Application 1: Estimation of age dependent Dose Conversion Coefficient

Aim of the study: The objective of the present study was to develop a model using Monte Carlo based code to simulate the photon transport from the finite Gaussian plume source under various meteorological conditions to the adult and child male and female reference phantoms. This model has been used to estimate age dependent dose conversion coefficients (DCCs) for overhead plume exposure.

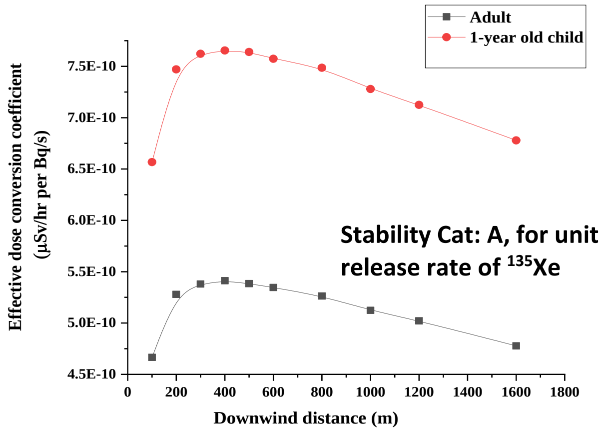
Methodology: The FLUKA Monte Carlo method-based code and ICRP 110 adult voxel phantoms along with NCI – UF (Lee et al., 2010) recommended 1 year old child voxel phantoms are the two major components of the present study. These computational phantoms are represented as a three-dimensional array of cuboid voxels, arranged in columns, rows, and slices. The information of reference phantom is given as an input to FLUKA through a special file having a format of ‘. vxl’. In this study, photons emitted from the radionuclide present in the plume, as well as secondary electrons generated by photon interactions are transported. Among various built-in scoring options, three scoring cards have been used in this study namely, the ‘USRBIN’ card for the estimation of energy deposition at a receptor site, the ‘USRBDX’ card for the estimation of surface crossing fluence and the ‘USRTRACK’ card for the estimation of volume averaged fluence.

The Gaussian plume model: The radioactive pollutant (gas or aerosol) disperses in the atmosphere depending upon the prevalent meteorological conditions and its physical properties. For a steady-state finite plume, the Gaussian Plume Model (GPM) is used to represent the concentration distribution of the radionuclides as a function of the downwind distances (x), mean wind speed (u), release height (h) and stability category given by,

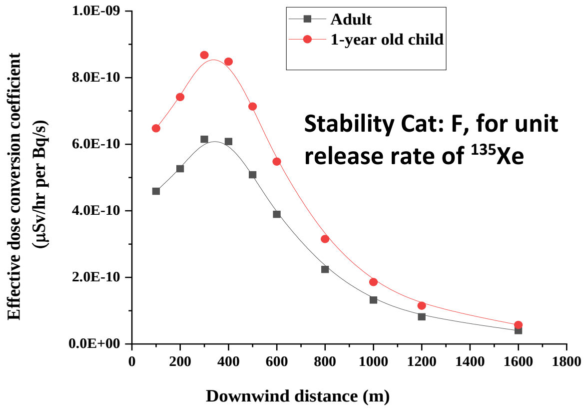
$$\chi(x,\ y,\ z) = \frac{Q}{2\pi\sigma_y(x)\sigma_z(x)u}\, exp\left(-\frac{y^2}{2{\sigma_y}^2(x)}\right)\left[exp\left(-\frac{(z-h)^2}{2{\sigma_z}^2(x)}\right) + exp\left(-\frac{(z+h)^2}{2{\sigma_z}^2(x)}\right)\right] \quad (1)$$

where, $\chi(x,\ y,\ z)$ is the radioactive concentration (Bq/m^3) at a point (x, y, z) downwind of the release, x is the downwind distance (m), y is the crosswind distance (m), z is the vertical distance (m), u is the mean wind speed (m/s), h is the release height (m), Q is the release rate for radionuclide from stack (Bq/s), σ_y, σ_z are the dispersion coefficients in the horizontal and vertical directions (m) from Pasquill-Gifford (P-G) parameterization scheme (Eimutis and Konicek, 1972; Gifford, 1976; Hukkoo et al, 1988). In the present work, the initial positions (x, y, z) of the primary photons in the Gaussian plume are sampled following the distribution given in Eq. (1) using the FLUKA code.

Results and discussion: The present model demonstrates that both the KERMA rate in free air and the effective dose rate follow the same trend with the downwind distances. The ratio of the effective dose rate to the KERMA rate for a particular radionuclide remains constant along the downwind distances irrespective of the stability category and the cloud model (semi-infinite or overhead plume). The ratio of 1-year old child to adult DCC is 1.39 - 1.42 for ^{135}Xe and 1.29 – 1.32 for ^{41}Ar at different downwind distances.



Stability Cat: A, for unit release rate of ^{135}Xe



Stability Cat: F, for unit release rate of ^{135}Xe

Publication: Riya Dey, H K Patni, Kapil Deo Singh, M S Kulkarni, S Anand (2019), Effective dose conversion coefficient for gamma ray exposure from an overhead plume, Physics in Medicine and Biology. Vol. 64, No. 15, pp. 155001, https://doi.org/10.1088/1361-6560/ab2c92.

Application 2: Decommissioning studies for NPPs

Aim of the study: The dismantling of structural objects during decommissioning of nuclear facilities needs radioactive source characterization for the planning of decommissioning strategies in compliance with the ALARA (as low as reasonably achievable) principle. The sources may arise from neutron activation of the structural components in the reactor core as well as contamination due to the radioactive release from the fuel occurred during normal operation or unplanned events in a nuclear power plant (NPP). To illustrate this, a guide tube made up of zircaloy – 4 has been considered. This study has identified and quantified the activity inventory in a guide tube at the end of the operation of the reactor using the ORIGEN2 code, and then estimated the associated external gamma dose-rate using the FLUKA Monte Carlo code. The findings will help the management of radioactive waste, cost optimization and collective dose budgeting during the decommissioning stage of a typical PHWR.

Methodology: The activity inventory in the guide tube is estimated using the ORIGEN2 code (Croff 1983). The ORIGEN2 code also gives as output the 18 - group photon energy spectrum due to decay of radionuclides. Using the spectra, external gamma dose rates are calculated at the receptor locations of 5 cm, 30 cm and 100 cm from the face of the guide tube using the FLUKA Monte Carlo Code. Activation calculations need a collection of several input parameters such as: type of nuclear reactor, neutron flux seen by the structural components, geometry and masses of the structural components, plant operational history (irradiation period), material compositions considering all the trace elements present in each of the structural component, duration of cooling period following the shutdown of the reactor.

To estimate the effective dose, simulations have been carried out by placing the ICRP 110 adult reference phantom (ICRP 110, 2009) at a distance of 1 m (from the face of a guide tube to the mid-width of phantom) with the front and back side of the body facing the guide tube source. The geometry plots of the ICRP 110 adult male reference phantom facing the zircaloy - 4 guide tube in these two postures using the FLUKA geometry plotter are shown in Fig. 1 and Fig. 2

Results and discussion: The present study shows that the effective dose rate is higher when the front side of the body is facing the radiation field as compared to when the back side of the body is facing the field. This is because most of the organs that are dominant in determining the effective dose are located towards the front of the body. When the back side of the body is irradiated, these frontal organs are shielded by thicker layers of tissue than is the case for photon incidence from the front of the body.

Major radionuclide: During initial cooling period, the major radionuclides are ^{95}Zr ($T_{1/2}$ = 64.032 days) and ^{95}Nb ($T_{1/2}$ = 34.991 days), whereas, after 50 years of cooling period, the major radionuclides are ^{14}C ($T_{1/2}$ = 5732 years), ^{60}Co ($T_{1/2}$ = 5.26 years), ^{63}Ni ($T_{1/2}$ = 100 years), ^{93}Zr ($T_{1/2}$ = 1.53E+06 years), ^{93m}Nb ($T_{1/2}$ = 16.13 years), ^{121m}Sn ($T_{1/2}$ = 43.9 years).

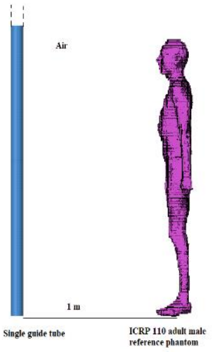


Fig.1

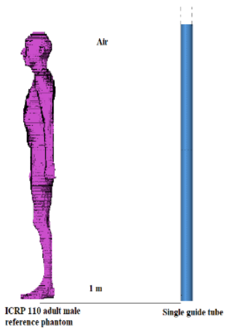
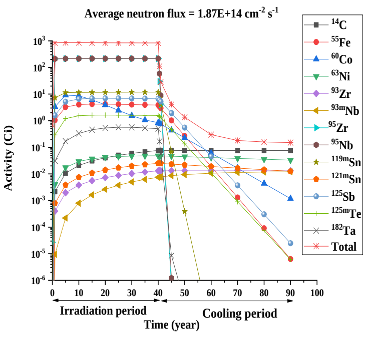
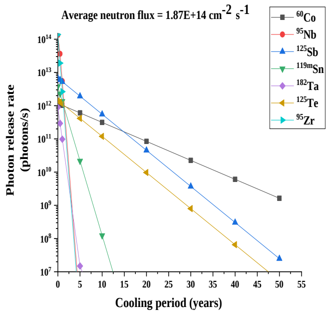


Fig.2





Publication: Riya Dey, Tanmay Sarkar, Chitra Subramanian, Srinivasan Anand, Kapil Deo Singh, Mukund Shrinivas Kulkarni (2020), Temporal evolution of activation products in Zircaloy - 4 guide tube and estimation of its external gamma dose rate for decommissioning activities, Journal of radiological protection, 40(1): 197-214.https://doi.org/10.1088/1361-6498/ab55c9.

Application 3: Incorporation of latest voxel data (ICRP 143, 2020 and ICRP 110, 2007) of various age group (new born, 1 yr, 5 yr, 10 yr, 15 yr, adult) in FLUKA code for dosimetric calculations

Aim of the study: Organ absorbed dose or effective dose to a person cannot be measured directly, rather appropriate dose conversion coefficients (DCCs) are required to convert measurable field quantities such as fluence, KERMA etc. to protection quantities (absorbed dose, effective dose). Estimation of age dependent DCCs is needed in cases where individuals across a wide range of age groups can be potentially exposed. The magnitude of organ equivalent doses from external exposures depend on body size, weight and increasing amounts of overlying tissue which enhances body shielding of internal organs. So, separate estimation of DCCs for different age group is necessary while adopting a conservative approach towards radiological impact assessment for external exposure. As a first step, the voxel data needs to be incorporated in FLUKA code for further dosimetric studies.

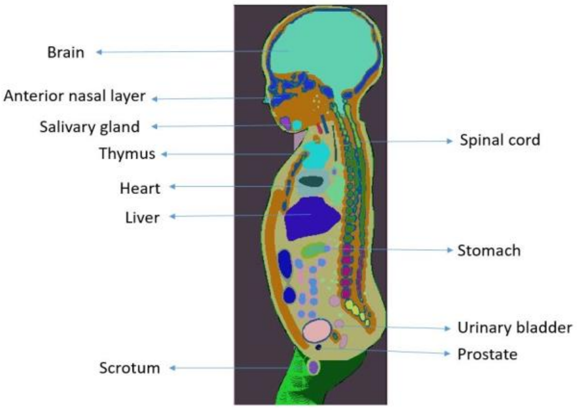
Methodology: For a particular age and gender, the human body contains large number of voxels. All these voxels create 141 organs inside each human body. There are total 57 types of media/material present. Each organ is filled up with a certain type of medium. Each medium has certain chemical composition. For example, in case of adult male phantom, some input parameters are tabulated below:

Organs	Media/material	Material ID	Density of material (g/cc)
Adrenal, left	Adrenal glands	43	1.03
Stomach wall	Stomach wall	36	1.03
Stomach contents	Stomach contents	51	1.03

Chemical composition:

Media/Material	H	C	N	O	Na	Mg	P	S	Cl	K	Ca	Fe	I
Adrenal glands	0.1044	0.2263	0.0282	0.6311	0.001	0	0.0018	0.0028	0.0022	0.002	0	0.0002	0
Stomach wall	0.105	0.1137	0.0248	0.7495	0.001	0	0.001	0.0013	0.0023	0.0013	0	0.0003	0
Stomach contents	0.1	0.222	0.022	0.644	0.001	0	0.002	0.003	0.001	0.004	0.001	0	0

For paediatric age group (new-born, 1 yr, 5 yr, 10 yr, 15 yr), the voxel data have been taken from ICRP 143, 2020. For adult, reference voxel phantom data have been taken from ICRP 110, 2007. The information of reference phantom is given as an input to FLUKA through a special file having a format of '.vxl'. After assigning material composition in each voxel unit, the phantom geometry can be viewed in FLUKA using in-built geo-viewer. Some of the geometries are shown below.



00 M

05 F

15 F

These FLUKA inputs can been used for various dosimetric studies.

Application 4: Monte Carlo simulation of luminescence dating in soil

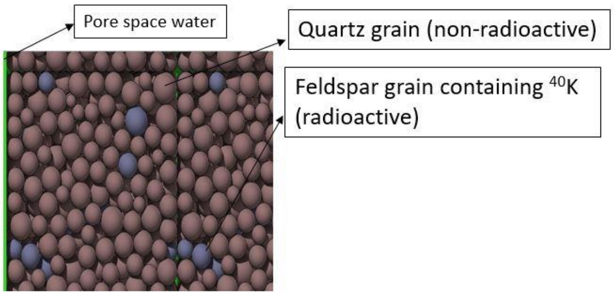
Aim of the study: Single grain Optically Stimulated Luminescence (OSL) dating methodology is the most commonly used technique for estimating chronological history of sediments (Roberts et al, 1999; Olley et al, 2003; Thomas et al, 2005). A common property of some naturally occurring minerals e.g. quartz, feldspar is that when they are exposed to radiation emitted due to radioactive decay of radioisotopes present in soil, they are able to store a small proportion of that energy in form of electrons trapped at metastable states formed by impurities present in crystal. These trapped electrons can be released from the minerals by exposing the electrons to heat (Thermo-luminescence (TL) technique) or light (optically stimulated luminescence (OSL) technique). Thus, the age of the sediment (which is basically time of irradiation) can be estimated as using the single grain OSL technique can be obtained as

$$age = \frac{dose\ acquired\ by\ crystal}{Annual\ rate\ of dose\ deposition} = \frac{D_e}{\dot{D}}$$

However, a significant amount of scatter is observed in the dose estimates using single grains of quartz for natural sediments (Mayya et al, 2006; Guerin et al, 2014). The present work addresses this issue by estimating the scatter due to variable potassium content in the sediment and variable grain sizes using the FLUKA Monte Carlo radiation transport code.

Methodology: The arrangement of grains randomly packed in the sediment matrix has been obtained using the PackLSD code – a general molecular-dynamics (MD) code (https://cims.nyu.edu/~donev/Packing/PackLSD/Instructions.html). In the output of PackLSD code, the compactness of the grains, their position coordinates are listed. This information has been fed into the FLUKA code and an infinite sediment matrix containing quartz (non-radioactive), ^{40}K containing feldspar (radioactive) and pore space water has been generated. A close-up of simulation geometry is shown here where various input parameters are: random close packing of grains with compactness 0.594, water content: 12%, potassium content: 0.5%, mean grain size: 155 µm, SD: 10 µm.

Estimation of mean dose and relative standard deviation (RSD):



The mean dose (D_{mean}) refers to the arithmetic mean of absorbed doses of the grains.

$$D_{mean}(quartz) = \frac{sum\ of\ absorbed\ doses\ in\ all\ quartz\ grains}{total\ no\ of quartz\ grains}$$

$$D_{mean}(feldspar) = \frac{sum\ of\ absorbed\ doses\ in\ all\ feldspar\ grains}{total\ no\ of feldspar\ grains}$$

The RSD values are calculated for each type of grains using the following formula:

$$RSD(\%) = \frac{Standard\ deviation}{mean(\mu)} \times 100 = \frac{\sqrt{\frac{\sum_{i=1}^{N}(x_i - \mu)^2}{N}}}{\mu} \times 100$$

$$x_i = absorbed\ dose\ in\ i^{th}\ grain\ ,\mu = mean\ dose, N = total\ number\ of\ grains$$

The scatter in dose rate distribution is expressed in terms of relative standard deviation (RSD).

Results and discussion: For both feldspar and quartz grain, RSD decreases with increasing potassium content for fixed grain size; RSD value increases with increasing mean size for fixed potassium content. This is due to the fact that the average distance between source and dosimeter grains is increased as the potassium content is decreased because of a reduction in the number of feldspar grains; as a result, fewer quartz grains are close to potassium sources and most are at a distance from any potassium containing feldspar source.