Recent advances in NDE techniques during PIE of irradiated nuclear materials

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### PIE Techniques for fuel and structural components examination in hot cells

#### Non-Destructive
- Visual Examination by Periscope, In-cell Camera
- Leak testing by Liquid Nitrogen & alcohol
- Ultrasonic Testing
- Eddy Current testing
- Three Point Micrometer
- Profilometry by LVDT & Laser
- Gross Gamma scanning
- Gamma spectrometry
- Micro-$\gamma$-scanning
- Neutron Radiography

#### Destructive
- Optical Microscopy
- Fission gas analysis
- Mechanical testing
- Small punch & ABI tests
- Fracture toughness
- SEM
- X-ray fluorescence
- $\beta/\gamma$ and $\alpha$ autoradiography
- X-ray diffraction/texture
- Burn-up measurement
- Hydrogen analysis
- Chemical analysis

### Mechanical tests on irradiated Materials
1. Tension tests (Pressure tube, Cladding, Garter Spring)
2. Fracture toughness test (pressure tube)
3. Slit Burst Test (PT)
4. Crush test (Garter Spring)
# PIE facilities in BARC

<table>
<thead>
<tr>
<th></th>
<th>Old hot cells</th>
<th>New Hot cells</th>
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<tbody>
<tr>
<td><strong>Commissioning</strong></td>
<td>1974</td>
<td>2015</td>
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<tr>
<td><strong>Capacity of handling radioactivity</strong></td>
<td>$10^2 - 10^5$ Ci of Co$^{60}$</td>
<td>$2.5 \times 10^5$ Ci of Co$^{60}$</td>
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<tr>
<td><strong>Port size for loading fuel/components</strong></td>
<td>150 mm diameter</td>
<td>500 mm x 500 mm section</td>
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<td><strong>Length of the cell</strong></td>
<td>4.8 m (6 Cells)</td>
<td>16.9 m and 4.8 m (2 Cells)</td>
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<td><strong>Material lifting equipment</strong></td>
<td>Manipulators</td>
<td>Manipulators &amp; Incell crane</td>
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540 MWe fuel failure investigation
Bundle configuration

Peripheral/outer pins- 18 nos.
Intermediate 1- 12 nos.
Intermediate 2- 6 nos.
Central- 1 no.
Transfer of the fuel bundles inside the hot cell

Docking of the fuel transport cask

Bundles inside the cassette inside the cell
Fuel Bundle Visual Examination and Dimensional measurement

Ridge marks on the outer pins of the high burn-up fuel bundle
Bundle Dismantling

19-pin Fuel Bundle Dismantling

Universal Fuel Bundle Dismantling Set-up

End view after dismantling

Fuel Bundle

Saw Blade

Fuel pin stand
Visual examination of KAIGA-4 fuel pin

Circumferential detachment of end plug by weld region massive hydriding

Yellow colour shows oxidation to higher oxide $\text{UO}_3$
Ultrasonic testing of end cap weld

Fuel element

Probe

Ultrasonic signal from a sound end-plug weld

UT for weld fusion line and root crack in one rotation

Ultrasonic signal from a lack of fusion defect in the end-plug weld
Acceptable if fusion > 90% of WT
Root cracks ≤ 0.04 µm
Ultrasonic detection of incipient flaws in the clad wall

Offset probe for axial flaws

Angled probe for circumferential flaws

For fuel pin clad, UT beam enters from OD surface
For Pressure tube UT beam enters the wall from ID surface
UT of fuel pin clad for incipient flaws

ULTRASONIC IMMERSION SCANNER FOR IRRADIATED PHWR FUEL PIN CLAD

Flaw signal

Surface signal

GATE-SL Gate-A
A-START 10.00m
A-WIDTH 5.00m
A-THRSH 40%

Power Ramped Bundle No.025730

clad

High burnup Bundle no. 145530
Neutron Radiography
Why Neutron Radiography, not X-Radiography?

- X-radiography can not detect zirconium hydride blister in fuel pin clad/weld
- X-rays limited penetration in dense nuclear fuel pellets
- Gamma radiation from irradiated fuel pin fog the optical films/CCD camera

Advantages of Neutron Radiography

- NR is based on attenuation of neutrons, different kind of interaction with diff. atoms
- Penetrate dense nuclear fuel pellets
- Fuel densification/swelling/cracking pattern
- Change in the fuel pellet shape.
- Pellet dish gap closure.
- Clad collapse/deformation.
- Enrichment mix up in BWR/FBTR.
- Neutron poisons Cd, Gd, B, In, Dy,
- Water inside a failed fuel pin.
- Pellet crack central hole.
- Fuel pin internal geometrical details/end cap weld scoop/plenum springs etc.
Neutron Radiograph of calibration defects

- PHWR fuel pin
- BWR fuel pin
- PHWR fuel pin with central axial hole
Neutron radiograph of failed fuel pin 2

Zirconium hydride in the clad in the crack region

Zirconium ring hydride

Crack

Dished end of the pellet washed out

Pellet crack
Hydride blister predicted by Neutron Radiography at the tight crack near the end of the fuel pin confirmed by Metallography
$\text{UO}_2 + \text{D}_2\text{O} = \text{UO}_{2+x} + \text{D}_2$

$\text{D}_2\text{O}$

$\text{UO}_2$

$\text{Pellets}$

$\text{Crack}$

$\text{ZrD}_2$
Nodular Corrosion on Pressure tubes
White spots are of nodular corrosion
Nodule detection on irradiated pressure tube by immersion angle beam ultrasonic testing
Conclusions

- The cause of fuel failures were mostly due to defects in the end plug region and hydriding from higher internal moisture content.

- Visual examination in hot-cell with proper illumination and magnification can find out the ridges on fuel pins and open cladding cracks.

- Ridge height and fuel swelling are measured by non contact Laser profilometry.

- UT detects the defects in the end cap weld and incipient cracks in the clad.

- Neutron radiography can find out the hydride blisters in clad, pellet crack pattern, filling of dish gaps, internal geometrical contours etc.

- An ultrasonic testing technique has been developed to detect nodular corrosion in irradiated pressure tubes.

- A number of NDE techniques are required to generate complete information about root cause of failures.
Thanks for your patience