NON DESTRUCTIVE EVALUATION OF IRRADIATED NUCLEAR FUEL PINS AT CIRUS RESEARCH REACTOR BY NEUTRON RADIOGRAPHY

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ABSTRACT

Neutron radiography can be used very effectively to investigate performance of nuclear fuels. Some of the details that can be resolved in irradiated fuels by neutron radiography are massive hydriding locations in the zircalooy cladding and the end caps of the fuel pin, cracking of fuel pellets, evidence of fuel densification, mix up of enrichment in the fuel column, etc. The difference in the attenuation characteristics of neutrons in different materials is taken advantage of in the neutron radiography process. Neutron radiography of irradiated PHWR fuel elements and experimental Thoria-Plutonia MOX fuel pins was carried out using the thermal neutron beam hole of CIRUS reactor. Massive hydriding was detected in the fuel element cladding which threw light on the cause of fuel failure. The pellet cracking, both axial and circumferential, were also detected by Neutron Radiography. The plenum spring and contours of top and bottom end plugs of the fuel element were also imaged using neutron radiography. The difference between the dished and the flat ends of the fuel pellets were clearly distinguishable in the neutron radiographs.

Keywords: Neutron Radiography, Irradiated Nuclear Fuel Pin, Thoria Plutonia MOX

INTRODUCTION

Radiography using thermal neutrons is most useful because in this energy range neutrons have favourable attenuation characteristics in the material of interest in an irradiated nuclear fuel and they are easier to detect by radiography. The data available from neutron radiography (NR) are direct and basic in nature and supplement the data obtained from other non-destructive tests required for planning the detailed destructive examination. This paper discusses the important features of the set up, the methodology followed for neutron radiography and the findings on irradiated nuclear fuels.

In view of the wide scope and immense advantages of NR, a shielded facility was set up at research reactor CIRUS, in BARC, for post-irradiation examination. Handling of irradiated materials is itself a difficult job, involving handling of highly radioactive fuel elements. Irradiated fuels require

<table>
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<th>Element</th>
<th>(\sigma_s) (barns)</th>
<th>(\sigma_a) (barns)</th>
<th>Element</th>
<th>(\sigma_s) (barns)</th>
<th>(\sigma_a) (barns)</th>
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<tr>
<td>Aluminum</td>
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<td>0.24</td>
<td>Hydrogen</td>
<td>38-100</td>
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<td>Beryllium</td>
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<td>0.10</td>
<td>Iron</td>
<td>11</td>
<td>2.62</td>
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<tr>
<td>Bismuth</td>
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<td>0.034</td>
<td>Lead</td>
<td>11</td>
<td>0.17</td>
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<tr>
<td>Boron</td>
<td>4</td>
<td>755</td>
<td>Nitrogen</td>
<td>10</td>
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<tr>
<td>Cadmium</td>
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<td>2450</td>
<td>Oxygen</td>
<td>4.2</td>
<td>0.0002</td>
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<tr>
<td>Carbon</td>
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<td>Sodium</td>
<td>4</td>
<td>0.53</td>
</tr>
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<td>0.0005</td>
<td>Uranium</td>
<td>8.3</td>
<td>7.68</td>
</tr>
<tr>
<td>Helium</td>
<td>0.8</td>
<td>0.007</td>
<td>Zirconium</td>
<td>8</td>
<td>0.185</td>
</tr>
</tbody>
</table>
casks with adequate shielding for transportation from hot-cells to the reactor facility for carrying out NR. The problem of NR of irradiated materials is complicated in view of the difficulty in handling the highly radioactive material. The problems are overcome by constant use of shielding as per the requirements at every step of the activities involved and use of indirect radiography method. Mainly three types of neutron sources are used for radiography i.e. nuclear reactors, particle accelerators and radioisotopes. The nuclear reactor as a source stands out for its source intensity. The neutron source used for the present work is the thermal neutron beam hole in CIRUS reactor. The thermal neutron cross section data for some of the elements is given in Table-1 for comparison.

**Imaging Technique**

Indirect radiographic method was used for radiography of highly radioactive materials to avoid undue fogging of the X-ray film used for recording. The screen material becomes radioactive on neutron absorption and is used for transfer of the image to the X-ray film. The half-life of the screen material should be, a) long enough to enable retention of maximum information in the stored image prior the transfer to the film, b) short enough for convenient transfer and re-use. The screen materials generally used are Indium (In) and Dysprosium (Dy), both of which are \( ^{144}\text{In} \) and \( ^{164}\text{Dy} \) in the activated state. The half life for \( ^{144}\text{In} \) is 54 minutes and for \( ^{164}\text{Dy} \) it is 140 minutes. In the present work Dy foil was used as it has sufficient half life for film exposure and decays to almost nil next day for re-use. The thickness of the Dy foil used is ~100µm. The neutron absorption in this thickness range is almost uniform and most of the \( \beta \) emitted from the foil is recorded on the X-ray film.

**Description of the Neutron Radiography Set up**

The neutron radiography set up consisted of 4 major parts; a) Bottom cask, b) Middle cask, c) Top cask and d) Neutron beam tunnel cask as shown in Fig.1. The bottom part is a cylindrical lead filled cask, which is below the neutron beam line. This cask has a central hole aligned with the top and the middle casks, where the fuel element cassette is to be housed. The middle cask is an intermediate cask with matching curved interface for accommodating the top and bottom casks. The middle cask is provided with a side hole for the neutron beam to reach the fuel pin and subsequently to the Dy foil placed in the cassette in it. The side hole in the middle cask is aligned with the neutron beam tunnel cask and the neutron beam hole in the reactor. A separate side hole, in the form of a slit at 90° orientation with respect to the beam hole, is provided in this cask for the cassette with dysprosium foil to pass across.
the beam hole, allowing the neutron beam to fall on the Dy foil for imaging. Both, the bottom and middle casks are provided with additional shielding of borated wax and lead bricks to achieve the necessary reduction in the radiation field for working (This additional shielding is not shown here in the drawing for clarity). The function of the neutron beam tunnel cask is to guide the neutron beam from the reactor to the fuel pin and the Dy foil for radiography. Both the tunnel cask and the middle cask are made of Pb-10% Cd alloy for neutron shielding and additional lead shielding to take care of gamma radiation. The tunnel beam cask is provided with a jacket of borated wax of 350mm thickness, encased in steel containment, as shown in the Figure.1, for augmentation of neutron shielding.

The top cask houses the fuel element in a sealed cassette made of Zircaloy tube. This cask is aligned vertically over the middle cask. The fuel element housed in the sealed cassette (fuel pin cassette) is lowered from the top cask in steps during the process of radiography. The fuel pin cassette is provided with top and bottom shielding arrangements, adequate to cut down the radiation to an acceptable level during transportation and handling for radiography. The top cask is also used for transportation of fuel pins from the hot cells to reactor hall.

A structural steel frame work encasing the top, middle and bottom casks is provided to avoid accidental toppling of any cask from the assembly. A wire rope and pulley arrangement is provided with the structural frame to hang the fuel pin cassette from the top and to move the fuel pin up and down for radiography. Entire fuel pin length is covered during radiography in nine segments. The set up is also provided with a facility to rotate the fuel pin at any angle about its axis, at any elevation.

**Neutron Radiographic Image Quality/Sensitivity**

The usual objective in radiography is to produce an image showing the maximum amount of details possible. This requires careful control of a number of different variables that can affect the image quality. Radiographic sensitivity is a measure of the quality of an image in terms of the smallest detail or discontinuity that can be detected. This is dependent on two independent sets of variables. One set of variables affects the contrast and the other set of variables affects the definition of the image. The variables affecting contrast are absorption / scattering difference, secondary radiation from scattering, film quality and film processing details. The definition of the image is affected by geometric factors for the set up such as source size, distance between the source to film and from the specimen to film, the film quality and film processing details. In the present exercise the exposure time for Dy foil and the transfer time from the foil to the X ray film were varied to obtain a good image. Intentionally introduced defects in an un-irradiated fuel pin were used as the sample for this purpose. Samples with the known defects were exposed for neutron radiography, with above mentioned two parameters as variable, and the radiographs were studied. Details of the samples and the NR generated in this exercise are given in Figs. 2-4. Two holes of 1mm and 2mm diameter at two locations along the length of the fuel pin were made and filled with wax, zirconium powder paste and cadmium. The NRs of the fuel pins are as in Figure.2 & 3.

a) A specially fabricated PHWR fuel pin with a central hole.

It was observed that the foil with an exposure of 15 minutes, waiting time of 10 minutes and with 9, 11, 15 minutes of film exposures gave satisfactory radiographs. The holes on the fuel pin and central hole in the fuel pin were visible with different film density over the pellet background of grey shade. The wax filled holes in the end cap weld region were clearly distinguishable, while the cadmium (poison) spot was seen as a bright spot. Pellet to pellet double dish gaps appeared black. The internal contours of end cap with inner ring were also distinguishable.

**Neutron Radiography of Irradiated Failed PHWR Fuel Pin from KAPS-II**

An outer pin of the 19 element PHWR fuel bundle from KAPS-II reactor had failed at a low burn up of 387 MWD/Te(U) and had an in-reactor residence period of only for 17 days. It had

![Pellet Cd ZrH₂ Wax](image1)

![Pellet ZrH₂ Wax](image2)

![Central hole](image3)
double dished pellets in a 0.4mm thick Zircaloy-4 clad tube of about half a meter length. One of the fuel pins was found to have cracked axially, near the end plug weld, spanning over the cladding portion covering the first two pellets. This low burn up fuel pin was selected for NR to correlate the cause for the early life failure. The outer surface of the fuel pin was cleaned and loaded in the Zircaloy-2 fuel cassette and was transported to the reactor site in the top shielding cask. The shielding cask was vertically oriented on the NR setup and fuel pin container was engaged with wire rope. The first exposure covered around 75mm of bottom end of fuel pin, coming in front of neutron beam. The bottom end segment containing the axial cracks was radiographed with 120° angular rotations (three orientations) of fuel pin. A white spot was observed in the radiograph, indicating the presence of massive hydriding (~2mm Ø region) as shown on left hand side of Fig.5. The hydride spot fell over the same distance range of the observed cracks.

The dysprosium foil in the cassette being in close proximity to the fuel pin gave the image having dimensions very close to the real dimensions of the fuel pin and the fuel pellets. In one of the angular positions of the same region of the fuel pin the radiograph showed that the corner of a fuel pellet had broken. The corners of the first pellet are also seen flattened, which can be probably attributed to be due to the degradation caused by the coolant entering inside the fuel pin through the failure. The internal contour of the end cap, such as the inner ring, is also seen clearly. The other end cap weld and the inner ring appear strikingly white which can be speculated to be due to ring-hydriding. The fuel pellet close to this region had a circumferential crack.

Irradiated Experimental ThO₂ Fuel Pin from BC-8 Fuel Cluster

The BC-8 cluster of experimental fuel elements consisted of 12 graphite coated Zircaloy-2 clad fuel pins of wall thickness of 0.38 mm, containing fuel pellets of (U, Pu)O₂, (Th, Pu)O₂, UO₂ and ThO₂ (94% T.D). The experimental fuel pin T-02 contained ThO₂ pellets with helium filler gas. The cluster BC-8 was irradiated in the Pressurized Water Loop (PWL) of CIRUS research reactor up to a burn up of 10,000 MWD/Te. Gamma scanning for the Cs¹³⁷ isotope showed an unusually large gap of 3 mm between two pellets in the mid length region of the fuel pin and hence this pin was selected for neutron radiography. Fig.6 shows the details of the NR obtained from this fuel pin.

The thoria fuel pin T-02 has performed well during irradiation as no wide cracks were observed in the neutron radiograph. All structural appendages are intact at both the ends.

Irradiated fuel pin from experimental fuel pin cluster AC-6 (ThO₂+4%PuO₂)

The experimental fuel pin cluster AC-6 was made up of six pins having ThO₂+4%PuO₂ (MOX) pellets and helium filler gas. Five of the pins consisted of ThO₂+4%PuO₂ fuel pellets encapsulated Zr-2 BWR clad tubes. The remaining one was
fuel pin that has ThO$_2$ pellets was seen to have performed well in the reactor, which might be attributed to the lower heat generation of the fuel pin as ThO$_2$ is not a fissile material. The AC-6 cluster fuel pin had 4%PuO$_2$ and consequently higher heat generation. The NR shows multidirectional cracks in number of pellets. The observed features from neutron radiography will be correlated with the results of metallographic studies which are in progress.

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REFERENCES


The neutron radiography of the low burn up failed fuel pin from KAPS-II reactor indicates massive hydriding in the cracked area of the clad. In the same pin the other end cap weld appears to be hydried circumferentially. In the fuel pin from BC-8 cluster a ~ 3mm gap is also observed from the NR, which corroborates with gamma scanning results. The BC-8 fuel pin that has ThO$_2$ pellets was seen to have performed well in the reactor, which might be attributed to the lower heat generation of the fuel pin as ThO$_2$ is not a fissile material. The AC-6 cluster fuel pin had 4%PuO$_2$ and consequently higher heat generation. The NR shows multidirectional cracks in number of pellets. The observed features from neutron radiography will be correlated with the results of metallographic studies which are in progress.

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