Passive Gamma Scanning : a Powerful Tool for QC of MOX Fuels

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Abstract

Passive gamma scanning (PGS) had been used in nuclear fuel industry for various applications such as characterization and assay of nuclear waste, enrichment monitoring of nuclear fuel pins and post irradiation examination of irradiated fuel. (U,Pu)O_2 mixed oxide (MOX) fuels have been developed in India for irradiation in thermal and fast reactors. MOX fuels for various reactors have been fabricated at Advanced Fuel fabrication facility (AFFF), BARC,Tarapur. PGS technique was modified and studies were carried out on these fuels to extract detailed information regarding the composition and configuration of a wide variety of MOX fuels.

Introduction

MOX fuels are fabricated through the powder metallurgical route starting from mixing of UO_2 and PuO_2 powders, granulation, compaction and sintering. Sintered pellets are encapsulated in Helium filled clad tubes and welded with end plugs [1].

Use of passive gamma scanning (PGS) has been reported for checking the enrichment and its uniformity in enriched UO_2 fuels [2]. Monitoring of Pu content in MOX fuel pins was tried with PGS, but high accuracy could not be attained due to low count rates [3]. Currently, PGS is being employed as a quality control inspection for enriched UO_2 fuel pins for TAPS fabricated at Nuclear Fuel Complex (NFC), Hyderabad and (U,Pu)Mixed Carbide fuel(MC) pins for FBTR fabricated at Radiometallurgy Division (RMD),BARC,Mumbai for enrichment check. Studies have been carried out with PGS at AFFF, BARC, Tarapur to extract detailed and accurate information regarding the composition, homogeneity and configuration of the MOX fuel stack covering a wide range of composition and configuration.

Gamma scanner at AFFF

The fuel pin scanner at AFFF with a fuel pin input and output magazines of 4m length each was originally designed for BWR fuel pins [Fig.1]. A 3" X 3" NaI(Tl) detector was used for the assay and a segmental scan was carried out. The detector was collimated using 25mm thick Tungsten-Nickel-Copper alloy with slit width 12mm to virtually divide the pin into a series of equally wide segments. The slit size and scanning speed were optimized so that each pellet (nominal length of 14mm) was assayed inside a welded BWR fuel pin to acquire a good count rate. Although the technique was effective in detecting cross mixing of enrichments, the accuracy of estimation of average PuO_2% of the pin was only ±0.2 %(abs.) [4].

Fig. 1: Gamma Scanner at Advanced Fuel Fabrication Facility, BARC, Tarapur loaded with a BWR fuel pin

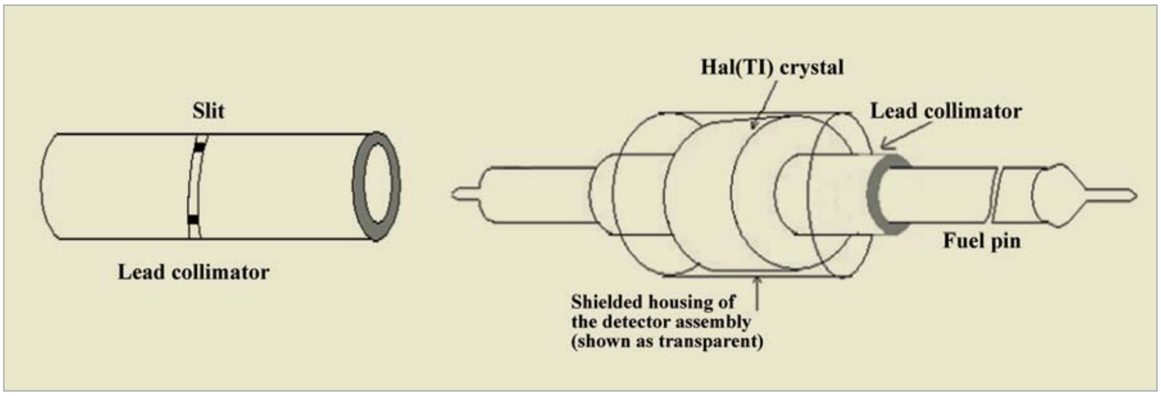

Fig. 2: Counting geometry with annular shaped detector and collimator

Annular shaped NaI(Tl) detector

An annular shaped NaI(Tl) detector with a pipe shaped Lead collimator was introduced for improving the counting geometry. The through well geometry provided a complete circumferential coverage to the source increasing the count rate drastically. Error in counting could be reduced to 1% with a reduced slit width and increased speed of scanning (10mm/sec). This further caused an improvement in the spatial resolution as well as in the accuracy of estimation of PuO_2% of the source. The detailed counting geometry of the annular detector assembly is shown in Fig.2.

A comparative study was carried out with both the detectors using BWR MOX fuel pins and the results are presented below.

MOX fuel for Thermal Reactors

Experimental MOX fuel assemblies have been irradiated in thermal reactors in India. MOX fuels loaded in thermal reactors are of low PuO_2 content varying from 0.4% to 3.25%.

MOX fuel pins for BWR

(U,Pu) MOX fuel was considered to be a viable alternative to the imported enriched UO_2 fuel. The fuel pins were of three different PuO_2% namely 0.9%, 1.55% and 3.25%. Gamma scanning studies conducted on these fuel pins showed a linear correlation between PuO_2% and count rates.

The correlations between the average PuO_2% of the pin and the average count rate were as shown below. The correlations were fitted by the method of least squares with a correlation coefficient better than 0.99.

$$\text{Count rate} = (1295*PuO_2\%) + 42.96 \quad (1)$$
[conventional detector]

$$\text{Count rate} = (2099*PuO_2\%) + 2107 \quad (2)$$
[annular detector]

From this correlation, Passive gamma scanning using annular detector set up was found to be capable of estimating the average PuO_2% of the fuel pin with an accuracy of ±0.1% (abs.) and a confidence of 95% (2σ). The sensitivity of the system increased by 100%, thereby, improving the accuracy of estimation ±0.1% (abs.) as compared to ±0.2% (abs.) in the conventional set up. Fig.3 shows a comparison of calibration graphs of both the detectors [5].

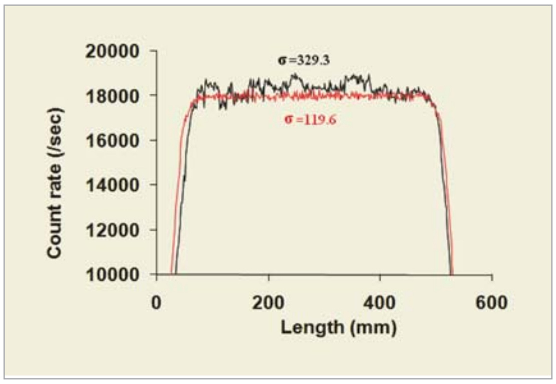

Fig. 3: PuO_2% Vs. Count rate – Comparison of two counting geometries

MOX fuel pins for PHWR

PHWR MOX fuel subassembly consisted of 7 MOX fuel pins with 0.4% PuO_2 surrounded by 12 natural UO_2 pins (MOX-7 design).

The PuO_2 content of the MOX fuel was specified to be 0.4 ± 0.1%(abs.). It was also specified that the average PuO_2 content of the central pin should not be less than 0.03%(abs.) than the surrounding 6 pins. Hence it was necessary to estimate the average PuO_2 content with accuracy better than ± 0.1%(abs.).

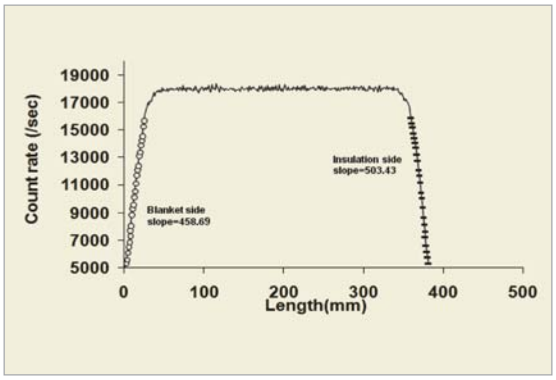

Fig.4: Gamma scan of a PHWR MOX pin with variation in PuO_2 content in the stack

Due to the through well counting geometry, the relative error also decreased from 3.9% (with conventional counting geometry) to 1.6% for this composition and hence, the estimations could be done with better accuracy and precision.

PGS was found to be effective in PHWR MOX fuel pins for :- [6]

- Estimating the average PuO_2 content of every fuel pin with accuracy of ± 0.02% (abs.) so that the pins could be screened for the central position.
- Detecting variation of PuO_2 content within a fuel stack by more than 0.03% if the deviant portion is atleast of length 15cm
- Gamma scan of a pin which contained pellets from two batches with deviance in PuO_2% by 0.02% is shown in Fig.4.

MOX fuel for Fast reactors

Fuel pellets for fast reactors are of small diameter and are annular in shape. So, effectively the thickness of the pellet to be probed was less in fast reactor fuel pellets. FBTR MOX fuel pins contain annular geometry fuel pellets of 5.52 ± 0.04 mm outer diameter and 1.8 mm (nominal) internal diameter. The effects of self shielding offered by FBTR MOX pellet and the probing depth of the technique was calculated and it was found that the penetration depth of 400keV gamma rays in MOX fuels for FBTR and PFBR ranged from 1.9-2mm [7].

MOX fuel pins for FBTR

Fuel pin for a few MOX subassemblies were fabricated at AFFF for the hybrid core of FBTR and irradiated in the reactor. PuO_2 content of these fuel pins were specified to be 44± 1%(abs.). The schematic diagram of the FBTR MOX fuel pin is shown in Fig.5.

PGS could be used during FBTR MOX fuel fabrication for

- Estimation of average PuO_2 percentage in

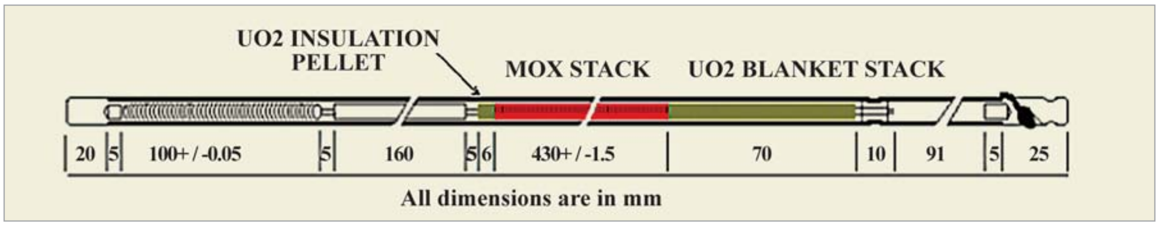

Fig. 5: Schematic drawing of FBTR MOX fuel pin

a fuel pin with an accuracy of ±0.6 % (abs.) and detecting heterogeneity in PuO_2 distribution beyond 1.5% (abs.).

- Ensuring correct sequence of loading of blanket, insulation and fuel pellets and no cross mixing of blanket pellets with fuel pellets and
- Detecting Pu rich agglomerates located anywhere in the fuel which is richer by 0.6% (abs.) or more and estimating the minimum richness of any detected agglomerate.

The passive gamma scans of two pins with large difference in σ value are shown below in Fig.6. Variation of σ from the theoretically estimated value indicated Pu heterogeneity.

It was possible to distinguish the blanket/insulation pellets (see Fig.6) from the slope of rising/trailing ends of the gamma scan as shown in Fig.7.

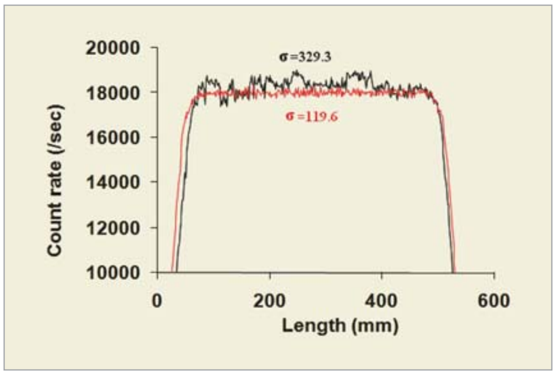

Fig. 6: Gamma scan indicating inhomogeneous distribution of PuO_2 in the fuel

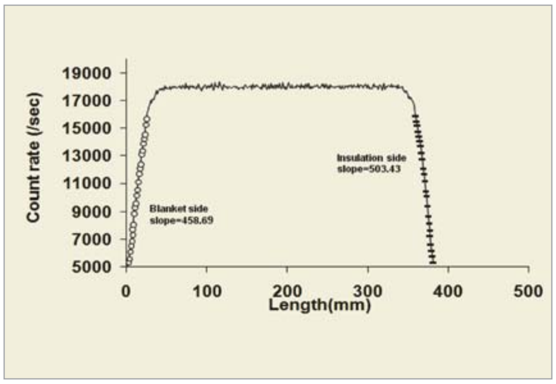

Fig. 7: Gamma scan of FBTR MOX fuel pin showing different slopes at Blanket pellets side and Insulation pellet

MOX fuel for PFBR

Fuel pins for PFBR are approximately 2.6m long with a 1000mm long MOX stack and 300mm long axial blanket (UO_2) on either side [8]. The composition of the fuel is 21wt% PuO_2- UO_2 (for the inner core region) and 28 wt% PuO_2-UO_2 (for the outer core region). Fuel for the initial core of PFBR is being currently fabricated at AFFF, BARC, Tarapur. PGS was used during the fuel fabrication for the following detections [9].

- Estimation of average PuO_2 percentage in a fuel pin with an accuracy of ±0.1%(abs.) with 3σ confidence.
- Detecting 100% PuO_2 agglomerates of large size (more than 1mm) located anywhere in the fuel and of size 550 μm or more located near the outer surface.
- Estimating the minimum richness and diameter of any detected agglomerate
- Ensuring correct sequence of loading of blanket and fuel pellets

Gamma scans of two PFBR pins with a variation of 0.15% in PuO_2 content are shown in Fig.8 and scan of a pin with cross mixed fuel and blanket pellets is shown in Fig. 9.

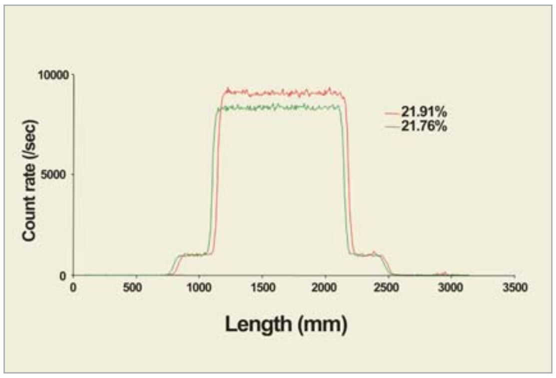

Fig.8: Gamma Scans of PFBR pins with varying average PuO_2 content

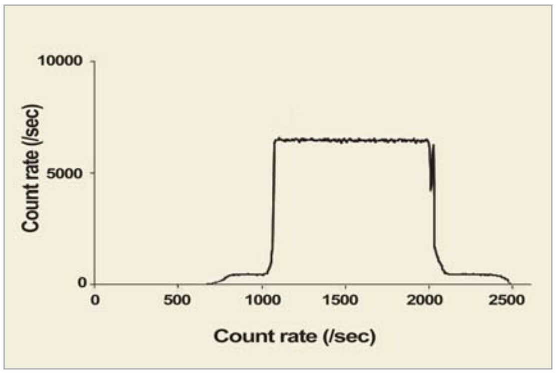

Fig. 9: Detection of a blanket pellet in MOX fuel stack in a PFBR fuel pin

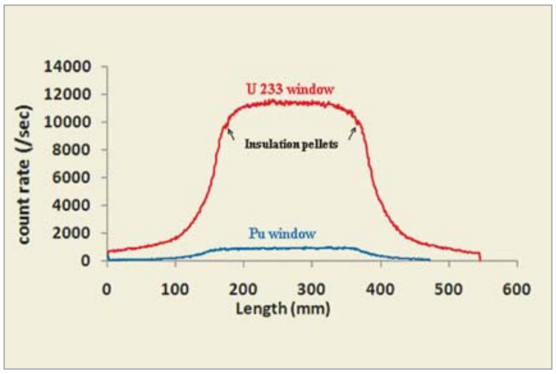

Fig.10: Gamma scan of a typical experimental fuel pin in dual window

U^{233} bearing (U,Pu) MOX fuel pins

A test subassembly simulating the fuel for PFBR was loaded in the Fast Breeder Test Reactor (FBTR) for irradiation. The composition of the fuel was (0.71U-0.29Pu) O_2 with 53.5% enrichment in UO_2 with $U^{233}O_2$. This unique composition is designed to simulate the thermo-mechanical conditions of the fuel composition of PFBR in FBTR. PGS was employed for monitoring the composition of the fuel both in terms of $U^{233}O_2$ and PuO_2. The counting window of 300-450 keV was used for the purpose of assaying the pin for its Plutonium content. The counting window was set to count gamma rays of energy from 600keV to 1.6 MeV for assaying U^{233}. Conventional 3"x 3" detector was used for counting as the count rates were very high.

A number of calibration pins were fabricated for the gamma scanning studies. Care was taken to use only one lot of PuO_2 and $U^{233}O_2$ powder while fabricating the calibration pins. PGS could be used in U^{233} bearing fuel [10]:-

- to monitor the variation of average $U^{233}O_2$ content beyond ±1%.
- to monitor the variation of average PuO_2 content beyond ±1% and
- to confirm the correct loading of insulation and fuel pellet

Passive gamma scans acquired through dual window,

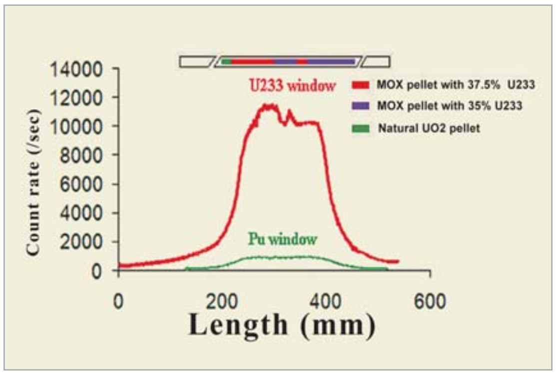

Fig.11: Dual window gamma scans and the schematic drawing of the calibration pin

of a typical experimental MOX fuel pin and a calibration pin are shown in Figs.10 &11. The scans were carried out both in Pu and U^{233}window individually.

Conclusion

Passive Gamma scanning with improved counting geometry has been carried out on (U,Pu) MOX fuels with a wide range of composition and configuration. The technique has been found to be capable of extracting detailed compositional information of MOX fuel pins such as average PuO_2 content, homogeneity of PuO_2 in UO_2 matrix, loading configuration of fuel and blanket pellets etc. It was possible to detect Pu rich agglomerates in MOX fuel and also estimate its size. It could also be used for independently estimating the variation in $U^{233}O_2$ and PuO_2 in fuel pins containing both. The technique being non destructive could be applied to all the fuel pins as opposed to the destructive techniques carried out on random samples. PGS is a prompt technique and hence suitable technique for fuel fabrication facilities with high throughput. It reduces load on conventional chemical analysis and hence could considerably reduce the generation of radioactive liquid waste. Since it reduces load on autoradiography techniques, radioactive exposure to personnel could also be significantly reduced.

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