RECENT DEVELOPMENTS IN POST-IRRADIATION EXAMINATION
TECHNIQUES FOR FUEL ELEMENTS

by

R Sumerling – UKAEA Windscale
C B Redding – UKAEA Winfrith
K Harding – UKAEA Winfrith

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This paper reports current developments in techniques for examining fuel pins at the UKAEA laboratories situated at Winfrith (Dorset), and Windscale (Cumbria) in the UK. The first item gives details on chemical cleaning of irradiated elements to remove crud deposit. These deposits obscure the pin surface and spread by-contamination, so that their removal has a double benefit in allowing more thorough visual examination and metrology, and easier maintenance of the cave facilities. The next two items deal with accurate measurement of diameters and profiles on complete fuel pins by air gauging (developed at Winfrith), and capacitance gauging (developed at Windscale). Comparison of the two methods is interesting.

The last two items deal with advances in techniques, using eddy-currents for flaw detection and measurement of oxide thickness, and ultrasonics for accurate measurement of cladding thickness.
A feature of boiling water reactor fuel is the build up of deposits of crud on the surface of fuel elements during operation. This crud layer plays an important, if totally unwanted, part in the reactor operation. In the first place if the layer grows too thick it will reduce heat transfer and cause damage to the fuel. However, by control of primary circuit conditions this can be avoided. Secondly, it is this crud layer on the fuel which is responsible for the production of activation nuclides, e.g., Co$^{60}$, which when subsequently released and transported to out-of-core parts of the system give rise to radiation fields which cause problems for maintenance and inspection. Finally, the presence of a masking layer of crud on the fuel gives rise to considerable problems when the post irradiation examination of the fuel takes place.

At the present time our knowledge of crud deposits on fuel has been obtained from small samples of material taken from elements either in the fuel handling pond or during in-cave examination. Although much valuable information has been obtained in this way it is extremely labour intensive and because of the possibility of large sampling errors the calculated values of total crud which are used in mass balance assessments are subject to uncertainty. In order to overcome the errors associated with discrete samples, and provide accurate data for the total crud and its composition on a fuel element, a rig has been built which can decontaminate full size fuel clusters. In addition to this information the decruded fuel available from the rig will enable post irradiation examination to be carried out more easily. Finally, the rig can be used for testing the effectiveness of alternative decontaminating solutions for removing crud from fuel elements.

Description of DECOR 3

The rig has been called DECOR 3, an acronym for Decruding Rig, and it is the decontamination rig in use at Winfrith. It is located in the Active Handling Building - where all the necessary facilities are available for handling irradiated fuel and relatively large volumes of active solutions. The plant consists of a vessel in which the decontaminating reagent can be mixed and heated to temperatures up to 95°C, a fuel cluster containment vessel in which an irradiated fuel cluster (held in a protective
carrier) can be placed. These two vessels are connected by 3'' diameter pipes and a pump circulates hot decontamination reagent from the heated header tank up through the fuel cluster at flow rates which are similar to those found in the reactor during a decontamination. A flow diagram of the rig is shown in Figure 7.1. The fuel cluster channel is located down a floor storage hole to provide the necessary shielding and other parts of the plant are shielded by concrete block walls. Access to the cluster channel for loading and unloading irradiated clusters is by use of a transport flask.

The rig is equipped with both physical and chemical instruments which enable the decontamination process to be followed in detail and to measure the total amount and composition of material removed from the element. In operation the degree to which each stage in the process is monitored will depend on the experimental requirements, eg, is crud inventory measurement or a clean fuel element the prime consideration or, alternatively, is a new decontaminating reagent being tested.
SECTION 2 - DIAMETER AND PROFILE MEASUREMENTS ON FUEL PINS USING AIR GAUGING

During three years of operational experience air gauging has been shown to be very suitable for in-cave measurement of the diameters of irradiated fuel pins and profile measurement. It has proved accurate and reliable in operation and being robustly constructed rarely requires any maintenance.

The operational procedure has been refined with the introduction of a new apparatus, which has improved the presentation of data and has reduced the amount of in-cave operation. The air gauge used for in-cave work consists of a saddle which is weighted to stay in position upon a horizontal fuel pin, Figure 2.1(F). The contact face is an anvil and, diametrically opposite is the air jet for measuring the diameters of the pins; a similar jet is positioned at 90° and is used to measure the profile changes. Here the contact face is in the same plane as the measuring jet. Each jet is connected by means of small-bore plastic tubing through the cave wall to the pressure measuring equipment outside.

The fuel pin to be measured is supported on stands 300 mm apart which are, slotted into an aluminium channel, and which can be lowered manually to avoid the passage of the air gauge. A chain driven trolley pushes the air gauge. The chain is driven by a motor via gearbox and a clutch. The clutch enables a rapid manual return to be made of the trolley. A separate motor and gearbox fitted with a chuck enables the pin to be rotated. Both these motor units and the chain drive are remotely removable for maintenance. The drive shaft of the pin rotating motor is fitted with a disc drilled with twelve holes around the circumference. When a solid state detector, behind a hole, detects the presence of a pin it can be used to control the motor drive and automatically rotate the pin (Figure 2.1(C)) through 30°.

The drive shaft of the axial motor is fitted with a similar but larger disc with many more holes, Figure 2.1(G), and detectors, enabling the trolley and air gauge to be moved along the pin, so that gauge readings can be taken at pre-determined intervals. The pressure readings are printed on a paper tape, and also onto a punched tape, together with the positional information. This punched tape is fed into a computer.

The air gauge is first placed on a gauge bar which has a number of diameters to cover the range of measurements required. The measurements are put onto the punched tape. This procedure is repeated for a profile.
measurement gauge-bar. From those measurements calibration curves are constructed and stored in the computer. The gauge and its trolley are placed at the beginning of the pin and the gauge traversed with the diameter and profile measurements displayed on a chart recorder. At specified distances along the pin, traversing is stopped and the pin rotated, and twelve measurements are made around the circumference. Traversing is then continued to the next position. When these pressure measurements are fed into the computer they are converted into actual diameters, and the maximum and minimum diameters selected. These diameters are then compared with the pre-irradiation measurements, Figure 2.2.

Examination of the chart output may reveal regions of the pin where high ridging occurs and the pin is then examined in more detail and further measurements taken, Figure 2.3. This technique is capable of resolving 2.5 μm on a prepared standard but under operating conditions the repeatable accuracy is found to be ±5 μm. From the measurements a detailed picture can be obtained of changes occurring as a result of irradiation of the fuel pin and can provide important information on the performance of the fuel element in the reactor.

\[ 0.0025 \text{ mm} \pm 0.005 \text{ mm} \]
At Windscale there was a need to develop a non-contact method of measuring displacement of fuel stringers undergoing test in a rig simulating gas-cooled reactor conditions. The system was developed specifically for extreme environments of high temperature; high noise and vibration levels, radiation and high gas flow velocities. The system uses a differential-charge carrier bridge amplifier (Figure 3.1(A)) which enables extremely small values of capacitance to be measured. These are typically $10^{-6}$ pF over cables 100 m in length, whose capacitance may be several tens of thousands of picofarads, without loss of sensitivity. It was realised that this capacitance gauge method could have other applications, including accurately measuring the profile or diameter of irradiated fuel pins.

A pair of gauge heads used to measure fuel pin diameters is shown schematically in Figure 3.1(B); each gauge head has two adjacent plates separated by an earth screen, and it is the mutual capacitance between these plates which varies with the proximity of the fuel pin (at earth potential). The amplifier measures the charge leaking between the two plates, this is related to the distance $D$ between the earth screen and the surface of the pin; thus, the output voltage is a measure of the separation between pin and gauge head. The gauge characteristic is not linear (Figure 3.2(A)) but by a suitable design of gauge head the working region A-B can be linearised to better than 1%. Thus, using the gauges separately the pin profile may be measured. If the outputs from the diametrically opposite gauge heads are summed then the output is a measure of pin diameter, providing that both gauges are working in the linear range. Displacement of the pin from the central axis may be monitored by measuring the differential output between the pair of gauge heads.

The head design objective was to maximise the linear range of the characteristic whilst making the head as small as possible in order to give good resolution. These requirements are conflicting and the final design was a compromise, using plates 12 mm x 1.5 mm in area either side of an earth screen 0.3 mm thick, which protrudes 0.25 ± 0.005 mm above the surface of the plates. The separation between plate and screen was 0.3 mm and the whole plate system was surrounded with an earthed case, with a minimum spacing of 0.5 mm.
The resultant characteristic is shown in Figure 3.2(B), with a 20 V pp 20 kHz carrier the total capacitance change for the maximum 1% linear range of 1.5 mm was almost $4 \times 10^{-3}$ pF. Because the amplifier is sensitive to variations in capacitance of $10^{-6}$ pF a resolution approaching 1 in 4000 is theoretically possible, ie $\sim 0.3 \mu$m on diameter under ideal conditions. However, to achieve an accuracy of $\pm 1 \mu$m, the pin must be concentric with the geometric centre to within $\pm 500 \mu$m parallel to the gauge heads and $\pm 125 \mu$m normal to the heads. With the present machine the measuring accuracy is $\pm 2.5 \mu$m, the area of measurement on the pin being $\sim 1$ mm in the axial direction and $\sim 2$ mm around the circumference. Further details of the gauge heads are given elsewhere\textsuperscript{(2)}.

In practice two pairs of gauge heads at $90^\circ$ to one another are used to measure diameters simultaneously in the two directions. The gauges are mounted in a test module approximately 10 cm x 10 cm x 3 cm (Figure 3.3(A)) which plugs into a pin-drive machine (Figure 3.3(B)).

Fuel pins are measured after crud removal, two typical traces along an irradiation fuel pin are shown in Figure 3.2(C). A modified form of the system employing a small diameter probe is being developed to measure oxide thickness\textsuperscript{(2)}.

References — Section 3

\textsuperscript{(1)} WALTON, H. Development of vibration measurements in severe environments. Int. Symp. vibration problems in industry Keswick 1973, UKAEA and NFL first joint meeting.

SECTION 4 - DEVELOPMENTS IN EDDY CURRENT TECHNIQUES

The use of eddy-current testing for examining irradiated fuel pins is now well established. The basic advantage of eddy-current techniques over ultrasonics is in the simplicity of the in-cell equipment. A pair of encircling test coils giving about 1 mm clearance either side of the fuel pin are contained in a plug-in module which fits in a pin-drive machine (Figure 3.3A). The pin-drive machine illustrated has space for two test modules so that various tests (diameter measurement, eddy-current testing or gamma-scanning) can be carried out simultaneously. The machine is fitted with stepping motors which drive the pin at speeds in the range 3 to 300 mm/minute, the slower speeds being used when gamma-scanning is being carried out.

The CNS Type 702D eddy current test equipment used gives two-phase output and is usually operated at 50 kHz; the encircling test coils are very sensitive to circumferential ridges and although this enables ridge heights to be estimated (to ± 5 µm) detection of cracks < 20% of the wall thickness is made more difficult. It is intended to carry out trials with an improved version of this equipment which uses two test frequencies simultaneously, this should enable better discrimination against unwanted signals.

The present equipment gives information on the axial location of a defect, and analysis of the two phase signals indicates whether it lies at the tube bore or outer surface. However, with defects giving signals equivalent to a hole ≤ 1 mm diameter it is often difficult to identify defects by metallographic sectioning. Suspect regions of pins are now given a second eddy current test in which the pin surface is helically scanned by a pencil type probe, with the output connected to a facsimile recorder, which displays the location and shape of the defect on a plan of the pin surface (Figure 4.1 and 4.2). The circumferential location and shape of any crack detected by this method is of value in deciding what type of metallographic section (if any) is required.

The eddy current system for this purpose was designed by Harwell (Type 3115), and is built up of modules which can be interchanged to suit inspection requirements. Whereas the system can operate at frequencies over a wide range (20 Hz to 10 MHz) a frequency of 120 kHz is used for testing fuel pins. The impedance changes in the search coil (wound on a
1 mm diameter ferrite rod) are quantised for display on the facsimile recorder.

Harwell have also developed another eddy-current system (Type 3134) for measuring the thickness of oxide in the outer surface of Zircaloy cladding (Figure 4.3). The oxide gauge is contained in a standard 10 x 10 x 3 cm module which plugs into the pin-drive machine described earlier. To measure the oxide thickness a probe coil wound on a 1.5 mm ceramic rod is pressed lightly on to the pin surface. The probe coil operates at high frequency (1.2 MHz) and senses the proximity of the metal underlying the non-conducting oxide layer. Between each measurement the probe is retracted from the surface to allow the pin to be moved to a new position, pneumatic control is used to actuate and retract the probe. The air supply is also used to clean the probe surface of dust between measurements.

The oxide gauge has a digital display which reads directly in μm; it is calibrated to read from 0 to 100 μm within ±3 μm accuracy on uniform oxide layers, or up to 200 μm with reduced accuracy. When dealing with nodular oxide the maximum oxide thickness can still be estimated from a knowledge of nodule geometry, providing a number of readings are taken, say at 1 mm intervals. However, at this point in time experience is still being gained with the instrument, and metallographic checks are still necessary. There is no doubt that in the future non-destructive measurements of this type will be increasingly used in order to avoid the expense of preparing and examining large numbers of metallographic sections.

References - Section 4

(3) PRESTWOOD, J and SOMERLING, R. NDT for irradiated reactor fuel pins by eddy currents and gamma scanning. Non-destructive testing, April 1975 pp 90-93.
The Non-destructive Testing Centre at Harwell has developed an ultrasonic thickness gauge (Type 3084-I/2) which measures metal thickness from 75 µm to 3 mm with an accuracy of typically ± 0.1%. This gauge has been adapted to measure the thickness of cladding on irradiated fuel pins. The gauge operates on the resonance principle; i.e., a pulse of ultrasonic energy of frequency $f$ is focused by an ultrasonic transducer on to the fuel pin through a water coupling (Figure 5.1) and the amplitude of the centre portion of the resultant echo pattern received back by the transducer from the cladding is measured (Figure 5.2). At the resonant frequency $f_r$, a sharp resonance absorption is obtained, the resonance frequency being a measure of the cladding thickness:

$$\text{Thickness} = \frac{v}{2f_r}$$

where $v =$ velocity of sound in the material ($\approx 4650$ m/s in Zircaloy).

For Zircaloy cladding ~0.7 mm thick a 3.5 MHz probe is used and the frequency is continually swept ± 15% of the centre frequency every $\frac{1}{30}$ second. If a 'good' resonance is found then the frequency sweep is automatically halted at the resonance dip (Figure 5.3) and the resonant frequency $f_r$ is measured; the reciprocal of this measurement is proportional to the cladding thickness which is displayed as a 4-digit number. Using cladding of known thickness the gauge is calibrated to read thickness directly in µm, the accuracy of measurement is within ± 3 µm. The measured cladding thickness includes the oxide thickness, and no correction is necessary provided the oxide film is thin ($<10$ µm).

The ultrasonic transducer is mounted directly under the fuel pin to be tested, and water coupling is achieved using a water column. The test block carrying the ultrasonic transducer can be moved along the pin while it is rotated, giving a helical scan of the pin surface. (The test block also carries an eddy current probe above the pin, on the helical scanning machine, Figure 4.1.) Output can be either on a pen recorder which plots maximum and minimum cladding thickness along the pin, or on a quantised facsimile recorder which maps the thickness contours over the pin surface. Where there is strong bonding of fuel to cladding resonance is not obtained, and cladding thickness cannot be measured. However, mapping of the areas of strong bonding along a fuel pin is useful in understanding fuel-cladding...
interactions. The present helical scanning machine is compact (≈45 cm long) but can measure pin lengths up to 1 metre long in 15 cm sections.
(A) RADIAL DRIVE END

(B) REMOVAL OF PIN ROTATING UNIT

(C) RADIAL POSITION INDICATOR (COVER REMOVED)

D) RECORDING EQUIPMENT

RATCHET REVERSING DRIVE
PIN LENGTH MEASURING GAUGE
FUEL PIN
SEQUENCE START HOLE
SOLID STATE DETECTORS
AIR GAUGE UNITS
FIG 2.2 TYPICAL DIAMETER CHANGES
FIG 2.3 CLADDING PROFILE TRACE
FIG. 3.1a. DIFFERENTIAL CHARGE AMPLIFIER SCHEMATIC.

FIG. 3.1b. PLATE CONFIGURATIONS OF CHARGE TRANSUDCERS.
FIG. 3.2a. DISPLACEMENT TRANSUDER CHARACTERISTIC.

FIG. 3.2b. DIAMETER MEASURING HEAD CHARACTERISTICS.

FIG. 3.2c. TYPICAL DIAMETER TRACES ALONG IRRADIATED FUEL PIN USING CAPACITANCE GAUGES.
FIG 4.1. HELICAL SCANNING MACHINE WITH EDDY-CURRENT PROBE (TOP) AND ULTRASONIC THICKNESS GAUGE (BOTTOM)
FIG. 4-2 FACSIMILE RECORDER OUTPUT USED WITH HELICAL SCANNING MACHINE. EDDY CURRENT SIGNAL FROM TUBE HAVING AN AXIAL STRESS-CORROSION CRACK ILLUSTRATED.
FIG 4.3. OXIDE THICKNESS GAUGE DEVELOPED BY THE N.D.T CENTRE, HARWELL.
**FIG. 5.1.** ARRANGEMENT OF TRANSDUCER AND WORKPIECE.

**FIG. 5.2.** ECHO PATTERN.

**FIG. 5.3.** RESONANCE ABSORPTION CURVE.