Quantitative Evaluation of shielding integrity of thick structures in nuclear facilities through Radiometry

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Abstract

In nuclear facilities controlling the radiation exposure to personnel is of paramount importance. Effective shielding of radioactive components and non destructive evaluation of these components are essential to reduce radiation level in areas. Depending on the nature of the shield components and their utility, these are made of lead, steel and concrete. The thickness of the structures can range from about 50 - 200 mm in case of steel and up to around 1200 mm in case of concrete. The presence of defects such as blow holes, voids etc that can arise during the fabrication would result in larger transmission of ionizing radiation which in turn would mean unacceptable radiation dose levels in the operating areas. Conventional NDE methods such as radiography and ultrasonics are difficult or not possible. Radiometry using sources such as Co-60 is one of the non conventional NDE methods that have been widely used by the authors for quantitative evaluation and fitness for purpose of such structures. There are two variants in this method. The first referred to as radiometry is based on the measurement of the transmitted intensity of radiation using a GM tube based detector. In the second case, a detector capable of energy resolution is used. Expected intensity as dose rate for given thickness is also calculated initially using analytical method for standard geometry (slab) of single material. In case of components/structures having complex geometry and different materials, dose rate estimation is carried out by modeling gamma transport in the medium to take into account of buildup factor. Sources such as $^{60}$Co, $^{137}$Cs etc with activities ranging from mill curie up to 70 Ci (gamma camera) depending on the thickness of component have been used. The challenge here is to ensure dose reduction to personnel and also when lead slabs are inspected, the corner effects need to be considered properly. Authors have designed a suitable collimator for source alignment and reduction of scattered radiation. Authors have used all these for quantitative inspection of roof slab of reactor, inclined shield structures of shielding of fuel transfer machine and Pump Intermediate Heat Exchanger (IHX) flask of Prototype Fast Reactor which is being constructed at Kalpakkam, India. This paper focuses on the methodology employed and challenges involved with typical case studies.

Keywords: Radiometry, Roof Slab, Radiation exposure, Intermediate Heat Exchanger
1 Introduction

Radiometric testing is one of the non-conventional non-destructive evaluation methods that have found wide applications especially in nuclear industries for evaluation of the integrity of components in nuclear reactors and fuel cycle facilities. In this method, the transmitted intensity of radiation is measured and then correlated to dimensional variations or gross defects such as voids in materials. At Kalpakkam, an indigenously designed 500 MWe Prototype Fast Breeder Reactor (PFBR) using mixed oxide as fuel and sodium as coolant is under construction [1]. Most of the components/structures employed in reactor is made of lead, steel and concrete. The thickness of the structures ranges from about 50 - 200 mm in case of steel, 50-250 mm in case of lead and up to 1200 mm in case of concrete. The presence of defects such as blow holes, voids, loss of thickness etc that can arise during the fabrication would result in larger transmission of ionizing radiation which in turn would mean unacceptable radiation dose levels in the operating areas. To control the radiation in operating areas, these structures need to be verified for these defects for suitable NDE methods. Among general NDE methods used in practice cannot be applied in such cases due to thickness limitation and grain size variation. Radiometry testing using high energy gamma sources is an innovative tool which is suitable for evaluating large components/structures composed of steel, lead and concrete. There are two variants in this method and first one referred to as radiometry which is based on the measurement of the transmitted intensity of radiation using a dose rate meter. Expected intensity as dose rate for given thickness is calculated initially using analytical method for standard geometry (slab) of single material. In case of components/structures having complex geometry and different materials, dose rate estimation is carried out by modeling gamma transport in the medium to take into account of buildup factor. The second case referred as gammatography in which a detector capable of energy resolution is used to measure the virgin flux without scattering component. Sources such as $^{60}\text{Co}$, $^{137}\text{Cs}$ etc with activities ranging from milli curie up to 70 Ci (gamma camera) depending on the thickness of component have been used.

The challenges involved during radiometric testing are source collimation, radiation exposure to operating personnel and corner effects when lead slabs are inspected. In order to control the exposure, a suitable collimator for source alignment was employed. These techniques were used for quantitative inspection of roof slab of reactor, inclined shield structures of shielding of fuel transfer machine and Pump, Intermediate Heat Exchanger (IHX) flask of Prototype Fast Reactor which is being constructed at Kalpakkam, India. This paper focuses on the methodology employed based on first variant discussed and challenges involved with typical case studies.
2 Principle of radiometry testing

Radiometric is based on the differential absorption of X-ray or gamma radiation as it passes through the material. It is identical to conventional radiography except that the radiation detector here is not conventional film but instead a NaI(Tl)-based radiation detector which measures the intensity of the transmitted radiation.

3 Optimization of source and its strength

Radiometry is primarily affected by the source strength. Higher source strength would give better sensitivity. As a rule of thumb, the activity of the source is chosen such that the intensity of the dose rate is three times the background level. $^{60}$Co would be the most appropriate source since it can penetrate up to about 225 mm of steel.

4 Gamma dose rate measurements

NaI(Tl) based survey meter - Identifier make detector: NaI (Tl) dia : 35mm Thickness: 51mm & GM Tube is mostly used for gamma dose rate measurements. Measuring Range: NaI : 0.01μSv/h to 500μSv/h and GM: 500μSv/h to 1000mSv/h.

5 Methodology of dose rate computation

Since the source dimension is very small, it is assumed to be a point source for dose calculations and self-absorption within the source medium is neglected. Then, the gamma dose rate is estimated using the exponential attenuation law,

$$D = kB(\mu t, E)s_0 \exp(-\mu t) \times \left(\frac{1}{r^2}\right) \quad (2)$$

where $D$ is the expected gamma dose rate after shielding in μSv/h, $s_0$ is the initial photon source strength in photons/s, $t$ is the thickness of shielding medium in cm, $\mu$ is the linear attenuation coefficient in cm$^{-1}$, $B(\mu t, E)$ is the dose build up factor for the medium, $k$ is the dose conversion factor (μSv/h per unit flux) & $r$ is the distance between source and detector in cm.

In case of complex geometries, the dose rate estimation was done by modeling the gamma transport in the medium. The point kernel method was used for dose rate calculation. The IGSHEILD, code was employed for this purpose [3]. In this method, the source was considered as a small volume source. It
was then divided into various smaller parts and the contribution from each was calculated with the appropriate buildup factor. The dose rate $D(r)$ is thus represented as an integral equation

$$D(r) = k \int_{V} S(r') B(\mu \mid r - r' \mid, E) \exp(-\mu \mid r - r' \mid) dV$$

$$\frac{4\pi \mid r - r' \mid^2}{3}$$

where $k$ is the flux-to-dose conversion factor, $S(r')$ is the source density (Bq/cc), $B(\mu \mid r - r' \mid, E)$ is the dose buildup factor at gamma ray energy $E$ in MeV, $\mu$ is the gamma ray linear attenuation coefficient at energy $E$ in MeV and $\mid r - r' \mid$ is the distance between the detector and the source point.

6 Quantitative inspections of structures by radiometry testing

6.1 Testing of roof slab of nuclear reactor

Roof slab forms the top shield of the of the reactor vessel which give biological and thermal shield in the axial direction of the reactor and also acts as a support system for various components such main vessel, IHX, control plug and Inclined fuel transfer machine. It is a box like structure filled with high density concrete. It is difficult to carryout in situ radiometric testing due accessibility problem hence testing was carried out for mock structure to standardize the procedure for concrete pouring to achieve the required density of the concrete without voids or defects. The dimesion of the structure is 1200 mm x 800 mm x 600 mm poured with concrete of density 3.6g/cc (Fig. 1.0).

![Fig. 1. Roof slab model block](image)

Results of testing reveals that structure is with uniform pouring of density 3.6g/cc without any void are defects. (Fig. 3)
6.2 Radiometry testing of inclined shield structures of shielding of fuel transfer machine (IFTM)

IFTM is used to transfer Irradiated fuel assembly from transfer inside reactor vessel to cell transfer machine. Shield structure consists of six numbers of cast iron rings, flange and cast iron block. (Fig.3)
Radiometric testing of IFTM shield structure made of cast iron block is having loss of thickness if any is within tolerance limit of 4% without any voids or defects. (Fig. 4 & 5)

6.3 Radiometry testing of Pump Intermediate Heat Exchanger (IHX) flask:

In PFBR Pump and Intermediate Heat Exchanger (IHX) flask is located in the main vessel - which becomes radioactive during reactor operation. These are shielded by PI flask to avoid exposure to operating personnel when they are moved out for repair or decontamination. These flask shells have annular shield plug filled with lead shots to achieve a packing density of 7.0 g/cm³. radiometric testing was carried to verify the density and uniform packing density.
Fig. 6 Images of PI flask and source guiding

Fig. 7 Radiometry testing results for PI flask

Results revealed that PI flask shells have uniform packing density of 7.0 g/cc without any voids as shown in Fig. 7.
7.0 Results and discussion

Results indicates that the components are having required thickness, density as per designed value and loss of thickness if any are within the acceptance limits without any void or defects.

Conclusion: Radiometric testing is a promising tool for Non destructive evaluation of large thickness components/structures made of steel, lead and concrete. It is a challenge to fabricate a source guide and collimation of source/detector for unique components and control the exposure to operating personnel during testing.

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References

