INVESTIGATION OF FAILURE OF HIGH BURN UP CARBIDE FUEL PIN OF FBTR THROUGH POST-IRRADIATION EXAMINATION

V. KARTHIK, RAN VIJAYKUMAR, V.V. JAYARAJ, V. ANANDARAJ, B.K. OHJA, C. PADMAPRABU, A.VIJAYARAGAVAN, T. ULAGANATHAN, C.N. VENKITESWARAN, SHAJI KURIEN, T. JOHNY, R. DIVAKAR, JOJO JOSEPH, S. VENUGOPAL AND T. JAYAKUMAR

Metallurgy and Materials Group
Indira Gandhi Centre for Atomic Research
Kalpakkam 603102, India

HOTLAB 2015 – Leuven, Belgium
Indira Gandhi Centre for Atomic Research (IGCAR)

- Development of Fast Reactor Technology
- Development of Fuel cycle technology for FBR
- FBTR as Test bed for Fuel & Structural materials irradiation

Fast Breeder Test Reactor (FBTR)
(40MWt Sodium cooled reactor operating since 1985)

500MWe Commercial Fast Reactor (PFBR) – to start operation in 2016
**FBTR Fuel Sub-Assembly and Fuel Pin**

![Diagram of FBTR fuel sub-assembly and fuel pin]

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of fuel pins per subassembly</td>
<td>61</td>
</tr>
<tr>
<td>Fuel</td>
<td>(U_{0.3} Pu_{0.7})C</td>
</tr>
<tr>
<td>Cladding material</td>
<td>20% CW 316 SS</td>
</tr>
<tr>
<td>Fuel stack length</td>
<td>320 mm</td>
</tr>
<tr>
<td>Type of bond</td>
<td>Helium</td>
</tr>
<tr>
<td>Fuel density</td>
<td>90% of T.D</td>
</tr>
<tr>
<td>Smear density</td>
<td>83% of T.D</td>
</tr>
<tr>
<td>Outer diameter of fuel pin</td>
<td>5.1 mm</td>
</tr>
<tr>
<td>Clad Thickness</td>
<td>0.37 mm</td>
</tr>
</tbody>
</table>
• Seven $\alpha/\beta/\gamma$ inert atmosphere concrete hot-cells • Glove boxes and Fume Hoods • Remote Handling and Viewing devices • Master-slave manipulators, power Manipulators • In-cell Cranes, periscopes, shielding windows, cameras • Alpha-tight material transfer systems • Inert Gas Ventilation System • In-cell Equipments & Gadgets • Waste-drum Pu assay system
Characterization of Irradiated Materials

- Fuel receipt
- Visual examination
- Sodium removal
- Profilometer & laser dismantling
- X & Neutron radiography
- Gamma scanning
- Fission gas extraction & analysis
- Remote metallography
- High temperature tensile testing
- Small specimen testing
- Electron microscopy
Major PIE Campaigns (since 1994)

- PIE of FBTR core components
  - PIE of fuel sub-assemblies from 25 to 155 GWd/t
  - PIE of Control rod assembly
  - PIE of Nickel reflector sub-assembly
  - PIE of pre-fabricated grid plate material (near core structure)
  - PIE of Failed FBTR fuel sub-assembly
- Evaluation and validation of PFBR MOX fuel design
  - PIE of experimental MOX fuel pin – Beginning of life studies
  - PIE of MOX test fuel sub-assembly after 112 GWd/t burn-up
- Development & installation of equipment in operating hot cell
- Maintenance and decommissioning of hot cell equipment
- PIE of Ferroboron shielding material & Sol gel fuel
- Gearing up for PIE of Metallic fuel pins
PIE OF 70% PuC - 30% UC CARBIDE FUEL

- Design burn-up limit for FBTR fuel – 50 GWd/t
- Stage wise assessment of fuel performance through PIE and burnup enhancement upto 155 GWd/t

- Experimental fuel pins
  - Fuel cracking and reduction in the fuel-clad gap at low burn-up
  - Amenability for operation at higher linear power

- PIE after 25 and 50 GWd/t burn-up
  - Absence of FCMI till 50 GWd/t (fuel-clad gap available)
  - Negligible wrapper and cladding strain

- PIE after 100 GWd/t burn-up
  - Gap closure at peak power location (**Initiation of FCMI**)
  - Low fission gas release & pressure

- PIE after 155 GWd/t burn-up and 400 W/cm LHR
  - Exhaustion of sinter porosities in the outer rim of the fuel indicating FCMI
  - Decrease in Strength & ductility of cladding
  - Reduction in Inter subassembly gap –Wrapper swelling

- Variation in flat to flat distance of hexacan
- Variation in center to corner distance of hexacan
- Diametral strain on fuel pins as a function of burn-up

- TEM micrograph showing extensive void formation in clad
- SEM fractograph
Around 1500 carbide fuel pins have attained burnup of 155 GWd/t

Earlier PIE campaigns were on Fuel from I ring or Central location

- A fuel pin failure was identified for the first time based on delayed neutron detector signals and cover gas activity

<table>
<thead>
<tr>
<th>Location of failed subassembly</th>
</tr>
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<table>
<thead>
<tr>
<th>Fuel</th>
<th>((U_{0.3}Pu_{0.7})C), Helium bonded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Burn-up</td>
<td>148.3 GWd/t (Failed FSA)</td>
</tr>
<tr>
<td>Peak LHR</td>
<td>280 W/cm</td>
</tr>
<tr>
<td>Location in Core</td>
<td>III Ring (03 06)</td>
</tr>
<tr>
<td>Na inlet/outlet Temp</td>
<td>348°C/435°C up to 125 GWd/t 380°C/480°C up to 148.3 GWd/t</td>
</tr>
<tr>
<td>Neutron Damage</td>
<td>85 dpa NRT</td>
</tr>
</tbody>
</table>
Identification of Failed Pin(s)

Failed fuel subassembly taken into hot cell
Subassembly wrapper dismantled and fuels pin retrieved
All pins screened visually through Periscope & CCD Camera

Failure location extends about
170 mm - 240 mm from the top of fuel pin top

• Failure identified in one pin only
• All other fuel pins were confirmed to be intact by He leak testing & Eddy current inspection.
**Strategy adopted to analyze cause of clad rupture**

- A set of pins across the hexagon were chosen for comprehensive assessment of condition of fuel/clad and to identify signatures of impending failures, if any

- **Severity of rupture in failed pin precluded inspections like metrology, eddy current and tensile**

- **Multiple NDE were done on 12 pins and based on the results, destructive examination on 4 pins**

- **Limited examinations were done on few pins from another III ring FSA (Unfailed)**

Comparison of PIE results

 III ring FFSA (Failed) - 148 GWd/t  
 vs  
 I ring FSA - 155 GWd/t – earlier examined  
 III ring FSA (Unfailed) - 155 GWd/t
Diametral & Axial strain of fuel pins

Diameter profile of pin adjacent to failed pin

Peak diametral strain of III ring fuel pins (6.2%) higher than I ring pins (5.3%)

Length increase higher in III ring pins (6.8 mm) compared to I ring (4.28 mm)

Ovality (profiles different in 2 orientations)

Localised bend/distortion

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<table>
<thead>
<tr>
<th>Dimensional changes of fuel pins</th>
<th>Diameter Increase (mm)</th>
<th>Length Increase (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I ring (155GWD) (13 pins)</td>
<td>0.180 - 0.270</td>
<td>1.90 - 4.28</td>
</tr>
<tr>
<td>III ring FSA (failed) (12 Pins)</td>
<td>0.185 - 0.320</td>
<td>2.49 - 5.92</td>
</tr>
<tr>
<td>III ring (unfailed) (4 pins)</td>
<td>0.270 - 0.320</td>
<td>5.40 - 6.80</td>
</tr>
</tbody>
</table>

LVDT traces

Location of bend matches with failure location of failed pin
Swelling & FCMI Components of Diametral strain

Total Diametral strain = Swelling creep + Creep strain

Low swelling clad in III ring pins (as compared to I ring pins)

Significant Mechanical Interaction (FCMI) induced strains in III ring pins (as compared to I ring pins)

Severe FCMI
# Fuel Swelling & FG Release

**Stack length Increase** - measured by X-ray, Neutron Radiography & Gamma scanning

**FG release** - by puncturing the plenum and measuring by Gas Chromatography

## Fuel Stack Length Increase

<table>
<thead>
<tr>
<th>Fuel Stack (ΔL/L)</th>
<th>FSA_{I ring-155GWd/t}</th>
<th>FFSA (III Ring)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L=320mm</td>
<td>8-12 mm (3.7%)</td>
<td>12-16 mm ~ 4.7%</td>
</tr>
</tbody>
</table>

## FG Release

| FG Release | 16 % | 8.4% |

The fuel pins from III ring has higher stack length increase (higher fuel swelling)

Lower LHR in III ring led to Higher FG retention & higher fuel swelling

**Neutron Radiograph of Intact pins**

![Neutron Radiograph of Intact pins](image1)

**Neutron Radiograph of Failed pin showing the fuel adhering to clad**

![Neutron Radiograph of Failed pin](image2)
Gamma Scanning

- Extensive redistribution of Cs\(^{137}\) in the failed pin and adjacent pins indicating higher fuel temperature in the vicinity of the failed pin.
- Ru\(^{106}\) distribution follows axial flux profile.

Redistribution percentages:
- Failed Pin: 14%
- Number Face 1203002:
  - a: Smooth Cs\(^{137}\) profile showing no redistribution.
  - b: Redistribution - 1.1%
  - c: Redistribution - 4.6%
  - d: Redistribution - 8.1%
  - e: Redistribution - 8.6%
Asymmetry in the circumferential crack & non-uniform dense fuel zone observed at middle & top sections of the fuel column, indicating anomaly in radial temp. gradients

Micrograph of 155 GWd/t fuel pin (I ring FSA) showing symmetric crack pattern & uniform dense zone

Absence of Fuel-clad gap

Ceramography of fuel pin sections

ADJACENT TO FAILED PIN
Clad microstructure indicates absence of carburisation

No evidence of Clad Carburization
Fracture Surface Analysis of Failed Fuel Pin

- Fracture surface analysis of the failed fuel Pin using a special fixture to replicate the fracture surface inside the hot cell, followed by gold coating for SEM.
- The morphology of the fracture surface indicates mixed ductile / brittle fracture modes.
Tensile stress-strain properties of Irradiated cladding

Strength and Ductility trends of cladding of III ring pins with dpa and Irradiation temperature are similar to that of I ring cladding

No evidence of any severe loss of tensile strength and ductility of cladding of adjacent pin at axial locations close to failure
Fuel pins with higher stack length increase show higher pin length increase.

Total number of pins: 61

Highly swelling fuel strains the clad axially.
# Analysis of PIE Data

<table>
<thead>
<tr>
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<th>FSA (I Ring)</th>
<th>FFSA (III Ring)</th>
</tr>
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<tbody>
<tr>
<td>Clad (ΔD/D)</td>
<td>~5.3%</td>
<td>&lt; ~6.2%</td>
</tr>
<tr>
<td>Clad (ΔL)</td>
<td>~4.3mm</td>
<td>&lt; ~6.0mm</td>
</tr>
<tr>
<td>Clad (ΔV/V)</td>
<td>~11.5%</td>
<td>&gt; 8.5%</td>
</tr>
<tr>
<td>Fuel (ΔL/L)</td>
<td>~3.7% (max)</td>
<td>&lt; ~4.7% (avg)</td>
</tr>
<tr>
<td>FGR (max)</td>
<td>16%</td>
<td>&gt; 8.4%</td>
</tr>
</tbody>
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## III ring FSA

- LVDT traces, Neutron & X radiographs, Visual: Local bending/distortion
- Gamma Scanning: Perturbations in Cs profile (in pins around failed pin)
- Fuel Microstructure: Asymmetry in Circumferential cracking (from peak power to fuel top)
- FG Release: Higher (17-19%) in pins close to failed pin

- Severe FCMI in FFSA Fuel pins
- Localized Coolant flow constriction
- Localized temperature increase around failed pin

- Cladding strain higher in III ring pins
- Low swelling clad + high swelling fuel
Analysis of Fuel Pin Failure

Low linear heat rating

- Lower fuel temperatures
  - Higher FG retention - higher fuel swelling
  - Lower fuel creep – Less swelling accommodation
  - FCMI stress

Higher Clad temperature

- Increased coolant inlet temperature

Higher clad creep - Increased diametral and axial strain

- Local bending in fuel pins (at region of axial location of failure)
- Higher fuel & clad temperature

Failure of clad under high FCMI generated stresses at higher temp.

Localised Coolant Flow constriction

Threshold
Conclusion

- Low swelling of clad with high swelling fuel lead to severe FCMI stresses, while bending of pins leads to localised coolant flow constriction

- The failure of the cladding in the form of a longitudinal rupture could be due to high FCMI generated stresses combined with higher temperatures, especially those caused by local coolant flow reduction.

- The fact that only one fuel pin had failed indicates the stochastic nature of failure which occurs only in pins with adverse combinations of local stress/temperature conditions and variations in fabrication tolerances.
We acknowledge the contributions of

✓ Service groups catering to the in-cell equipments, hot cell ventilation, electrical, electronics and Instrumentation systems

✓ Non-Destructive evaluation team

✓ Various groups of IGCAR like Reactor Operations and Maintenance, Reactor Design, Chemistry group and Quality Assurance Division during the course of PIE

Thank IAEA for the Support
Thank you
Back up slides
**Axial temperature profiles**

14C – 14\textsuperscript{th} campaign (upto 125GWd/t)
17C- 17\textsuperscript{th} campaign (125-148.3 GWd/t)

**Clad Mid wall nominal temperatures at axial location of failure**

Failed pin and adjacent pins have experienced higher temperatures ~ 565°C (nominal clad-mid wall) at the axial location of failure (after 14\textsuperscript{th} campaign)

Shift in clad temperatures at these axial locations beyond the peak swelling temperature (~510°C) of 20% CW SS316

After 14\textsuperscript{th} FBTR campaign, average rise in clad mid-wall temperatures for pins surrounding failed pin is 63°C
Campaigns in RML

- PIE of FBTR core components
  - PIE of fuel sub-assemblies from 25 to 155 GWd/t
  - PIE of Control rod assembly
  - PIE of Nickel reflector sub-assembly
  - PIE of grid plate material
  - PIE of Failed FBTR fuel sub-assembly
- Evaluation and validation of PFBR MOX fuel design
  - PIE of experimental MOX fuel pin – BoL studies
  - PIE of MOX test fuel sub-assembly after 112 GWd/t burn-up
- Preparatory work for PIE of metallic fuels
- Development and installation of new in-cell equipment
- Maintenance and decommissioning of in-cell equipment
Neutron Radiography

**Top plenum**

**NR of failed pin**

**Failed location in different orientations**

**NR of intact pins**

Fuel stack length measured by XR, NR & Gamma scanning confirmed higher swelling in fuel pins of FFSA - 12-16 mm as compared to 8.5-11.7 mm for I ring fuel pins

- Failed location indicated adherence of fuel to clad ID, suggesting bonding of fuel with clad (Fuel-Clad Mechanical Interaction - FCMI)
- Local bending in the failed pin and other fuel pins in the region corresponding to the failed location
Void Swelling Behaviour

- Numerous faceted voids are observed
- Both isolated and precipitates coupled voids are found to be present in the matrix
- The number density of these voids is in agreement with the void swelling of 7.2% obtained by immersion density measurement technique