Post Irradiation Examination of Thoria-Plutonia Mixed Oxide Fuel in Indian Hot Cells

J. L. Singh, P. Mishra, E. Ramadasan, K.S. Balakrishnan, G. K. Mallik, J. S. Dubey, H. N. Singh, P. M. Ouseph, V. D. Alur, P. B. Kondejkar, P.K. Shah, V. P. Jathar, A. Bhandekar, K.M. Pandit, R. S. Shriwastaw, A. Sharma, P.M. Satheesh, N. Kumawat and S. Anantharaman

Post Irradiation Examination Division
Nuclear Fuels Group
Bhabha Atomic Research Centre
Trombay, Mumbai, India

Facilities Available for PIE

Old Hot cell Facility

Non-Destructive	Destructive
Visual Examination by Periscope	Optical Microscopy
Profilometry	Mechanical testing
Gross Gamma scanning	Fracture toughness
Gamma spectrometry	SEM
Micro-γ-scanning	X-ray fluorescence
Leak testing	β/γ and α autoradiography
Fission gas analysis	X-ray diffraction/texture
Ultrasonic Testing	Burn-up measurement
Eddy Current testing	Hydrogen analysis
Neutron Radiography	Chemical analysis
Neutron tomography	Small punch & ABI tests

<u>Mechanical tests on irradiated Materials</u>

1. Tension tests (Pressure tube, Cladding, Garter Spring)
2. Fracture toughness test (pressure tube)
3. Slit Burst Test (pressure tube)
4. Crush test (Garter Spring)

New Hot Cell Facility

Cell-1 is 17 meter long with 7 pairs of MSM and adjustable partition wall for long PT & BWR fuel bundle.
Cell-2 is 5 meter long with 2 pairs of MSM

(Th +4% Pu)O_2 studies for Thorium Utilization

Uranium reserves are limited

Thorium is 3-4 times more abundant

India has devised a three-stage nuclear power programme

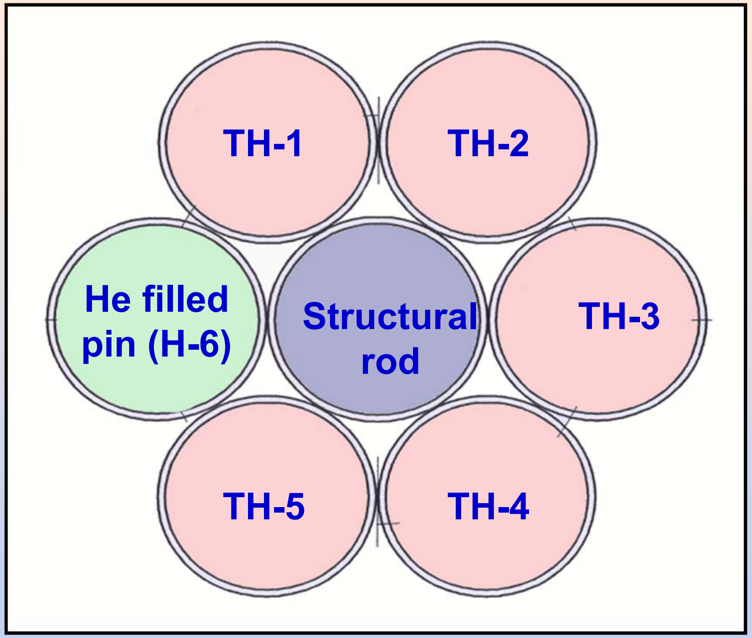
First Stage - utilization of Natural U in PHWRs- Reprocessing of spent fuel for Plutonium

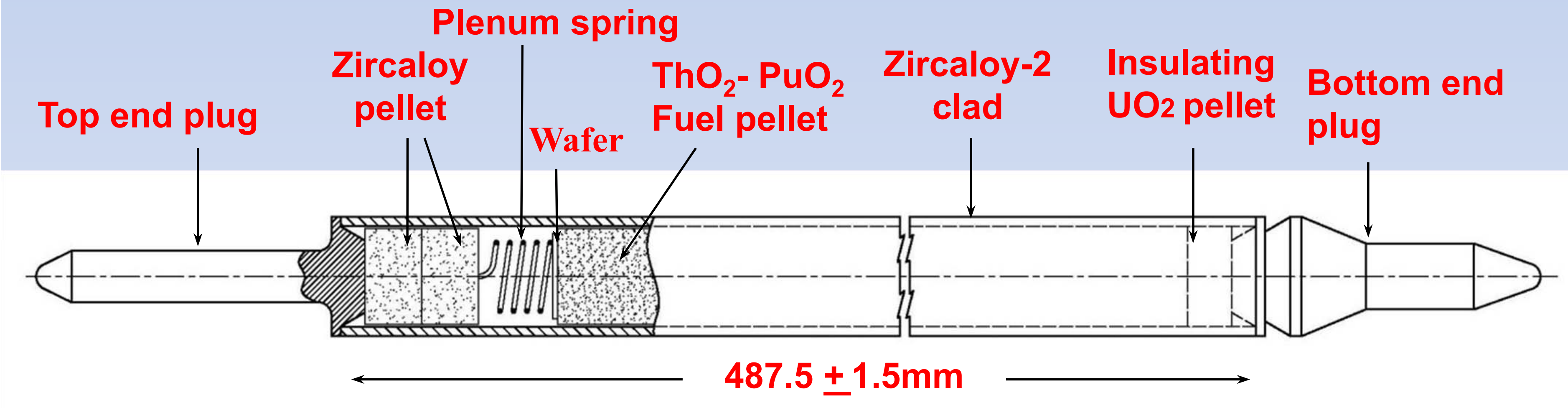
Second Stage - utilization of Pu in fast reactors – (Depleted U Blanket bundle in periphery)-Pu breeding, Later Th blanket – U^{233}

Third Stage - (Th + Pu), (Th + U^{233}) in AHWR

Different types of MOX fuels test irradiated, ThO_2 + 4%PuO_2 findings being presented

AC-6 Cluster


TH-1
TH-2
He filled pin (H-6)
Structural rod
TH-3
TH-5
TH-4


Plenum spring
Zircaloy pellet
Top end plug
Wafer
ThO_2- PuO_2 Fuel pellet
Zircaloy-2 clad
Insulating UO2 pellet
Bottom end plug
487.5 $\pm$ 1.5mm

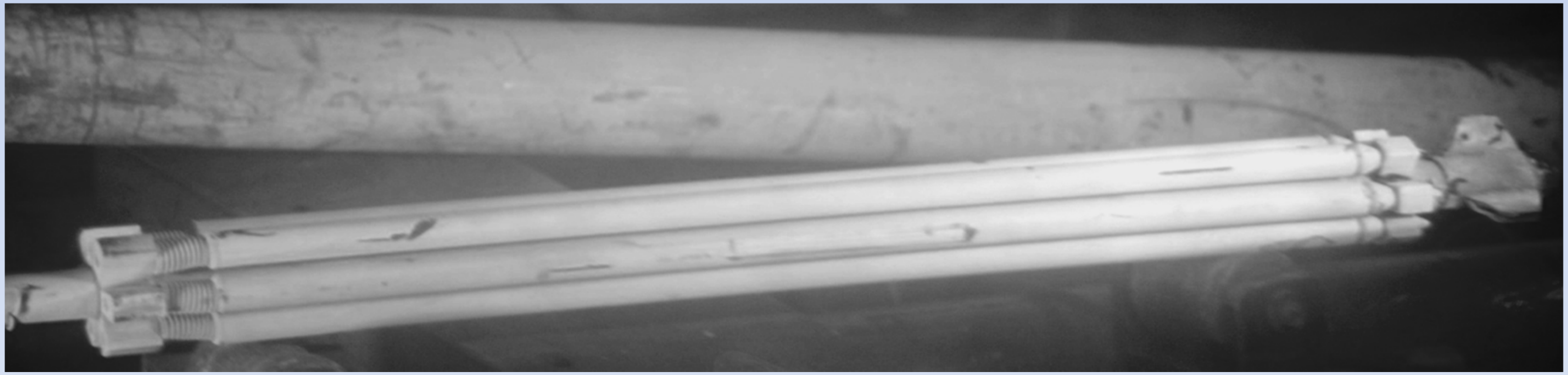
Fabrication details

Cluster	AC-6
Clad type	Free standing (Zr-2)
Number of pins	6 (5 ThO_2- 4% PuO_2 + 1 He filled pin)
PuO_2 enrichment	4%
Pellet diameter	12.22 ± 0.01 mm
Pellet length	12.0 ± 1.0 mm
Pellet density	92-94% TD
Stack length	435 mm
Cladding outer wall diameter	14.3 mm
Cladding wall thickness	0.8 mm
Cold plenum length	20 mm

Irradiation details

Thermal neutron flux	Temperature of the coolant	Pressure of the coolant	Burn up	Peak rating
5×10^{13} n/cm^2/sec	240^{o}C	105 Kg/cm^2	18,500 (MWd/Te)	40 (kW/m)

Vertically aligned in the PWL of CIRUS reactor



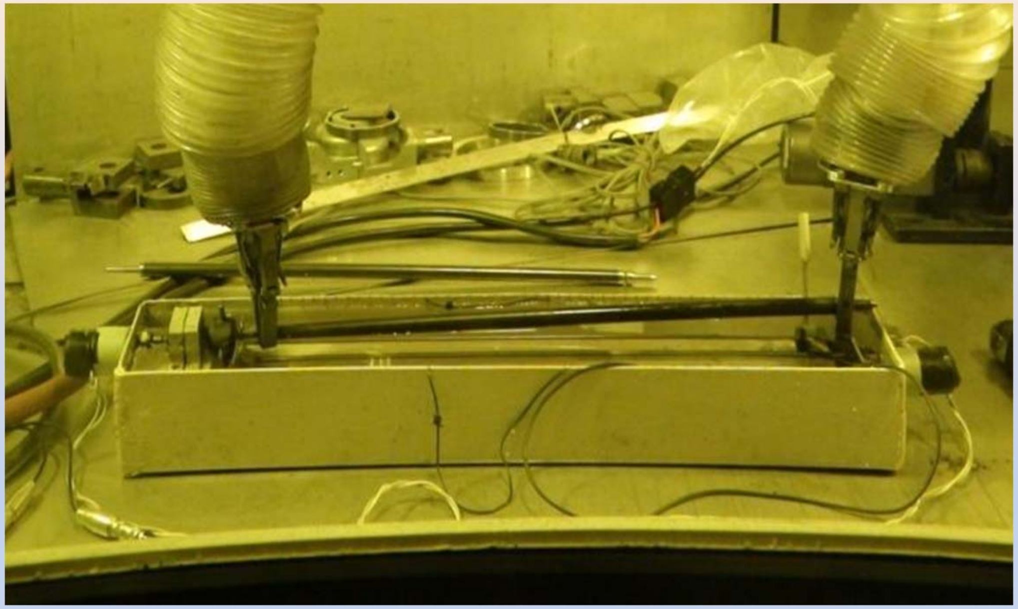
Irradiated fuel cluster AC-6 inside the hot cells for PIE

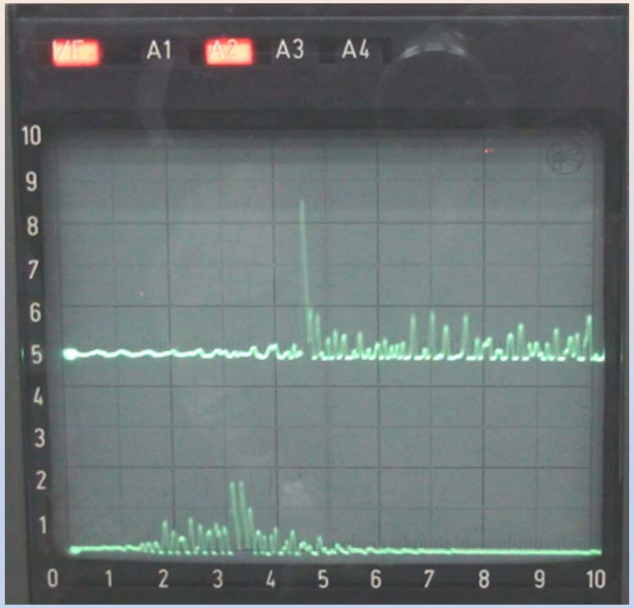
PIE Carried out

Non destructive testing	Destructive testing

- Visual examination
- Diameter measurement
- Leak testing (liquid nitrogen and alcohol leak test)
- Ultrasonic testing
- Eddy current testing
- Gamma scanning
	- Fission gas analysis (Released fission gases)
	- Metallographic examination
	  - Optical metallography
	  - SEM studies
	  - α&β-γ autoradiography

Ultrasonic Testing



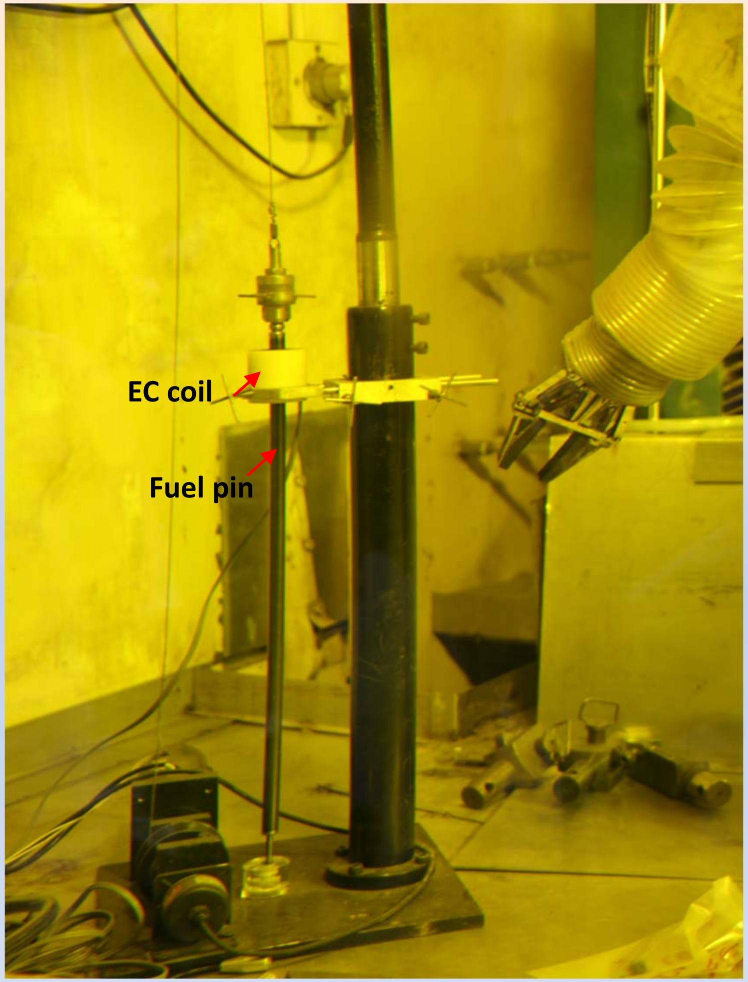


10 MHz line focused immersion probes for axial and circumferential defects.

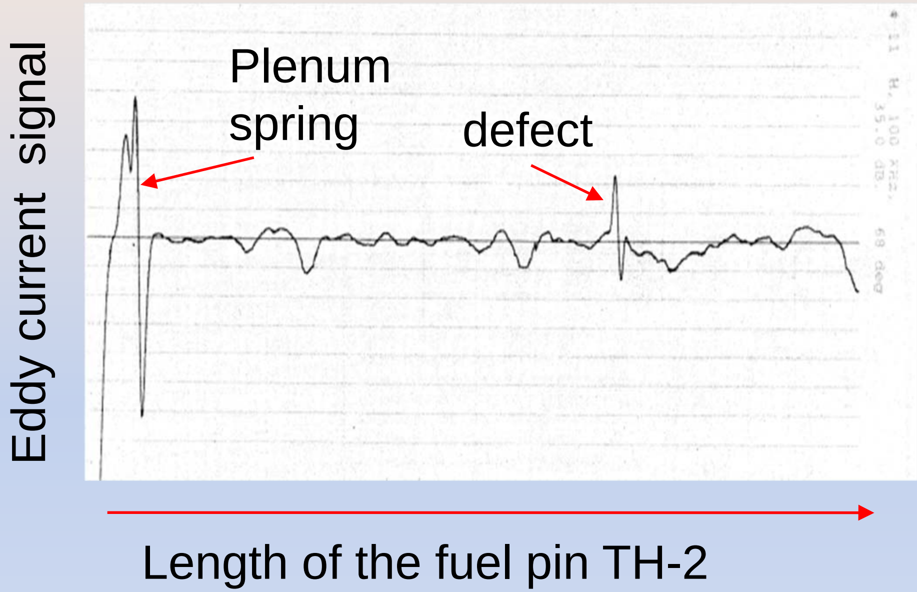
Two channel ultrasonic flaw detector.

Slow helical scan combining axial probe translation and rotation of fuel pin.

Surface roughness signals are seen, defect signal difficult to discern.



Eddy Current Testing



Gamma ray spectroscopy and gamma scanning

AC-6 fuel pin cluster was irradiated in PWL for 2 Yrs

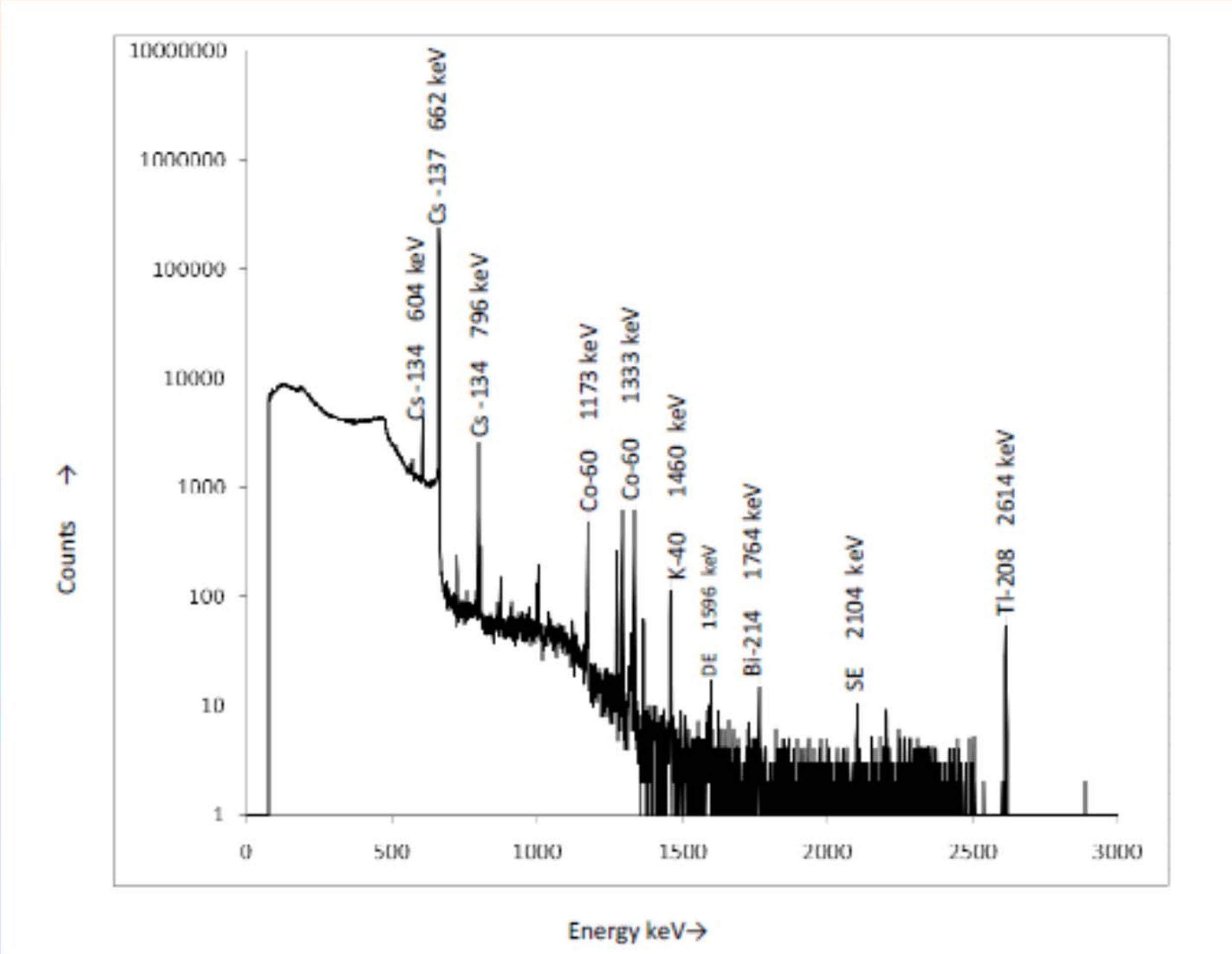
Gamma spectroscopy by HPGe detector

Cs^{137} & Co^{60} sources were used for calibration

The spectra obtained from these elements revealed the presence of Cs-137, Cs-134, Eu-154 and Tl-208 etc.

Fuel pins TH1, TH3, TH4 were scanned

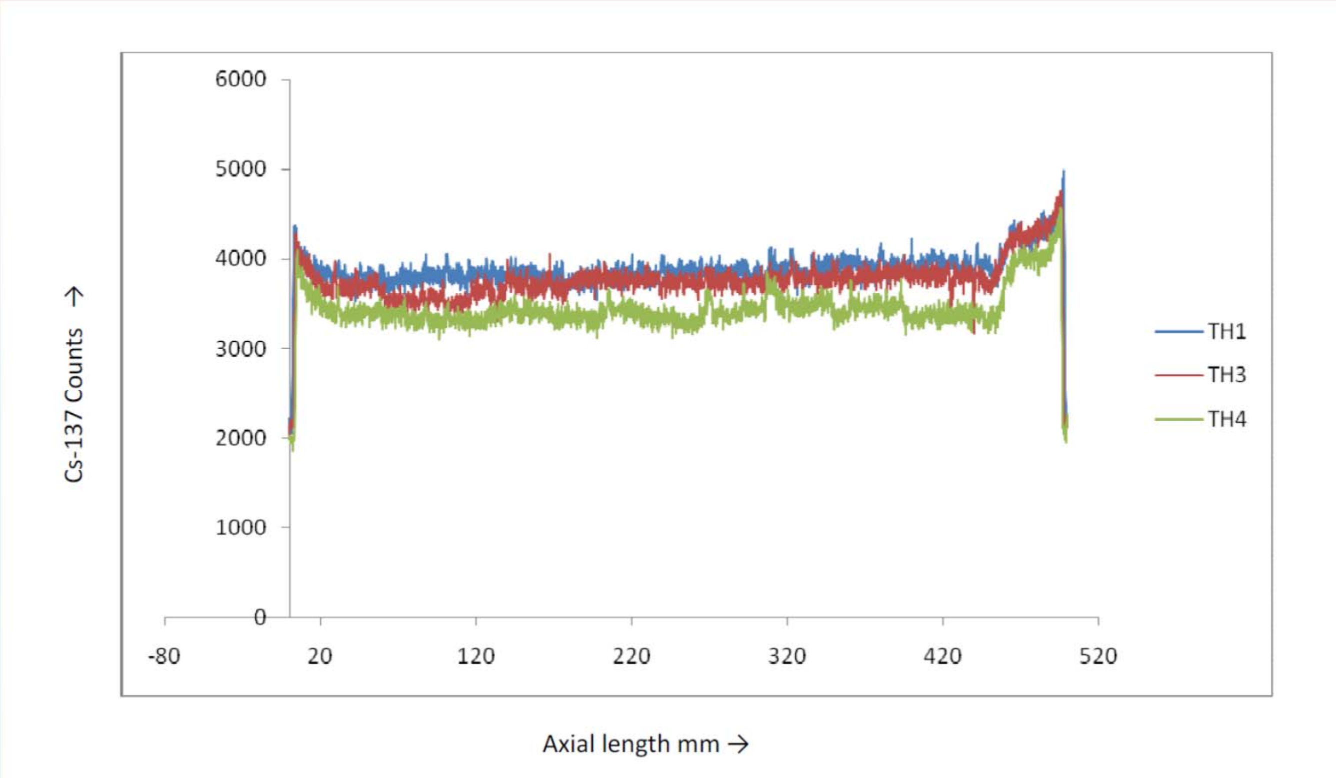
Gamma ray spectrum of (Th-4% Pu)O2 fuel pins



Cs-137 (661.64), Cs-134 (475.35, 563.33, 569.37, 604.74, 795.8, 801.86, 1365.13), Co-60 (1173.2, 1332.5)
Eu-154   (723.3, 873.2, 1004.8, 1274.8, 1004.8, 1278, 1494.4, 1596.5)

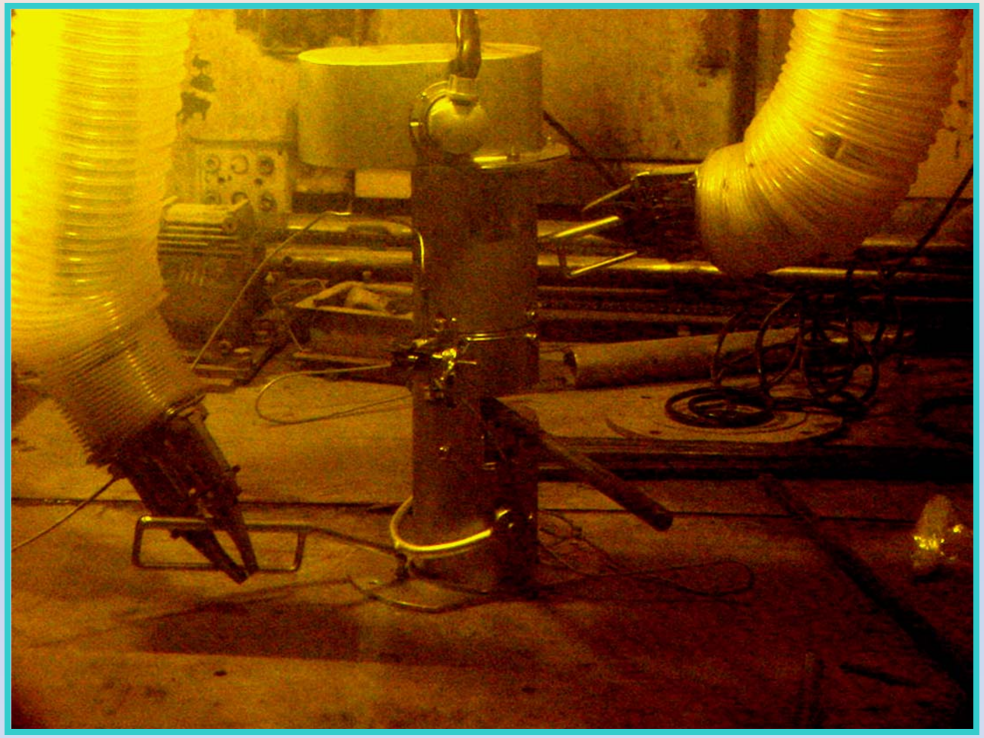
Natural Background
Bi 214 (1120.29, 1366, 1407.98, 1509.23, 1764.49, 2204.22) Ar41 (1293), K-40 (1460), Tl-208   2614.47

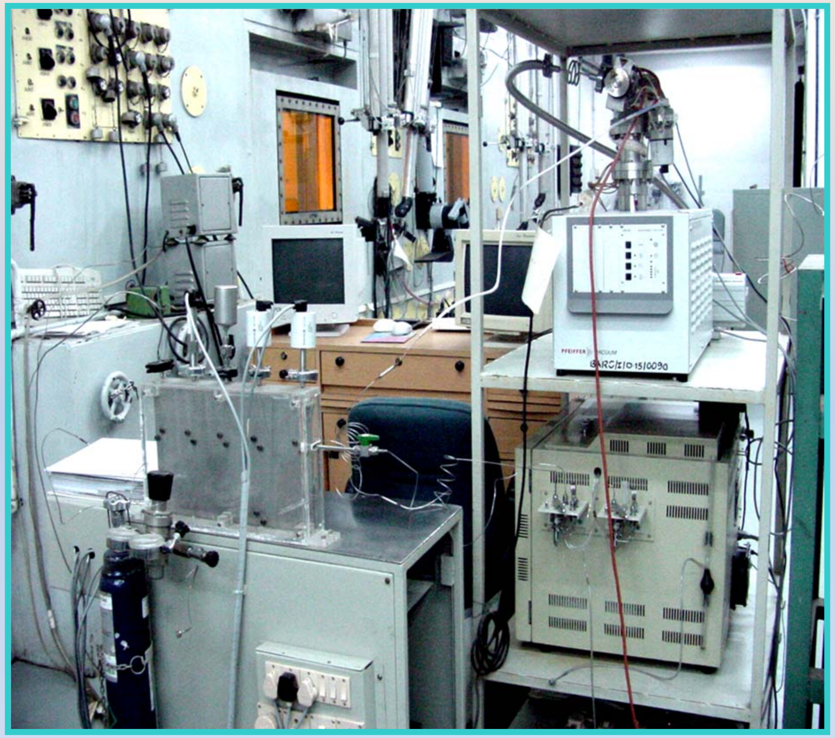
Each element was scanned for Cs-137 over the entire length. Scanning of each element was accomplished in about 5 hours.



The scans showed higher counts of Cs-137 near the top and bottom portion of the elements. This can be attributed to the fact that some caesium might have migrated in these regions which are relatively cooler. The scans showed nearly flat response along the rest of the elements.

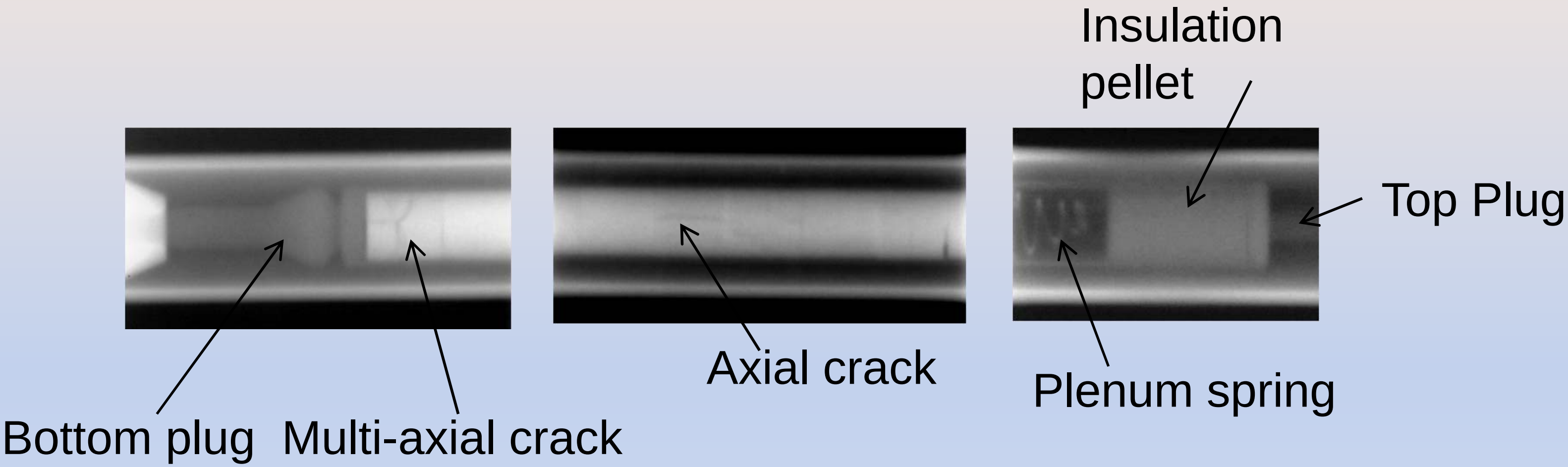
Fission Gas Release Measurement





FGR was measured on TH-2, TH-4, TH-5
TH-2 fuel pin no fission gas
FG pressure in TH-4, TH-5 fuel pins was 4.4 & 3 atmosphere.
He, Xe and Kr

Neutron Radiography

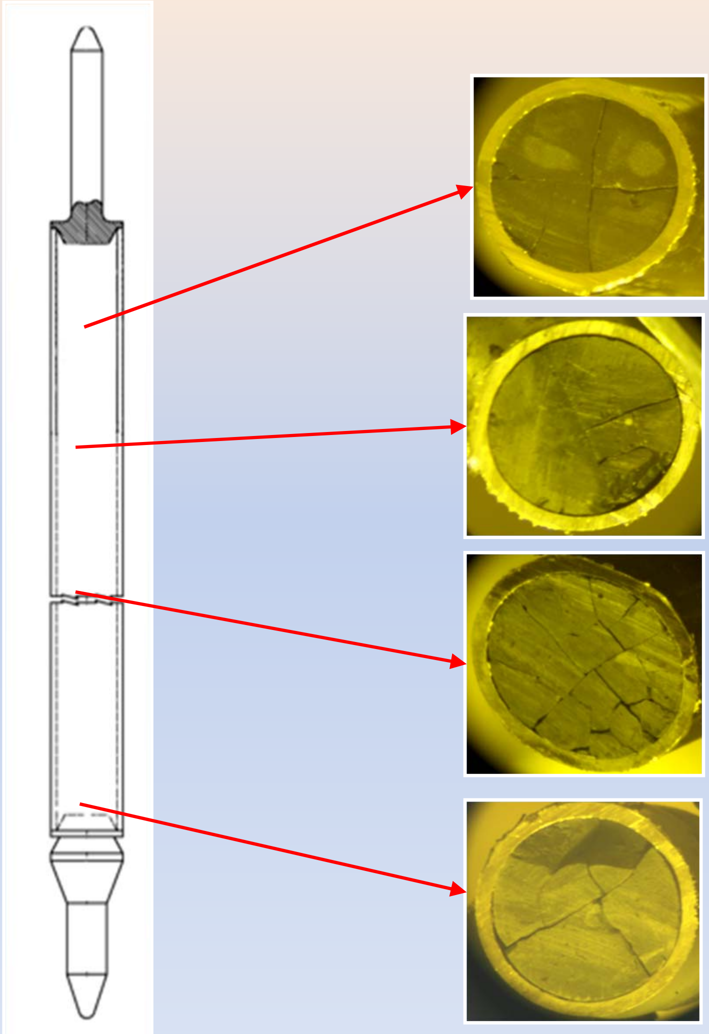


AC-6 cluster, Pin Th-4

No abnormality was found in the appendages

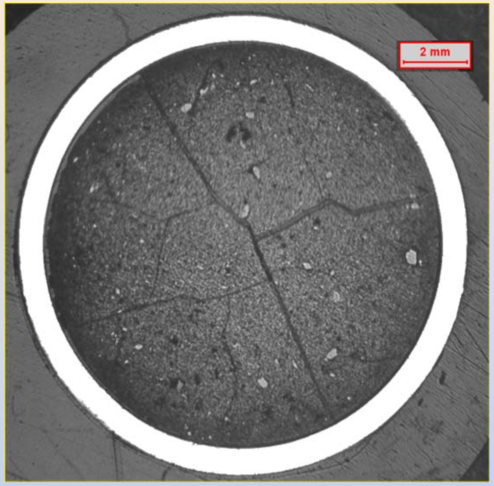
Pin ID →	AC-6 He	AC-6 Th-1	AC-6 Th-2	AC-6 Th-3	AC-6 Th-4	AC-6 Th-5
Physical Observation	Loose white layer	Loose white layer	Loose white layer	Loose white layer	Loose white layer	Loose white layer
LN_2/Ethanol Leak test	No Leakage	No Leakage	No Leakage	No Leakage	No Leakage	No Leakage
γ-scan for Cs^{137} Distribution	None	Higher at Top & Bottom than Centre	Higher at Top & Bottom than Centre	Higher at Top & Bottom than Centre	Higher at Top & Bottom than Centre	Higher at Top & Bottom than Centre
Eddy Current Test	OK	OK	Defective	OK	Defect suspected	Not done (Fuel pin could not pass through the EC coil)
Ultrasonic Test	OK	OK	OK	OK	OK	OK
Fission Gas Analysis	Not Done	Not Done	No fission gas	Not Done	4.4 Atm with He,Kr,Xe	3 Atm with He,Kr,Xe

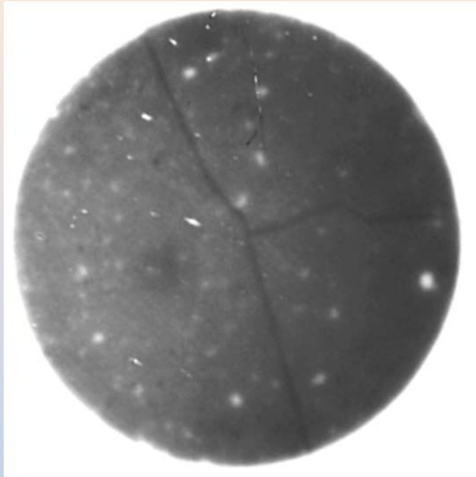
Observations on Fuel Pin TH5

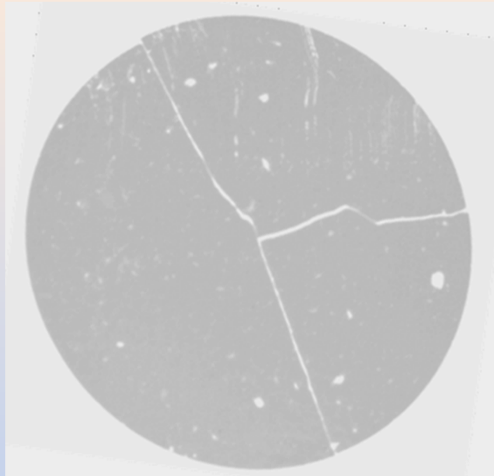


Periscopic view of the cut surfaces of the fuel pin, TH-5 at different axial locations, cracks also seen in Neutron Radiograph

Section at 285 mm from the top end plug weld

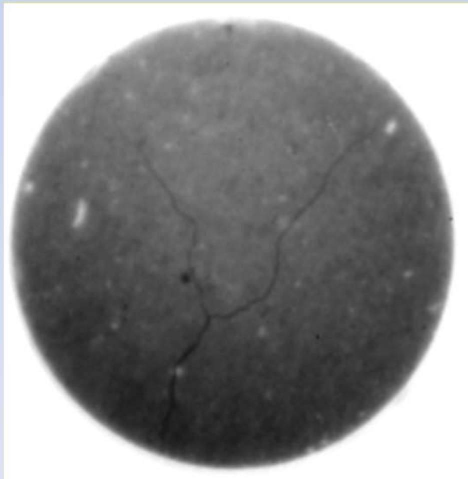


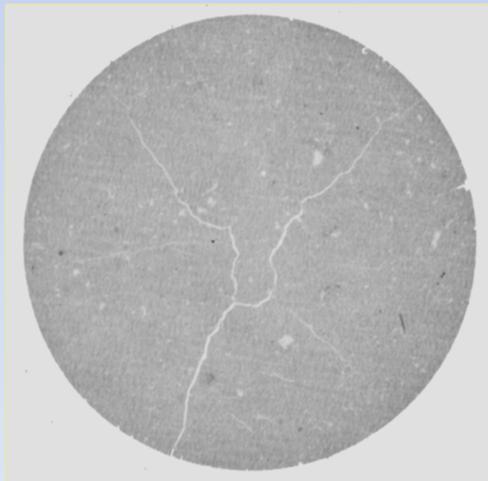




Photomacrograph β-γ autoradiograph α-autoradiograph

Section at 350 mm from the top end plug weld





Microhardness studies:

In general the hardness was

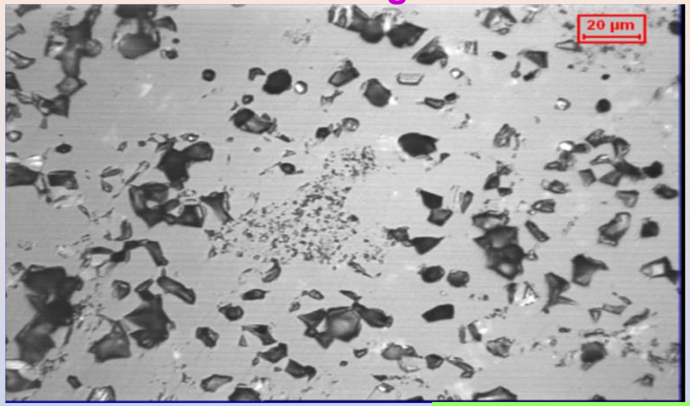
Cladding: 240VHN

Irradiated Fuel: 1245VHN

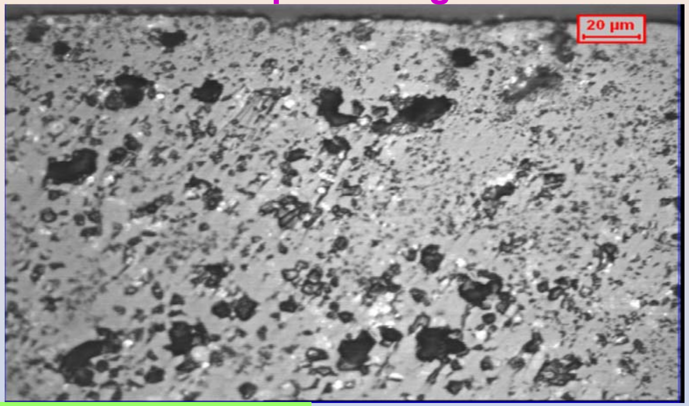
Unirradiated Fuel: 1156VHN

Microstructure of the fuel sections TH-5

Central region

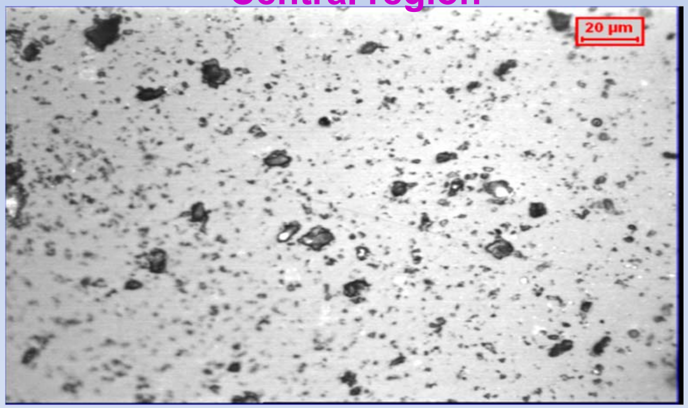


Peripheral region

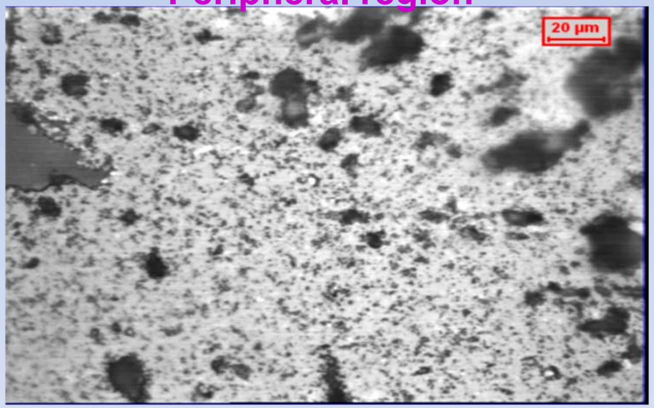


At the axial location of 285 mm

Central region



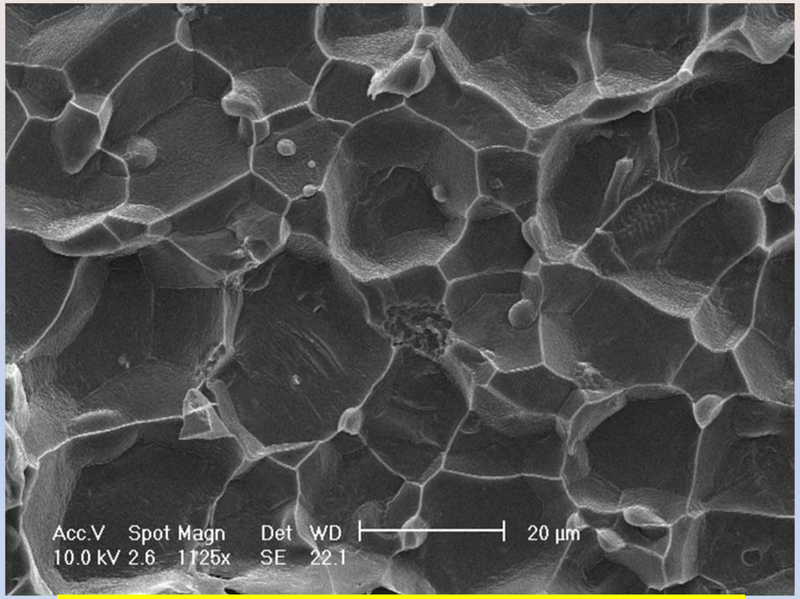
Peripheral region



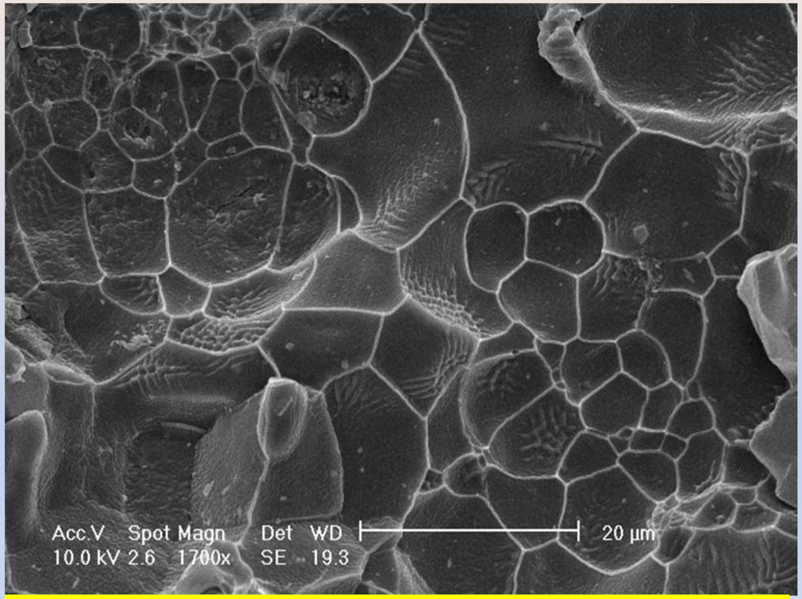
At the axial location of 350 mm

SEM Examination

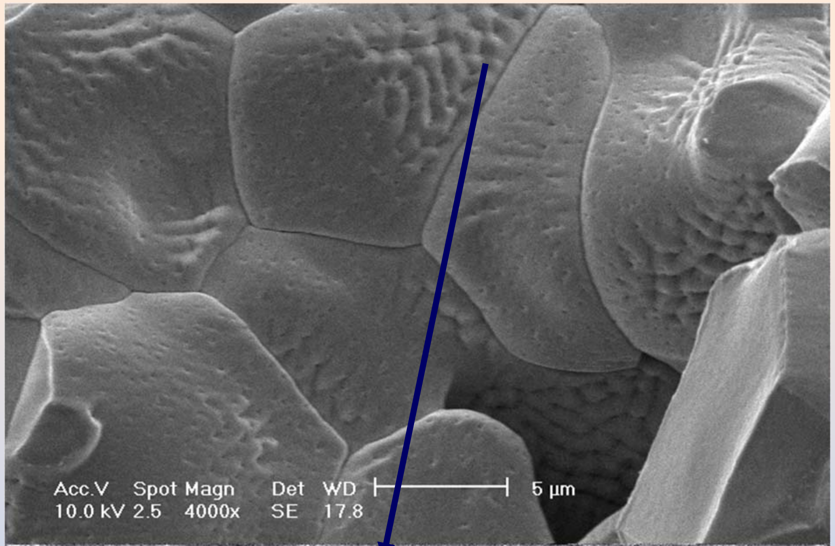
carried out on replica of fractured surfaces



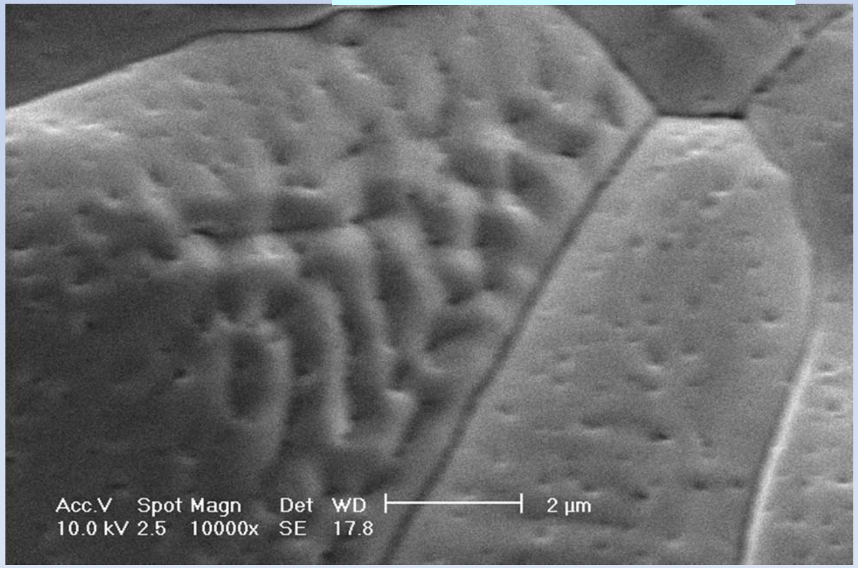
General microstructure



Combination of small & large grains

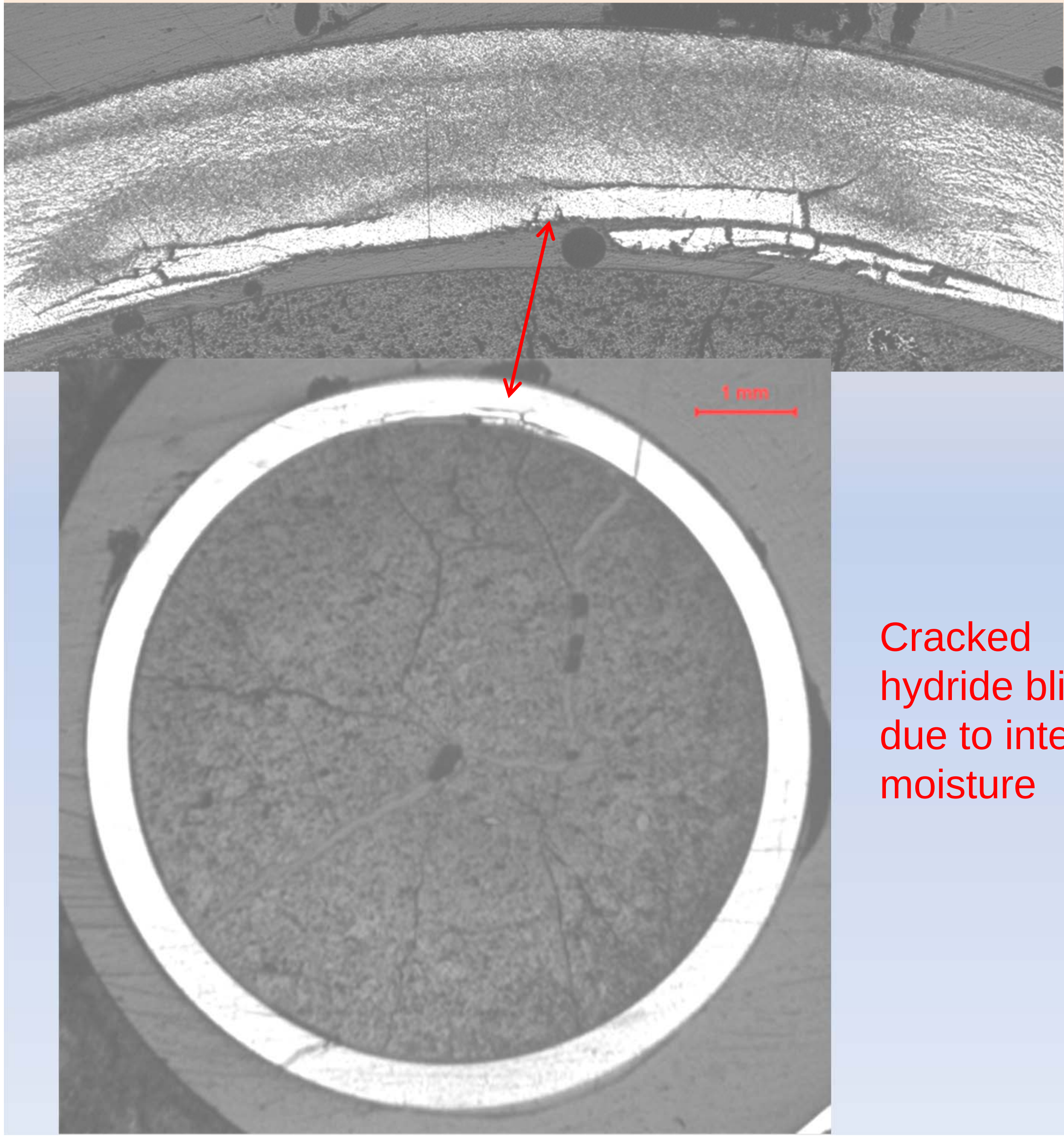


Magnified view

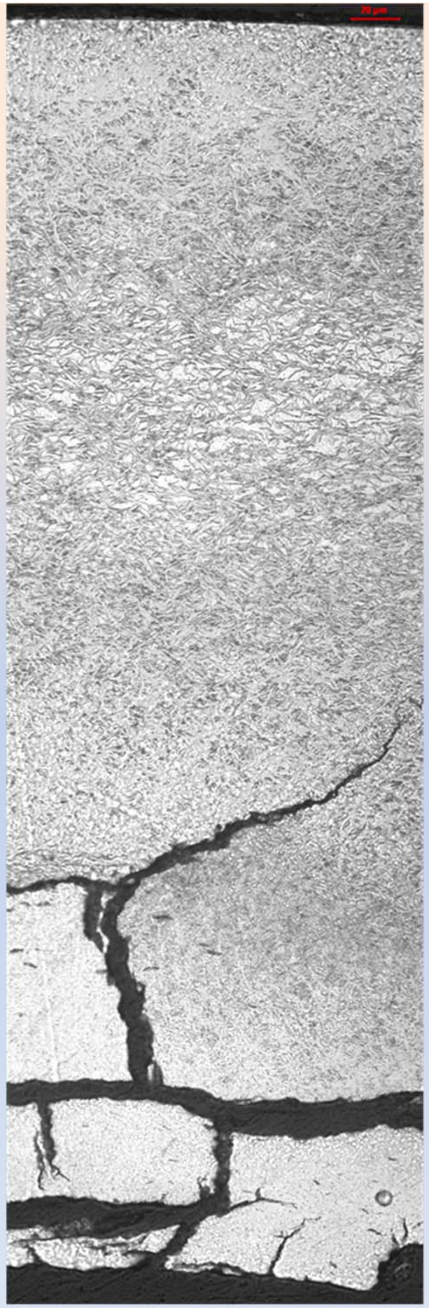


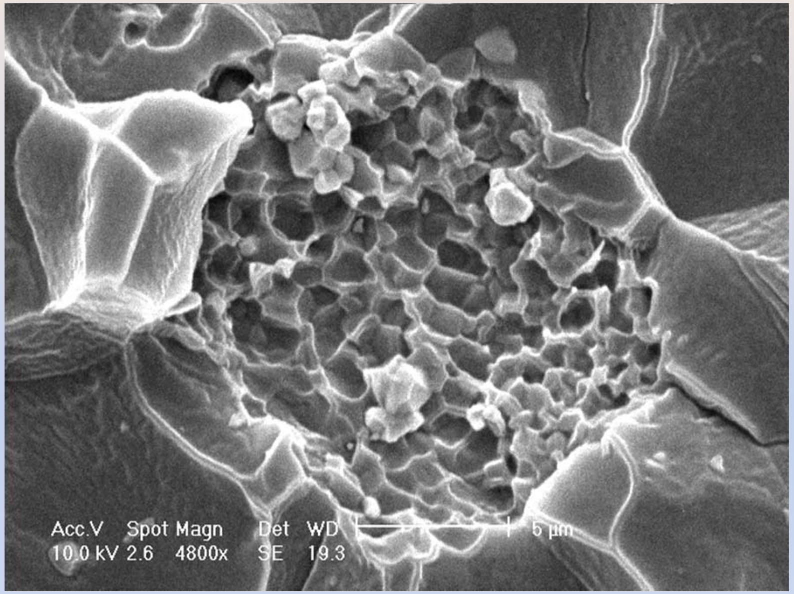
Fission gas bubbles on fuel grain faces

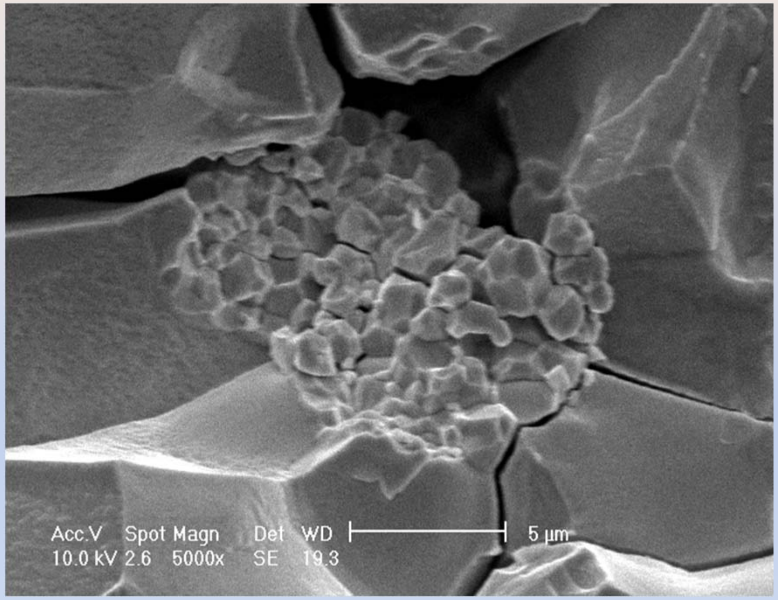
ECT marked region metallography on Fuel Pin TH-2



Cracked
hydride blister
due to internal
moisture







Cluster of small Grains

Conclusion

- Pin TH-2 had failed during due to internal hydriding.
- Pin TH-1 and TH-3 have been qualified by non destructive examinations for further irradiation.
  - Presence of radial cracks in the fuel
  - Visible grain growth or columnar grain formation were absent
  - The grain size and grain morphology was similar to that of the as-fabricated fuel; average grain size of 14 µm
  - Non uniform grain size with a few grains up to 30 µm and at some locations clusters of fine grains of 2-3 µm
  - Bimodal grain size distribution in some regions of the fuel
  - Reduction in porosity in the central portion of the fuel
  - Appearance of submicron size fission gas bubbles on the fuel grain surfaces in the central region and evidence of inter-linking of bubbles
  - Almost uniform distribution of Pu activity in the fuel section

Thanks for your patience