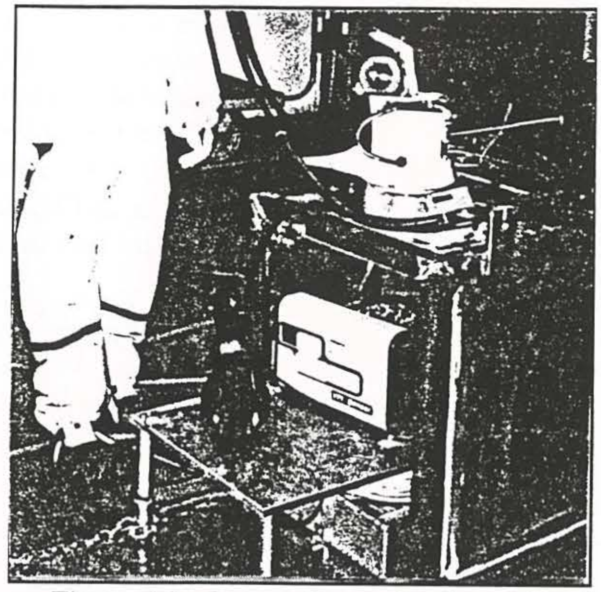

Figure 14. Laser vibrometer in vault

The software that was written for the laser vibrometer produced a velocity spectrum for each endfitting, and then produced a map, seen in Figure 15, for the reactor showing the vibration levels.

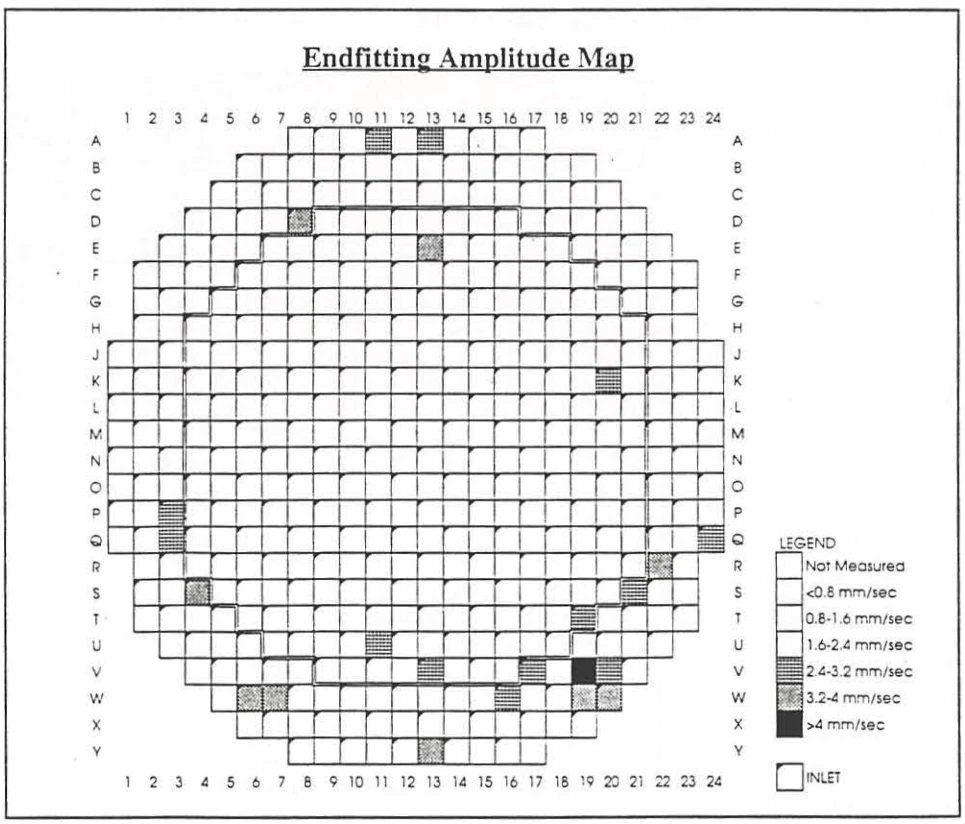

Figure 15. Reactor face map showing vibration amplitudes of endfittings

Computer vision for fuel bundle length measurement. A feasibility study was performed by GE Canada and OHT to test the concept of using a single video camera in an underwater housing to view fuel bundles in the irradiated fuel bay at Bruce-B NGS. At the time, the concept being explored was to distinguish between standard length fuel bundles (19.5 inches) and proposed extra-length bundles (20.0 inches). An experimental system was tested at Bruce-B using an aluminum mast to hold the camera and lights about 12 feet below the surface of the water, so that the camera could view the spent fuel in the receiving mechanism, as indicated in Figure 16.

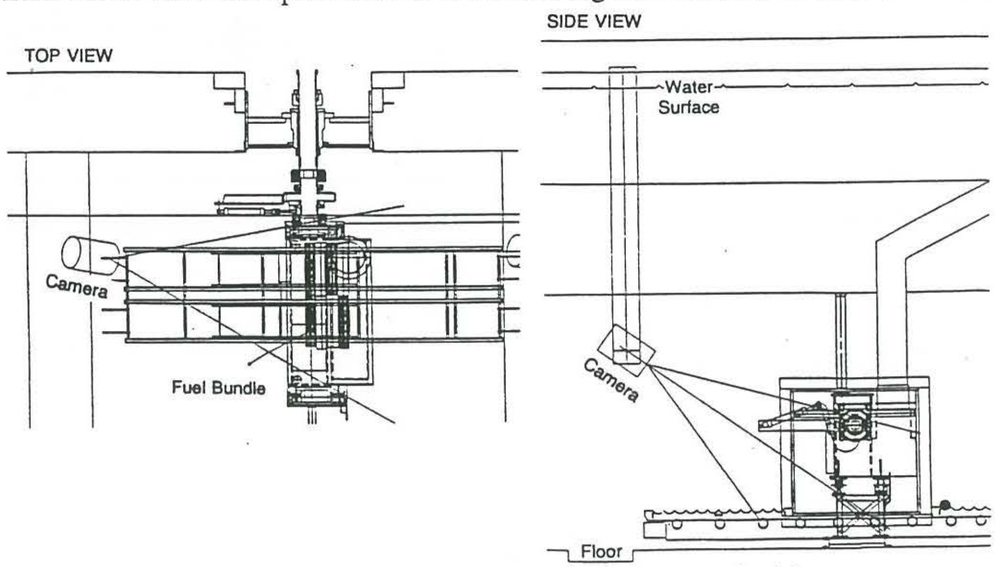

Figure 16. Position of video camera in spent-fuel bay.

Figure 17 shows a pair of standard bundles whose lengths were measured as 19.51 and 19.49 inches, respectively. In the figure (top) the image is overlaid with a computer-generated graphic to depict the outline of the bundles' endplates. The lower half shows the output of an algorithm that measured the striations along a vertical line in the image due to the fuel pencils. This function drops to a low value at the ends of the bundles, and was "sub-pixelized" to obtain high precision. The repeatability of bundle-length measurements was monitored automatically over several weeks, leading to the statistical expectation that less than one bundle would be mis-classified in the operating life of a reactor.

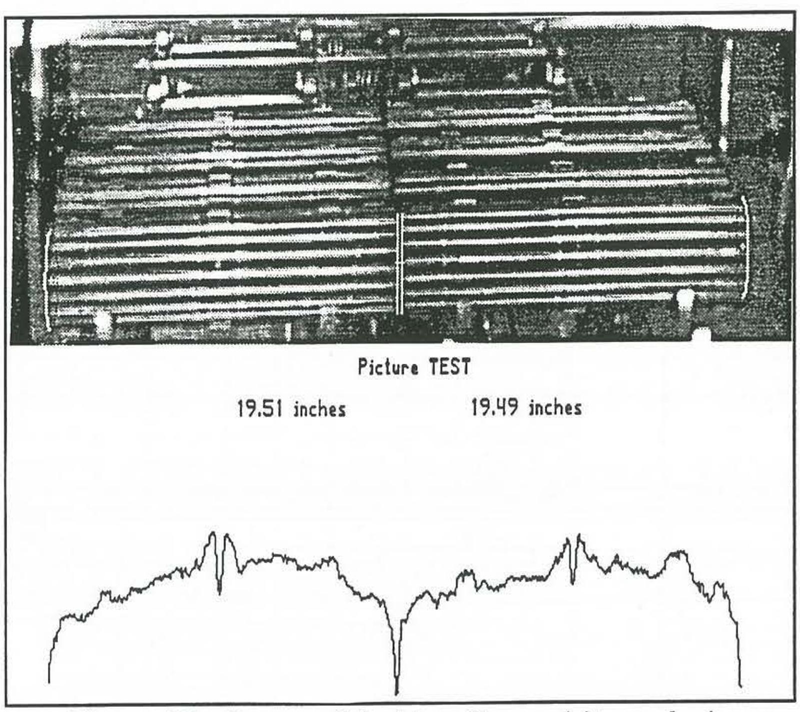

Figure 17. Image of fuel bundles and its analysis