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International Agreement Report

Using VARSKIN for Hot Particles Ingestion Dosimetry Evaluation

Prepared by:
Shlomi Halfon, Ph.D.

Soreq Nuclear Research Centre
Yavne 81800 Israel

Vered Shaffer, Ph.D., NRC VARSKIN Project Manager
S. Bush-Goddard, Ph.D., NRC RAMP Project Manager
J. Tomon, CHP, NRC RPB Branch Chief

Division of Systems Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
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ABSTRACT

Small highly radioactive particles referred to as "hot particles" have been a radiological concern and dosimetry challenge in the last few decades, especially in and around nuclear industry facilities. VARSKIN has been used for decades to calculate hot particles dose in the case of skin exposure largely due to contamination scenarios. To test the feasibility of VARSKIN for dosimetry analysis of hot particle ingestion scenarios, VARSKIN was benchmarked against Monte Carlo N-Particle (MCNP) simulations and data from the literature, to evaluate its ability to be used for the calculation of beta doses to the digestive tracts in the case of hot particles ingestion.

VARSKIN was found to a large extent in alignment with the calculation of the maximum dose from ingested hot particles. The VARSKIN code results were found to be within approximately 10 percent of those from MCNP, for electron energies between 0.2 to 2.5 megaelectronvolts (MeV) and hot particle sizes no larger than a few hundred micrometers in diameter.

However, to perform such calculation in VARSKIN, it was found that few enhanced parameters must be included in the calculation. The first is to cancel the backscatter correction. Second an appropriate volume averaging parameter according to the International Commission on Radiological Protection (ICRP) organ model must air be included. Third, the user must set the averaging area to give the maximum Dose Area Product (DAP).

With these enhanced parameters, the dosimetry from VARSKIN will be able to estimate the worst case for the hot particle exposure which will mainly relate to the local dose for a potential ulceration risk or the average dose for cancer risk.

The dose distribution around a cylindrical brachytherapy source inside the body was also calculated using VARSKIN. VARSKIN results compared well to MCNP version 6.2 and the Electron Gamma Shower (EGSnrc) software package when a point source was modeled without self-attenuation with the source at distances more than approximately 1 millimeter (mm) away from the source. When realistic source composition was included in the models, VARSKIN produced results that were approximately 30 percent lower than those from EGSnrc.

FOREWORD

The U.S. Nuclear Regulatory Commission (NRC) established the Radiation Protection Computer Code Analysis and Maintenance Program (RAMP) as part of their international cooperative research program in March of 2014. The purpose of RAMP is to develop, maintain, improve, distribute and provide training on NRC-sponsored radiation protection and dose assessment computer codes. RAMP computer codes encompass radiation protection and dose assessment in the areas of emergency response, decommissioning, environmental dose assessment and NPP licensing dose assessments. Dr. Shlomi Halfon from the Soreq Nuclear Research Centre performed this work as part of an agreement on research participation and technical exchange.

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EXECUTIVE SUMMARY

Small highly radioactive particles (less than 1 millimeter (mm) in diameter) referred to as "Hot particles", have been a radiological concern in the last few decades, in and around nuclear reactor facilities. Hot particle dosimetry poses a challenge due to the difficulty in predicting the potential carcinogenic and ulceration effect because of local irradiation by those distinct small particles. The difficulty arises due to the lack of studies using radioactive particles and the lack of calculation techniques for dose estimation for such non-uniform exposure. Such hot particle exposure is of particular concern for US aging light-water reactors.

VARSKIN has been used for decades to calculate hot particles dose in the case of skin exposure from contamination. Ingestion of hot particles might create exposure, which is similar to the skin, with a source located on or close to the surface of the tissue. Out of all the alimentary tract regions, in the case of hot particle ingestion, the estimated doses to the rectosigmoid region of the colon, at the last part of the ingestion system, are the greatest. The use of VARSKIN for this case of digestive tracts hot-particle dosimetry, mainly rectosigmoid dose, is examined in this report.

The case of a hot particle located on the tissue surface of the rectosigmoid, which is constantly in the closest position to the tissue, was evaluated. The Monte Carlo N-Particle (MCNP) code 6.2 simulations and the Materials Test Reactor (MTR) fuel fragments hot particles exposure in Dounreay [1], were used as references for the VARSKIN benchmark study. The Dounreay report [1] has referred to this scenario as the maximum dose scenario for hot particles ingestion. VARSKIN results were averaged over the whole rectosigmoid surface area, creating dose evolution for the case of a particle moving along the rectosigmoid but maintain contact with the rectosigmoid wall. A method was developed to perform the rectosigmoid dose calculation with VARSKIN which include modification of the code to calculate the dose in homogeneous water environment, and a method to set the averaging area according to the maximum energy deposition.

VARSKIN was found to large extent accurate for the calculation of the maximum dose from ingested hot particles. The results were found close (within approximately 10 percent) to the MCNP calculations, for most of the electron energies and hot particle sizes (up to few hundred micrometers in diameter). Such calculation can estimate the worst case for the hot particle exposure related to the maximum average dose for cancer risk, when the hot particle is moving in contact with the wall of the rectosigmoid, or to local dose evolution for ulceration risk when the hot particle is held stationary against the wall for a long period of time.

Following these results, the use of VARSKIN was also examined to calculate the dose distribution around a source inside the body. The source is assumed to be a brachytherapy source which usually have a cylindrical shape. VARSKIN gave a good dose evaluation comparing MCNP 6.2 and the Electron Gamma Shower (EGSnrc) computer code, when calculating a point brachytherapy dose distribution in cylindrical geometry, for distances above approximately 1 millimeter (mm) from the source. However, when realistic source geometry was considered, VARSKIN results were significantly lower (approximately 30 percent) from EGSnrc.

ABBREVIATIONS

Bq	becquerels
cm	centimeter
cm^2	RAMP Radiation Protection Computer Code Analysis and Maintenance Program
CFR	Code of Federal Regulations
DAP	Dose Area Product
DFR	Dounreay Fast Reactor
DPK	Dose Point Kernel
EGSnrc	Electron-Gamma Shower software package
GI	gastro-intestinal
Gy	gray
HATM	Human Alimentary Tract Model
h	hour
ICRP	Interactional Commission on Radiological Protection
keV	kiloelectronvolt
MCNP	Monte Carlo N-Particle
MeV	megaelectronvolt
mg	milligram
MTR	Materials Test Reactor
NRC	Nuclear Regulatory Commission
RAMP	Radiation Protection Computer Code Analysis and Maintenance Program

1 INTRODUCTION

"Hot particles" are defined as high-activity radioactive particles with a diameter ranging between several micrometers (μm) to several millimeters (mm) and behave like a single particle. Hot particles have been a radiological concern for the last 40 years in and around nuclear industry facilities [3]. The ‘hot particles’ that occur most commonly in the nuclear industry, are predominantly beta/gamma emitters. Due to rapid beta attenuation and the near inverse square fall-off in fluence with distance for small sources, the spatial dose distribution around ‘hot particles’ is highly non-uniform. This leads to a difficulty in predicting the potential carcinogenic and ulceration effect as a result of localized irradiation by the small particle that might be orders of magnitude higher compared to a uniform distribution of the same dose. Dose estimation from an ingested hot particle [2] is not considered internal dose because there is no biokinetic principles guiding the movement of the hot particle. This report provides a methodology for calculating a dose from an ingested hot particle that resides stationary in the body for a length of time.

Small particles (<10 μm) can be inhaled and reach the deep lung and get caught there for a long period of time, increasing a potential lung cancer risk. Larger particles might be hazardous due to ingestion or from external exposure to the skin. The potential hazard of large ‘hot particles’, rather than smaller respirable particles, has been the main concern in recent years regarding ‘hot particle’ risks in the nuclear industry. The exposure of skin and digestive tracts has been the most dominant actual practical experience, particularly for ageing US light-water reactors became a concern sources of "hot particles" [3].

In the nuclear power industry, hot particles could be the results of two main routes [4]:

1. Corrosion of irradiated fuel with defective cladding either in the core, or in fuel cooling/storage facilities.

2. Neutron activation of corrosion product particles originated from the coolant circuit and spend some time around the core and released after transport back to an accessible part of the coolant circuit or from the surface of discharged fuel element.

Hot particles originating from both processes above are of concern for US aging waterpower reactors [5][6]. The emission of such particles is more common in pressurized-water reactors then in boiling-water reactor, and there are more frequently found during outages, about five times more than during normal operation. Mixed fission corrosion products along with cobalt (Co) -60 are the most common hot particles from water reactors [7]. The particle activity distributions are approximately log-normal with geometric mean activities of a few kilobecquerels (kBq) [4].

If an individual ingests a hot particle, internal dosimetry methodology does not apply due to the stationary nature of the particle in the body. Instead the exposure is then similar to that of a skin contamination exposure with some modifications. Ingested particles will flow with the digested material through the colon in highly variable manner. Movement in the rectosigmoid, at the last part of the ingestion system, does not occur as a constant flow but rather as mass movements, resulting from periodic contractions between longer periods of quiescence. Local doses within the rectosigmoid may therefore be substantially greater than the average dose within the region.

The US Nuclear Regulatory Commission (NRC) has developed a code called VARSKIN for the calculation of skin dose from a radioactive skin contamination. VARSKIN is used to calculate occupational dose to the skin resulting from exposure to radiation emitted from hot particles or other contamination on or near the skin [9]. These assessments are required by Title 10 of the *Code of Federal Regulations* (10 CFR) Part 20.1201(c), which states that the assigned shallow dose equivalent is to the part of the body receiving the highest exposure over a contiguous 10 square centimeter (cm^2) of skin at a tissue depth of 0.007 centimeter (cm) (7 milligram (mg)/cm^2). This report will analyze whether VARSKIN can be used to calculate dose from a hot particle that has been ingested and might be stationary in the digestive tract.

2 BACKGROUND

2.1 Alimentary Tract Mode

The International Commission on Radiological Protection (ICRP) approach for alimentary tract internal dosimetry was described in ICRP Report No. 30 [10]. The ICRP methodology considers the transition of the radioactive material in four sections of the alimentary tract: the stomach, small intestine, upper large intestine and lower large intestine. Transit time was taken from clinical studies and the mean transition times were taken as: 1 hour for the stomach, 4 hours for the small intestine, 13 hours for the upper large intestine and 24 hours for the lower large intestine.

In ICRP Report No. 30, the doses to the different sections were calculated separately and to the mucosal layer only. For non-penetrating radiation, electrons and alphas, the absorbed fraction for the mucosal layer was estimated as 0.5 v/M where M is the mass of the contents of that section of the tract and v is a factor between 0 and 1 representing the proportion of energy reaching sensitive cells. The factor of 0.5 was introduced because the dose at the surface of the contents will be approximately half that within the contents for non-penetrating radiations. For electrons (beta particles), v was taken to be 1. For alpha particles, an arbitrary value of 0.01 was used.

The new ICRP Human Alimentary Tract Model (HATM) from ICRP Report No. 100 [12] has a updated methodology such as:

1. Dose calculation to finer alimentary tract regions (Figure 2-1), including- oral cavity, esophagus, stomach, small intestine, right colon, left colon and rectosigmoid (including the rectum) [13].

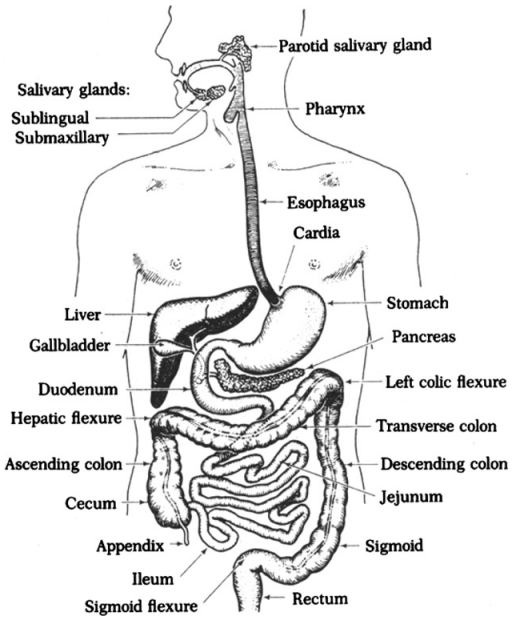

Figure 2-1 General Structure of the Human Alimentary Tract System

2. Age-dependent and gender-depended parameter values for the dimensions of alimentary tract regions and associated transit times of contents through the regions were considered. The parameters used in [12] are copied and presented in Tables 2-1, 2-2 and 2-3. In general, the stomach and particularly the colon are of greatest importance in terms of dose and cancer risk. While the small intestine may receive greater doses than the stomach, it is not sensitive to radiation-induced cancer [12]. The colon generally receives the highest doses because of long transit times (see Table 2-3) and is of greatest importance when considering deterministic effects. Doses are calculated separately for the right colon, left colon and rectosigmoid based on the available transit time data. The rectum is taken to be part of the rectosigmoid because of difficulties in determining transit times separately and because the rectum does not have a specific tissue weighting value.

Table 2-1 HATM Reference Values for Physiological Length of the Large Intestine (cm)

Segment	Newborn	1 year	5 years	10 years	15 years		Adult	
					Male	Female	Male	Female
Right colon	14	18	23	28	30	30	34	30
Left colon	16	21	26	31	35	35	38	35
Rectosigmoid	15	21	26	31	35	35	38	35
Total	45	60	75	90	100	100	110	100

Table 2-2 HATM Assumed Values for the Internal Diameter of the Large Intestine (cm)

Segment	Newborn	1 year	5 years	10 years	15 years	Adult
Right colon	3	4	4.5	5	6	6
Left colon	2.5	3	3.5	4	5	5
Rectosigmoid	1.5	2	2.3	2.5	3	3

Table 2-3 Default Transit Time for Right Colon, Left Colon and Rectosigmoid, used in HATM

Segment	Transit time (h)				
	Newborn	1 year	5–15 years	Adult male	Adult female
Right colon	8	10	11	12	16
Left colon	8	10	11	12	16
Rectosigmoid	12	12	12	12	16

3. An important update in the new ICRP model is an explicit consideration of doses to target cells for radiation-induced cancer to the various regions. The doses in the various region, for non-penetrating electron and alpha radiation, were calculated considering the different locations of the target tissues related to cancer induction. The targets are taken to be the epithelial stem cells, located in the basal layers of the stratified epithelia of the oral cavity and esophagus and within the crypts that replenish the single cell layer epithelium of the stomach and small and large intestines [12].

In the large intestine, deep, straight crypts penetrate the "lamina propria" from an intercryptal plate (see Figure 2-2, left). The stem cells are in the base of the crypts. In the HATM, the code MCNP was used to calculate the adsorbed dose fraction for electrons, together with the geometric model for each region. This was done using simple geometric representations of alimentary tract anatomy. Figure 2-2 shows an example of a geometric representation of the epithelial lining of the large intestine. The left Illustration of Figure 2-2 displays the cross-sectional structure of the epithelial lining of the large intestine, showing crypt and stem cell position. The right illustration of Figure 2-2 displays the geometric representation of the epithelial lining of the large intestine, showing the location of target cells at the base of the crypts, 280–300 μm below the intercryptal plate [12]. All tubular regions of targeted cells of the alimentary tract were treated as simple cylinders that formed a continuous layer at a specified depth below the luminal surface. Table 2-4 shows the assumed target cell depths in each region and the mass of the target tissue in adult males [12].

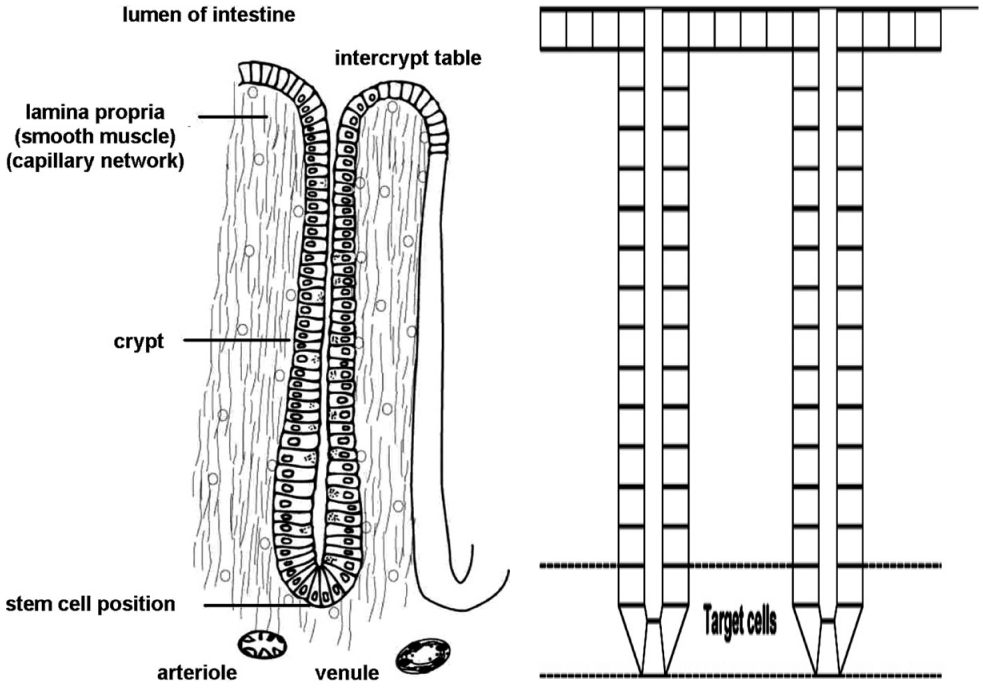

Figure 2-2 Geometric Representation of the Epithelial Lining of the Large Intestine

Table 2-4 Target Cells Depths and Masses for Each Region in the Digestion Tract for Adult Male

Region	Target cell depth (μm)	Target cell mass[a] (g)
Oral cavity	190–200	0.23
Oesophagus	190–200	0.091
Stomach	60–100	0.62
Small intestine	130–150	3.6
Right colon	280–300	1.3
Left colon	280–300	1.2
Rectosigmoid	280–300	0.73

2.1.1 Hot Particles in the Alimentary Tract

Ingested particles will flow with the digested material through the colon in highly variable manner. Movement in the rectosigmoid, at the last part of the ingestion system, does not occur as a constant flow but rather as mass movements, resulting from periodic contractions between longer periods of quiescence. Local doses within the rectosigmoid may therefore be substantially greater than the average dose within the region. Out of all the alimentary tract regions, In the case of hot particle ingestion, the estimated doses to the rectosigmoid region of the colon were found to be the greatest [1].

2.2 VARSKIN Introduction

VARSKIN is a US NRC computer code used by staff members and NRC licensees, developed to calculate occupational dose to the skin resulting from exposure to radiation emitted from a contamination on or near the skin [9]. Soon after the release of VARSKIN, the industry encountered a “new” type of skin contaminant, discrete microscopic radioactive particles, “hot” particles. These particles differ radically from uniform skin contamination in that the particles have a thickness associated with them, and many of the skin exposures result from particles on the outside of protective clothing. VARSKIN became an important tool for hot particles dose calculation to the skin.

Since the original version released, several improved versions have been made along the years. Improvements to the earlier VARSKIN versions included enhanced photon and electron dosimetry models, as well as models to account for air gap and cover materials for photon dosimetry. VARSKIN 6 [14] gives the user the option to have the code automatically include all decay products in dosimetry calculations or to allow the user to manually add progeny. Although the user can choose any dose-averaging area, the default area for skin dose calculations is 10 cm^2, to conform to regulatory requirements.

2.2.1 VARSKIN Calculation Principles

VARSKIN is based on Dose Point Kernel (DPK) method and rely on numerical integration of a point kernel over the dose region of interest and the entire source volume [14]. The point kernel simplification allows much faster calculations compering Monte-Carlo simulations, while the calculation accuracy is usually lower. In VARSKIN the DPK medium is typically water which closely models tissue.

For electron, the main input for the DPK calculation is the “scaled absorbed dose distribution”, which is the spatial distribution of absorbed dose in a water medium around mono-energetic point-isotropic electron sources. The distribution was originally calculated analytically [16]. The development of Monte-Carlo electron transport codes opened the possibility to create increasingly accurate tabulated input data for DPK. In VARSKIN 6 the Monte-Carlo transport code EGSnrc, was used to calculate the radial energy distributions at electron energies between 0.01 megaelectronvolts (MeV) and 8 MeV [14].

2.2.2 VARSKIN Backscatter Correction

Accordingly, electron DPK calculation assumes an infinite homogenous medium (water/water interface). Thus, DPK assumes that an electron emitted away from the dose point can scatter back in the water and possibly contribute to the dose at the point of interest. In skin dose calculation, an air medium is usually surrounding the skin (air/water interface), hence an additional correction is required to compensate for the less scatter in air. This scenario is important especially for skin dose calculations from hot particles. A backscatter factor is calculated in VARSKIN by taking the ratio of the dose in a case where scattering material other water is present (non-homogenous case) to that when only water is present. The backscatter factors are dependent on electron energy, the effective atomic number of the backscattering medium, normal depth and the dose averaging area. In VARSKIN, scattering corrections are applied each step of the numerical integration, rather than the overall correction factor to the final dose calculation [14].

3 USING VARSKIN FOR HOT PARTICLE INGESTION DOSE ESTIMATION

3.1 Benchmark Study

In order to evaluate whether VARSKIN can be used to estimate hot particle ingestion, where the internal dosimetry methodology does not apply, a benchmarking study was performed. The Health Protection Agency report “Health Implications of Dounreay Fuel Fragments Estimates of Doses and Risks” [1] was used to benchmark this dosimetry evaluation.

To summarize the Dounreay scenario, discrete fragments of irradiated nuclear fuel had been discovered on the foreshore at the Dounreay nuclear site in Scotland, nearby public-access beaches. The case was studied extensively due to the public exposure concerns, identified as hot particles exposure. A report commissioned by the Scottish Environment Protection Agency (SEPA) was published [1], designated to assess potential doses and risks to individuals from the fuel hot particles fragments. In reference [1] the new ICRP HATM [12] (see section 2.1) were reviewed and applied for hot particles exposure dose evaluation.

There were two main types of particles: fragments of Materials Test Reactor (MTR) and the Dounreay Fast Reactor (DFR) fuel. The more abundant MTR particles originated as swarf generated during milling to remove aluminum cases from fuel elements. Dose and risk assessments in the report related primarily to the MTR particles and were determined to be conservative when applied to DFR particles. The principal radionuclides contained within the particles are the fission products cesium (Cs) -137 and strontium (Sr) -90/yttrium (Y) -90 with small amounts of plutonium (Pu) -238, Pu-239, and americium (Am) -241). Particles are generally characterized by their Cs-137 activity. The most active particles found contained around 10^5 becquerel (Bq) Cs-137.

Analyses of possible doses and risks in this case indicate that the principal concern following skin contact, ingestion or inhalation is the possibility of localized ulceration of skin and the mucosal lining of the colon or extra-thoracic airways. Among the three exposure channels the risk of deterministic effects following fuel fragment ingestion has been determined in [1] based on doses to the rectosigmoid region of the colon, since this region of the alimentary tract receives the greatest doses, as discussed in Section 2.1. Doses from electron and photon emissions were calculated using the radiation transport code MCNP [18]. For dosimetric purposes, spherical Uranium/Aluminium (15 percent uranium) particles of homogenous elemental composition and radionuclide distribution were assumed, the uranium content of particles was assumed to be 15 percent and the density to be 3.1 gram (g) per cubic centimeter (cm^{-3}). Dose-rate coefficients (Gray (Gy) h^{-1} Bq^{-1}) for the rectosigmoid wall were computed for fragments of Sr-90 (Beta (β-), 28.79 y), Y-90 (β-, 64 h) and ^{137}Cs (β-, 30.08 y), with diameters of 3 μm and 3 mm, located at a range of positions along the axis of the lumen. The calculations considered internal diameters of the rectosigmoid corresponding to adults and one year old children (see Tables in Section 2.1).

In the Dounreay report, the calculated doses to the rectosigmoid for an adult was performed using MCNP from a 10^8 Bq Cs-137 hot particle. To summarize the three scenarios that were evaluated:

1. Random movement of the hot particle within the lumen during transit, resulting with a local dose of 0.3 – 0.4 Gy to the lumen.

2. The hot particle moving in contact with the intestine wall. In this case, the dose was estimated to be around 1 – 2 Gy to the intestine wall. The estimated threshold dose for lethal damage to the colon from ingested radionuclides is 20 Gy.

3. Movement of the hot particle in the rectosigmoid where it is modeled not as a constant flow, but rather as mass movements resulting from periodic contractions between longer periods of quiescence. In this case the doses were calculated for a particle held stationary against the rectosigmoid wall for 6 hours. Such case would deliver about 240 Gy to a 1 cm^2 tissue in a depth of 400 μm. Local doses of 200 – 300 Gy are likely to cause ulceration that might not repair readily in the environment of the large intestine while doses of less than 1 Gy will result in localized crypt sterilization that should be replaceable by regeneration of new crypts.

This report uses VARSKIN to calculate the dose to the same scenarios as mentioned above. This will allow VARSKIN to be benchmarked against this study for ingested hot particle dosimetry. In the next sections, the analysis in the Dounreay report will be used for the VARSKIN gastro-intestinal (GI) dose calculation benchmark.

3.2 Methodology for Hot Particle Local Dose to a Digestive Track Using VARSKIN

Figure 3-1 shows a typical scenario for VARSKIN is of for calculation of skin dose. In this case the source is located in the air, somewhere on or above the skin. The source- tissue interface is air/water (tissue). The relevant tissue depth is 70 μm and the averaging area is 10 cm^2 with planar geometry.

In the case of rectosigmoid dose calculation (see Figure 3-2), the source (hot particle) is located inside the rectosigmoid lumen, surrounded by the lumen content, which can be approximated by water for the tissue, for the dose calculation. Hence the source-tissue interface in this calculation is water (tissue)/ water (lumen content). It is possible to change the interface in VARSKIN from air/water to water/water by eliminating the scattering correction, as describe in Section 2.2.1.2.

The locations of the target tissues related to cancer induction in the rectosigmoid case is 280 – 300 μm (Table 2-4). The geometry of the rectosigmoid lumen is cylindrical, hence the dose calculation should be averaged upon a cylindrical surface. However, cylindrical averaging area is not possible in VARSKIN so one of the goals of this work is to find if VARSKIN can be applicable to this scenario. Table 3.1 summarize the differences between skin and rectosigmoid dose calculations parameters.

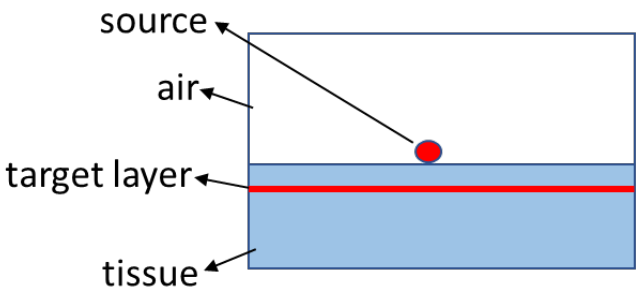

Figure 3-1 Skin Dose Calculation Scenario, Air/Water Interface, Plane Target Cells Layer 70 µm Deep

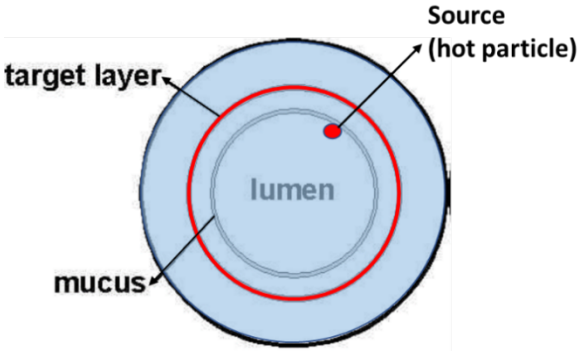

Figure 3-2 Rectosigmoid Dose Calculation Scenario, Water/Water Interface, Cylindrical Target Cells Layer 280 – 300 µm Deep

Table 3-1 The Differences Between Skin and Rectosigmoid Dose Calculations Parameters

	Skin	rectosigmoid
Target cell depth	70 µm	280-300 µm
Geometry	plane	cylinder
Interface	Tissue- air (water - air)	Tissue - lumen content (water- water)

Based on the capabilities of VARSKIN 6, three parameters should be considered for the dosimetry of an ingestion of hot particles. The parameters are cancelation of backscatter correction, adjustment of volume-averaging, and settlement of the averaging area.

3.2.1 Backscatter Correction

When adding a nuclide to the VARSKIN user library, a .rad file is created for the electron dosimetry in the “dat” folder. The “.rad” file contain the average beta energy, the half-life,

maximum beta range, yield, electron emission distribution and the backscatter factors. The final 160 lines of data written to the file (by SadCalc.exe, [14]) are the scattering corrections for use in normal half-space air/water VARSKIN scenario. The factors are marked by "sngBSCF[0-159]" in the file. Changing manually each of these factors to "1" will eliminate the air/water scattering correction in the VARSKIN calculation. Changing the scattering corrections to one will make VARSKIN model a homogeneous water medium – a water/water interface needed for GI tract dose calculations. An example for such file adaption is discussed in Section 3.1.5 [14].

3.2.2 Volume Averaging

The locations of the target tissues related to cancer induction in the rectosigmoid case is 280 – 300 μm (Table 24, [13]). To model this in VARSKIN, the option "Perform Volume Averaging" needs to be checked. Volume of cell card of depths of 280 μm (28 mg/cm^2) to 300 μm (30 mg/cm^2) should also be selected.

3.2.3 Averaging Area – Dose Area Product

The averaging area for skin dose calculation is distinctively defined in the regulatory requirements (Section 2.2). However, in the case of rectosigmoid local dose for this study, the averaging area is not known and needs to be set by the user for VARSKIN. To set the average area in VARSKIN, the Dose Area Product (DAP), a good estimation of the total radiation energy deposit in the tissue, is then defined as (Equation 3-1):

$$DAP = \mathrm{D} \times \mathrm{A} \propto \frac{E}{\rho} \tag{3-1}$$

Where D is the effective dose in Gy, A is the averaging area in cm^2, E is the energy deposited in joules, and ρ is the area density in kg/m^2. Accordingly, the DAP has the units of Gy-cm^2. Since the rectosigmoid surface area is large (358 cm^2 for adult) relative to the electron's ranges, the principle to find the appropriate averaging area is to find an area where the DAP reaches the maximum value [17].

Iterations of VARSKIN calculations were performed to determine the DAP for this scenario. The iterations should increase the averaging area until the DAP reaches it maximum and stays almost constant with further averaging area increments. For each isotope, or electron energy, the averaging area for maximum DAP should be calculated separately. The DAP can be used for dose assessments of the maximum local dose and for rectosigmoid average dose, depending on the normalization of the results.

3.3 VARSKIN Inputs for the Benchmark

The following section describes the VARSKIN inputs for GI dose calculations based on the parameters described in the Dounreay report for Sr-90 and its daughter Y-90.

3.3.1 Material Composition and Geometrical Parameters

The hot particles MTR fuel fragment modeled as spherical U/Al particles of homogenous elemental composition and radionuclide distribution. The uranium content of particles was assumed to be 15 percent by weight (0.02 by atoms), correspond to density of 3.1 g/cm^3.

For the VARSKIN benchmark calculations, two sources were selected Sr-90 and Y-90, with sphere geometry, diameter of 3 μm, density of 3.1 g/cm^3 and volume averaging was selected between 280 μm to 300 μm thick. The exposure time was set to 1 hour. The effective atomic number of the MTR fuel fragments was calculated for VARSKIN input according to the atomic ratio of U/Al=0.02, as follows (Equation 3-2):

$$Z_{eff-MTR} = \sqrt[2.94]{f_1 \times (z_1)^{2.94} + \cdots f_n \times (z_n)^{2.94}} \quad (3\text{-}2)$$

$$= \sqrt[2.94]{0.874 \times (13)^{2.94} + 0.126 \times (92)^{2.94}} = 45.8$$

Where f_n is the fraction of the total number of electrons associated with the aluminum and the uranium in the fuel, and Z_n is the atomic number of each element (Z_{Al}=13 and Z_U=92). An example of adding a Sr-90 source to VARSKIN with effective atomic number of 45.8 is shown in Figure 3-3.

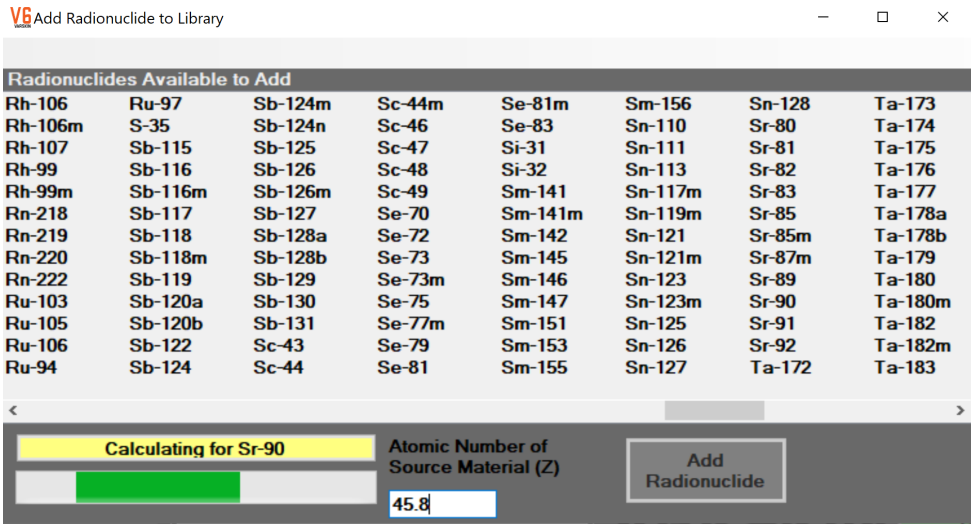

Figure 3-3 Screenshot of VARSKIN "Add Radionuclide to Library" Card for Sr-90

Summary of input parameters are shown in Table 3-2 followed by a VARSKIN screenshot from the calculation in Figure 3-4 and the of the volume of cell card for the calculation of volume average dose between 280 μm (28 mg/cm^2) to 300 μm (30 mg/cm^2) in Figure 3-5.

Table 3-2 VARSKIN Input Parameters for Hot Particles GI Dose Calculation

VARSKIN Inputs	
Source geometry	sphere
Special options	preform volume averaging
Exposure time	60 minutes
Sources	^{90}Y* ^{90}Sr* *air backscattering correction canceled
Source effective atomic number	45.8
Source activity	1 Bq
Source diameter	3 μm
Source density	3.1 g/cm^3

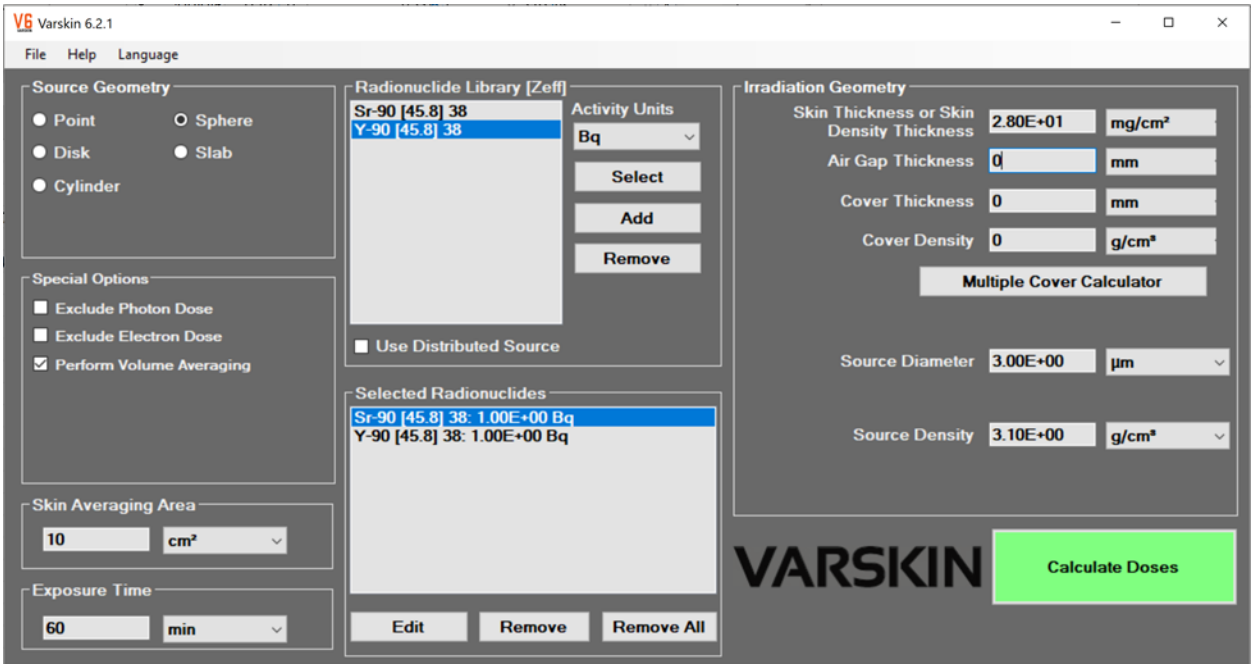

Figure 3-4 Screenshot of VARSKIN Input Card for the GI Dose Calculations

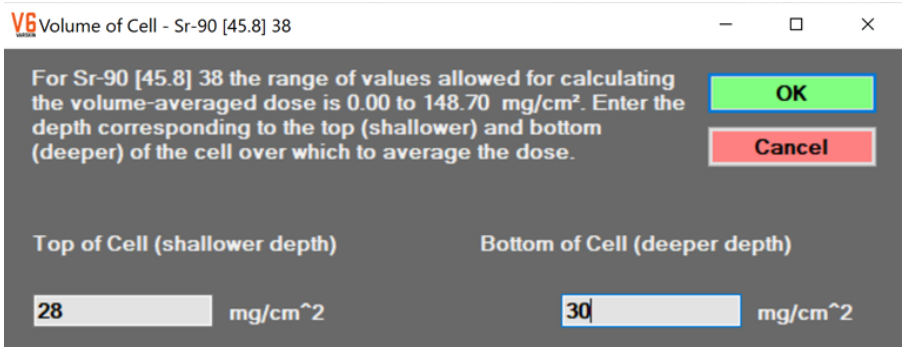

Figure 3-5 Screenshot of VARSKIN Volume of Cell Card for the Calculation of Volume

3.3.2 Cancelation of Backscatter Correction in VARSKIN

In order to use VARSKIN for GI dose calculation the scattering correction for air-water interface need to be canceled to create water/water interface, the method to do it is discussed in Section. 3.2.1. Two .rad files were created in the "dat" folder- Sr-90 [45.8] 38 rad and Y-90 [45.8] 38 rad. In each of the rad files, the last 160 parameters were changed to 1 to cancel backscatter correction. The source activity was set to 1 Bq. An example of the change of the Sr-90 ".rad" file, is illustrated in Figure 3-6.

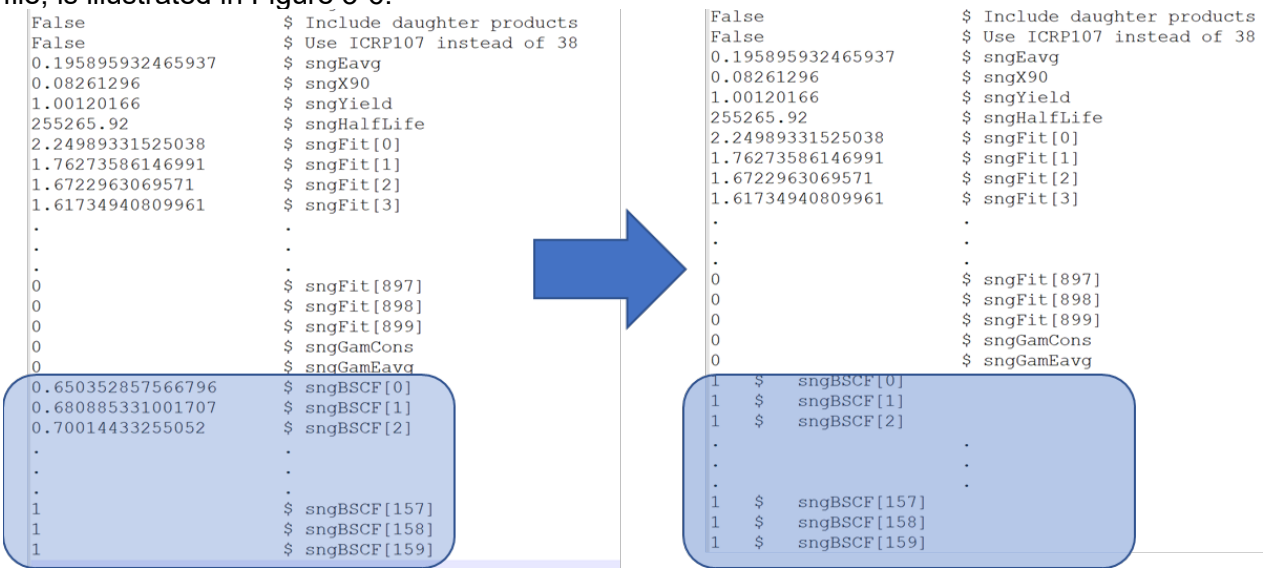

Figure 3-6 Changes to ".rad" File to Cancel Scattering Correction for Air-Water Interface

3.3.3 Rectosigmoid DAP Evolution

The DAP for various VARSKIN averaging areas were calculated based on the input described in the previous section, for Y-90 and Sr-90 sources, until an area where it reaches maximum and stays constant with further averaging area increments (as described in Section 3.2.3). An example of the process can be seen in Table 3-3, where averaging area above 1.5 cm^2 was found for the calculation of Y-90 dose.

Table 3-3 Increasing Averaging Area to find the Maximum DPA in VARSKIN Calculation of Y-90 Dose

	Averaging Area (cm^2)	VARSKIN Dose Rate (Gy/h/Bq)	DAP (Gy/h/Bq-cm^2)	Energy Deposited (Percent)
Y-90	0.1	1.08E-05	1.08E-06	69
Y-90	1	1.53E-06	1.53E-06	97.5
Y-90	1.5	1.04E-06	1.56E-06	99.3
Y-90	2	7.83E-07	1.566E-06	99.7
Y-90	10	1.57E-07	1.57E-06	100
Y-90	100	1.57E-08	1.57E-06	100

3.3.4 Benchmark Results

Two types of dose rate coefficients calculations took place in the Dounreay report - for adult, with rectosigmoid in diameter of 3 cm and length of 38 cm (358 cm^2), and for a one-year-old, with rectosigmoid in diameter of 2 cm and length of 21 cm (132 cm^2). For each case, the VARSKIN result of maximum DAP was divided by the relevant rectosigmoid surface area. For example, the maximum DPA for Y-90 was found to be 1.57E-06 Gy/h/Bq-cm^2 as illustrated in Table 3-3, this value was divided by 358 to get the rectosigmoid dose rate coefficients to adult, 4.39E-09 Gy/h/Bq, and by 132 to get the rectosigmoid dose rate coefficients to one year old- 1.19E-08 Gy/h/Bq. The same method was used to calculate the Sr-90r dose rate coefficients.

The VARSKIN results are presented in Tables 3-4 through 3-7 below and compared to the data from the Dounreay report MCNP calculations. The comparison tables included are also the regular VARSKIN calculations, in which the backscatter corrections were not canceled.

Table 3-4 Y-90 Rectosigmoid Dose Calculations for Adult, Comparison Between MCNP and VARSKIN

	Dounreay Report (MCNP) [1]	VARSKIN (no backscatter corrections)	VARSKIN (with backscatter corrections)
Dose-Rate (Gy/h/Bq)	4.47E-09	4.39E-09	3.21E-09
Ratio to MCNP	1.0	0.981	0.718

Table 3-5 Y-90 Rectosigmoid Dose Calculations for One Year Old, Comparison Between MCNP and VARSKIN

	Dounreay Report (MCNP) [1]	VARSKIN (no backscatter corrections)	VARSKIN (with backscatter corrections)
Dose-Rate (Gy/h/Bq)	1.22E-08	1.19E-08	8.71E-09
Ratio to MCNP	1.0	0.978	0.716

Table 3-6 Sr-90 Rectosigmoid Dose Calculations for Adult, Comparison Between MCNP and VARSKIN

	Dounreay Report (MCNP) [1]	VARSKIN (no backscatter corrections)	VARSKIN (with backscatter corrections)
Dose-Rate Gy/h/Bq	1.67E-09	1.59E-09	1.38E-09
Ratio to MCNP	1.0	0.952	0.826

Table 3-7 Sr-90 Rectosigmoid Dose Calculations for One Year Old, Comparison Between MCNP and VARSKIN

	Dounreay Report (MCNP) [1]	VARSKIN (no backscatter corrections)	VARSKIN (with backscatter corrections)
Dose-Rate (Gy/h/Bq)	4.57E-09	4.33E-09[9]	3.74E-09
Ratio to MCNP	1.0	0.947	0.818

The VARSKIN results for Y-90 doses are within 2.5 percent from the MCNP doses that the Dounreay study reported, both for adults and for one-year-old, when the backscatter correction was eliminated. When backscatter correction was not eliminated, the difference is significantly larger, around 30 percent. The reason for this is the fact that the rectosigmoid environment should be consider made of homogenous water, water-water interface. Calculations of this scenario with backscatter correction reduce the dose since the backscatter back to the dose point is lower than water scattering.

Similar results were found in the Sr-90 calculations, although in this case, the results are within 5 percent from MCNP (when backscatter correction was eliminated) and about 18 percent lower in a regular VARSKIN calculation (with air-water correction). The reason for a slightly lesser agreement with MCNP, might be related to the fact that Y-90 emits significantly higher energy betas (mean energy: 933.7 kiloelectronvolt (keV) and max energy: 2280 keV) than Sr-90 (mean energy: 195.8 keV and max energy: 546 keV). The lower energy Sr-90 betas will have a mean range of 450 μm in water as compared to 4500 μm range for the average Y-90 beta. The Sr-90

beta range is close to the target cell depth of 280 – 300 μm. In VARSKIN 6 report [14] and in [15] it was found that the VARSKIN electron dose calculation accuracy decrease as the electrons reaches its maximum depth, which explains the higher discrepancy for Sr-90. This point will be discussed in the next section where the calculation accuracy dependence on the beta energy is examined.

3.4 Energy Dependence Evaluation

To further analyze the ability of VARSKIN to provide dosimetry for stationary injected hot particles, VARSKIN was used to evaluate Y-90 and Sr-90 hot particles but looking at the dependency on the electron energy.

In order to benchmark VARSKIN rectosigmoid dose calculations in various energies, MCNP 6.2 model was used. An adult rectosigmoid was modeled in MCNP as a 38 cm long cylinder with diameter of 3 cm. The hot particle, a monoenergetic source, was located on the surface of the cylinder (or the lumen) and the dose was calculated in homogenous water environment to a target layer located between 280 – 300 μm deep around the cylinder (as illustrated in Figure 3.2). The source energy was changed from to 0.2 to 2.5 MeV, the relevant energy range for most of the beta sources. For each of the electron energies calculated in MCNP, a VARSKIN dose calculation was performed, the calculation was done as described in Section 3.4, with one modification. Instead of a Y-90 or Sr-90 source, a monoenergetic source was inserted using the "XX-MeV" option available in the VARSKIN radionuclides library. The comparison of the VARSKIN results to MCNP are presented in Figure 3-7. Above 0.3 MeV, the MCNP and VARSKIN results are very similar and within 1 percent of each other. At lower energies it seems that the VARSKIN calculation is about 4 percent larger than MCNP at 0.25 MeV. Below 0.25 MeV, VARSKIN results differentiate more and more significantly, becoming 15 percent lower at 0.2 MeV. At energies above 2.5 MeV, shown in Figure 3-7 insert, the discrepancy is also steadily increasing, reaching 40 percent VARSKIN underestimation at 8 MeV.

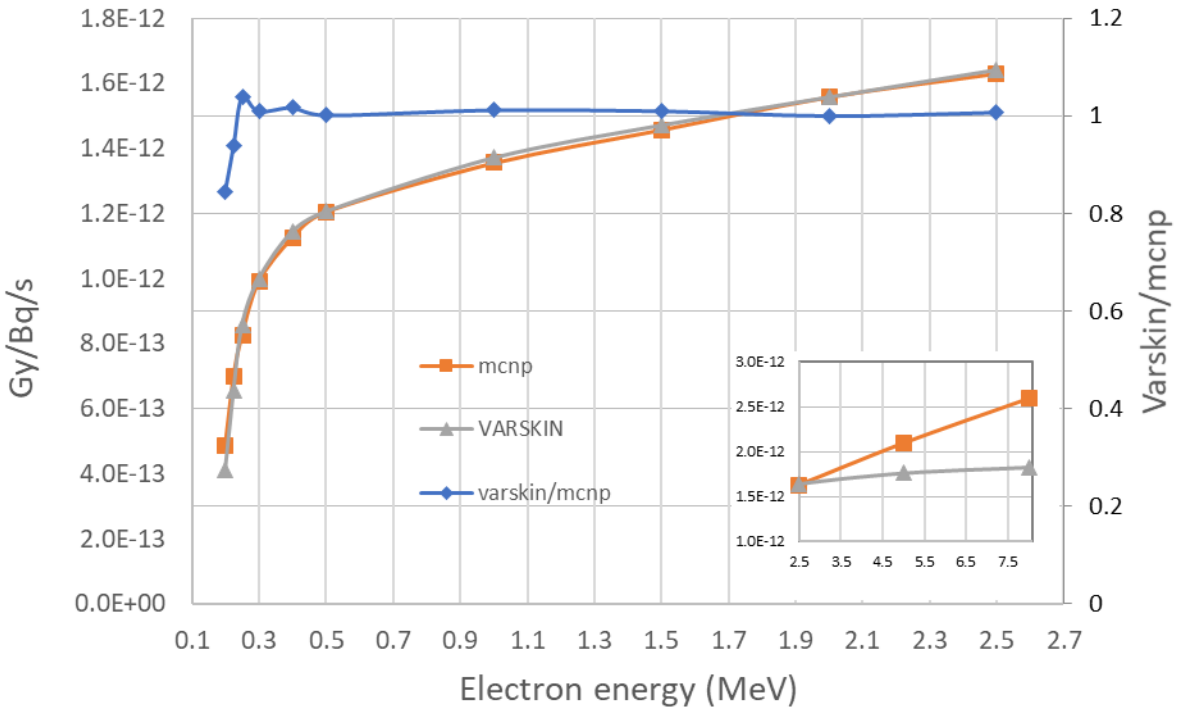

Figure 3-7 VARSKIN Versus MCNP6.2 Rectosigmoid Dose Calculation for Various Beta Energies

According to these results, VARSKIN can give a reasonable maximum rectosigmoid dose assessment for a large energy range of most common radionuclides. For sources with very low energy distribution, below 0.2 MeV, certain discrepancies might occur, as seen in the previous section, where the Sr-90 (mean beta energy: 195.8 keV) VARSKIN calculated doses where within 5 percent of the MCNP doses calculations, while Y-90 (mean bet energy: 933.7 keV) calculations had only 1 percent doses had discrepancy.

As mentioned above, the reason for the increase discrepancy at the lower energies is described in references [14] and [15]. VARSKIN validation and verification results described in [14] indicated differences between VARSKIN and EGSnrc, for beta dosimetry around depths where the electrons are reaching its maximum range. These larger deviations are apparent at the tail end of the beta-dose profiles as well [15]. It is clear from these results that the accuracy of VARSKIN decreases as the electron reaches its maximum depth. This claim is compatible with the results above (Figure 3-4), where the doses were calculated for the target cells depth of 280 μm, which is the range of a 150 keV electrons in water. The deviation increases for the lower energy electrons, toward 150 keV, with the target cells closer to their maximum depth.

At higher energies, 2.5 – 8 MeV, the range of the electrons becomes closer to the diameter of the rectosigmoid, the solid angles difference between the realistic cylindrical layer of the target cells (calculated in MCNP) and the VARSKIN calculation plain layer, become more and more significant, and hence the VARSKIN dose underestimation found at higher energies.

3.5 Hot Particle Size Dependence

In Table 3-8 the total maximum doses to the rectosigmoid taken from [1] are compared with the doses calculated with VARSKIN, for particles with Cs-137 activities ranging from 10^3 to 10^8 Bq, and with the corresponding Y-90 and Sr-90 activities) assuming Sr-90/Y-90: Cs-137 ratio of 0.9 [1]). The hot particle diameter was evaluated assuming a specific activity of 2 gigabecquerel Cs-137 g^{-1}. The maximum dose values are for particles remaining in contact with the wall during their transit in the rectosigmoid, hence their position is always on the internal surface of the tract. The calculation considered standard transit times and other standard model parameter values as discussed in Section 2.1. The VARSKIN doses in Table 3-8 are the sum of Y-90 and Sr-90 doses calculated with VARSKIN using the method describe above, with the specific particle diameter, and the Cs-137 doses taken from [1].

The results in Table 3-8 show that the VARSKIN calculation accuracy as compared with the MCNP decreases with an increase of the hot particle diameter. For diameters of approximately 300 μm, VARSKIN results are between almost identical to 10 percent higher than the MCNP results in [1]. For larger hot particles diameters, the discrepancy increases to 28 percent for 680 μm particles and 66 percent for 1300 μm particles. Discrepancies between VARSKIN calculation and EGSnrc for large self-absorbing source was discussed in [14].

In summary VARSKIN gives an accurate result, within 10 percent discrepancy from MCNP, for hot particles of few μm to few hundred μm diameters. For higher diameter hot particles, the discrepancy is larger and VARSKIN results are significantly higher and could be consider conservative.

Table 3-8 Total Dose to the Rectoigmoid from Hot Particles in Various Sizes

Cs-137 Activity (Bq)	Diameter (μm)	Adult Male Maximum Dose Dounreay Report [1] (mGy)	Adult Male Maximum Dose VARSKIN* (mGy)	VARSKIN/MCNP
1.0E+03	67	0.08	0.079	0.99
1.0E+04	150	0.7	0.74	1.06
1.0E+05	310	6	6.55	1.09
1.0E+06	680	40	51.2	1.28
1.0E+07	1300	230	382.9	1.66
*Sum of Y-90 and Sr-90 doses calculated with VARSKIN and Cs-137 dose taken from [9].				

3.6 VARSKIN Calculation for Hot Particles in the GI-Tract

The calculation discussed in the previous sections dealt with the dosimetry of a hot particle located on the inner surface of the rectosigmoid tract, i.e., in the closest position to the tissue, creating maximum dose. Such calculation will estimate the worst-case dosimetry scenario for the hot particle exposure. However, particles moving in the large intestine are not expected to maintain constant radial position and are expected to randomly move with the material that fills the rectosigmoid. Hence, the calculation of the realistic-average hot particle dose required the calculation of the dose distribution induced by the particle along the radial axis in the lumen. An average dose-rate coefficient <D> can be calculated using Equation 3-3 [1]:

$$< D >= \int_0^{R_L - R} R_p D(R_p) dR_p \Big/ \int_0^{R_L - R} R_P dR_P \qquad (3\text{-}3)$$

Where R_p is the radial location, $D(R_p)$ is the dose at this location, R_L is the radius of the lumen and R is the radius of the hot particle.

For the purpose of the average dose evaluation, the calculation of the point dose at various radial position inside the rectosigmoid lumen was examined with VARSKIN. The calculation took place as describe in Section 3.4. For adult rectosigmoid (3 cm in diameter), one difference was done with the source positions, or volume averaging thicknesses. The source positions were alternated for the various radial locations in the GI content, along the lumen radial axis, while the target layer stayed 280 – 300 μm deep in the tissue. The rectosigmoid filling material was taken as water.

Figures 3-8 and 3-9 show the comparison between MCNP results taken from [1] and the VARSKIN calculations, for Y-90 and Sr-90, respectively. For both plots the center of the lumen is the 0 coordinate. In the Y-90 case, with high energy betas and maximum range of 1.1 cm, VARSKIN calculations were performed for hot particle positions between 1.5 cm (the luminal surface) to 0.8 cm. As can be seen in Figure 3-8 the discrepancy between VARSKIN and MCNP grow sharply in deeper locations. At the tissue surface (at 1.5 cm) VARSKIN is about 2 percent lower than MCNP, but at 1.4 cm (0.1 cm from the tissue surface and 10 percent of the maximum range) VARSKIN results differ from MCNP by about 15 percent and at 0.8 cm the VARSKIN dose evaluation is about half of MCNP.

Similar results were found for Sr-90, where the beta energy is lower, and ranges are shorter (maximum range of 0.2 cm). The positions examined are within 0.1 cm from the tissue surface. VARSKIN results are again lower than MCNP at deeper locations, from a discrepancy of 5 percent at the tissues surface location, to 30 percent lower found 0.1 cm deep. The reason for the drop in VARSKIN results comparing to MCNP, for hot particles in the deeper locations, might be related to difference between the VARSKIN plane calculation area and the cylindrical shape of the rectosigmoid lumen. As the location of the hot particle becomes deeper in the lumen, the solid angle for the cylindrical target cells becomes larger compared to VARSKIN's flat target area, and therefore the VARSKIN dose calculation becomes significantly lower.

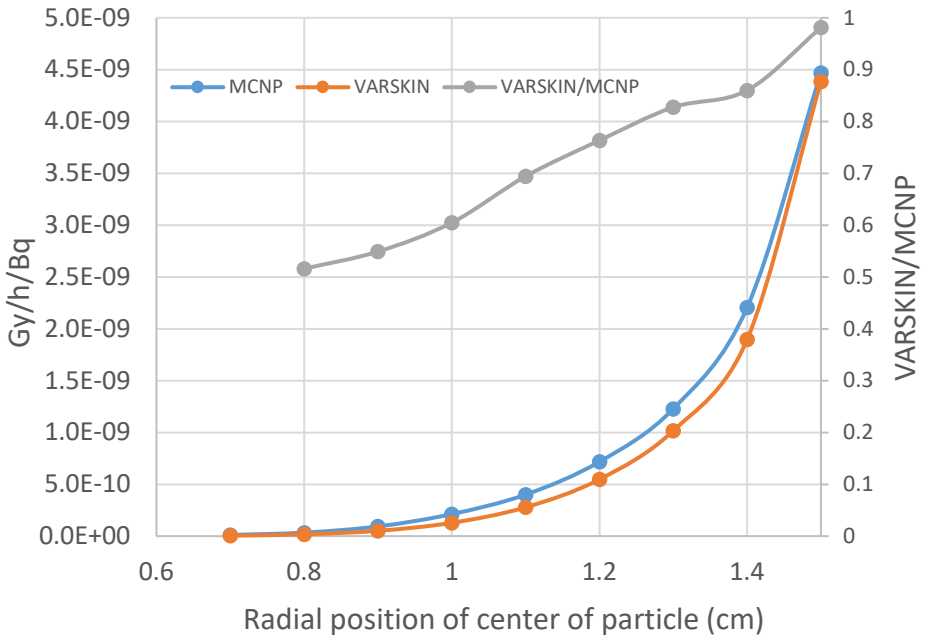

Figure 3-8 Rectosigmoid Y-90 Dose Coefficient for 3 µm Diameter Hot Particle, VARSKIN Versus MCNP

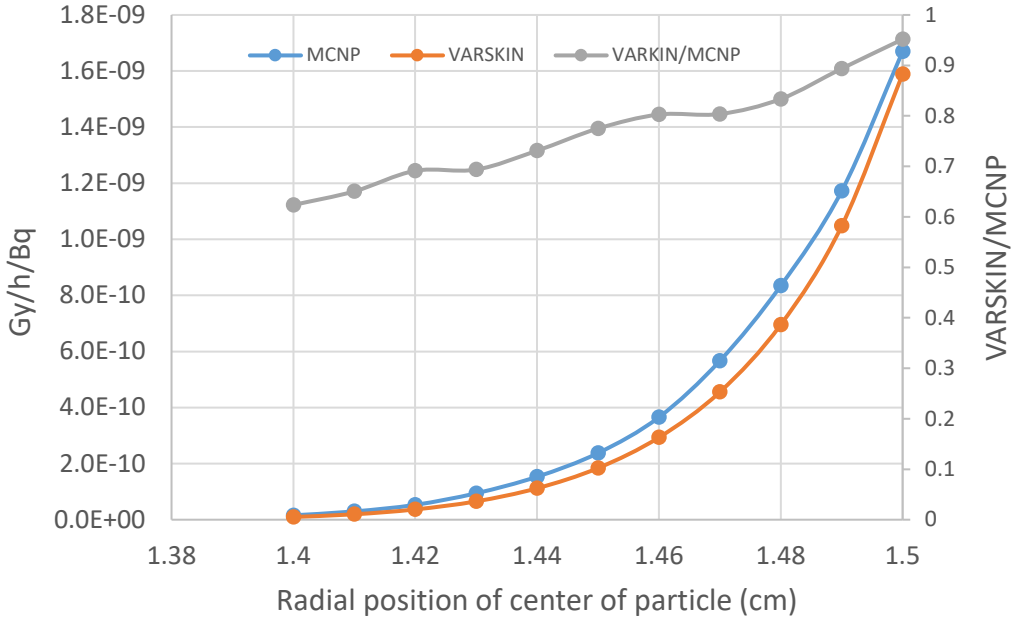

Figure 3-9 Rectosigmoid Sr-90 Dose Coefficient for 3 µm Diameter Hot Particle, VARSKIN Versus MCNP

4 DOSIMETRY OF BRACHYTHERAPY USING VARSKIN

VARSKIN was examined for calculating dose distributions around a source placed inside the body such as a brachytherapy source. Brachytherapy sources typically have a cylindrical shape. Therefore, they can be modeled by a cylindrical geometry with the source located at the center of the cylinder.

4.1 VARSKIN Benchmarking for Brachytherapy Sources

VARSKIN was benchmarked for brachytherapy sources against MCNP and EGSnrc. Cylindrical symmetric dose distribution around a brachytherapy beta source was performed. The MCNP and EGSnrc results were reproduced from Wang et al. [18]. VARSKIN was also compared to designated MCNP 6.2 simulations of the same scenarios. Wang et al. compared the calculations of the beta dose around a brachytherapy source using MCNP 4b, EGSnrc and EGSnrc. The dosimetry around 0.5 MeV, 1 MeV and 2 MeV point sources and around point and realistic Sr-90/Y-90 sources were performed.

4.1.1 Simulation Model

Wang et al. calculated the doses in water on a set of thin, short cylindrical shell around the source located in the middle of the cylinder. The electron deposition dose at a given point (r,0) on the transverse axis was averaged over the volume of cylindrical shell segment centered at the point source location. The cylindrical shells thickness was r+/-0.05 mm and their length were z=0.2 mm [18].

The VARSKIN model for these calculations is based on the following assumptions:

1. Backscatter correction was canceled, as in Section 3, since the source is in the body, assumed to be in homogenous water environment.

2. Because of the cylindrical symmetry of the case, the averaging area was set to minimum of 0.01 cm^2, the radius of the averaging plane is 0.56 mm.

3. The distance r to the source was inserted to VARSKIN as the density thickness, the dose point was in the middle of the cylindrical shells, without volume averaging.

4.1.2 Mono Energetic Point Sources

In order to validate the interpolation of the simulation model described in [18] and confirm its result, a separate MCNP 6.2 dosimetry model was built. The MCNP 6.2 calculation was done exactly as describe in [19]. In Figure 4-1, the results from MCNP 4b and EGSnrc taken from [19] are compared with the MCNP 6.2 calculation for a 0.5 MeV point source. As can be seen, the MCNP 6.2 results are identical to the EGSnrc results while MCNP 4b differ. The reason for that is that MCNP improved their algorithm for electron transport in MCNP 4c and implemented version 3.0 of the integrated tiger series (ITS-3). Since MCNP 4b was used in [19], results differ from EGSnrc and MCNP 6.2. For that reason, this report will compare VARSKIN results only to the EGSnrc results from [19].

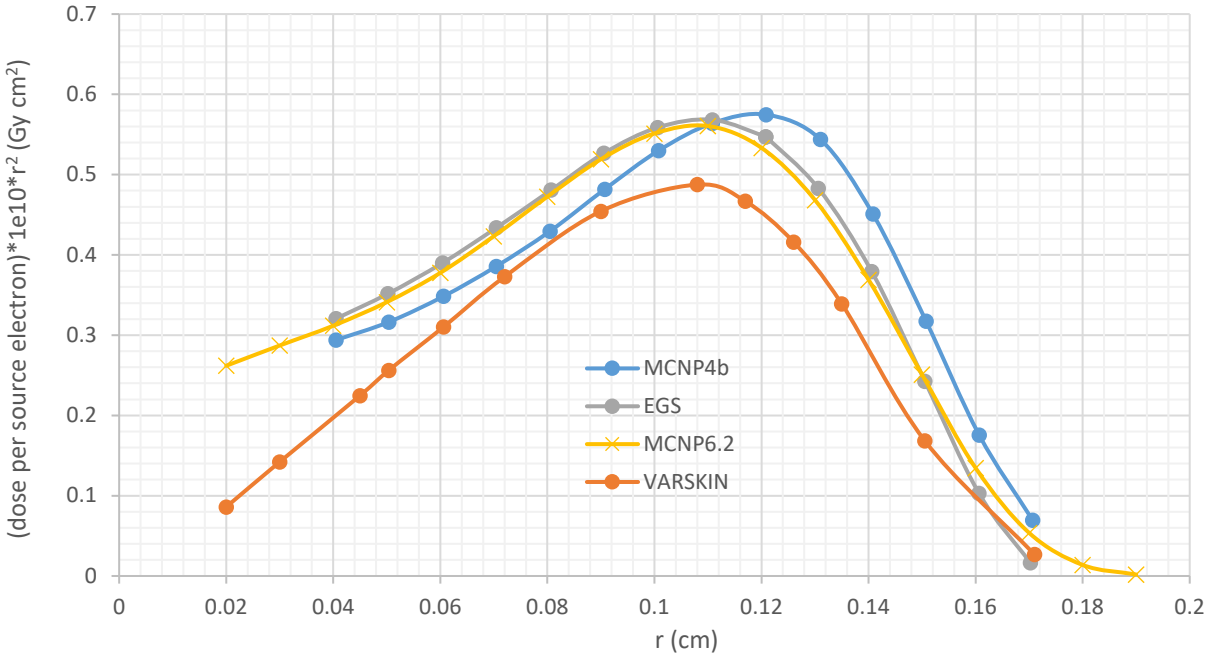

Figure 4-1 Dose Distribution around a 0.5 MeV Mono-Energetic Beta Source – VARSKIN Versus EGSnrc (MCNP 4b and MCNP 6.2)

The dose distributions around 0.5, 1 and 2 MeV point sources, along the electron's ranges, are shown in Figures 4-1,4-2 and 4-3. The doses were calculated with VARSKIN and compared to the EGSnrc results from [19]. In Figure 4-1, a 0.5 MeV point source, the VARSKIN results are between equal to about 20 percent lower along the range. At this energy the variation between VARSKIN and EGSnrc is the most significant along the whole short range and the differentiation is growing closer to the source. In Figures 4-2 and 4-3 (1 and 2 MeV sources), it seems that the VARSKIN results are almost identical to the EGSnrc results, along most of the electron range. In Figure 4-2 (1 MeV) below radius of 1 mm, the VARSKIN results start to differ significantly from EGSnrc and decrease sharply. For 2 MeV (Figure 4-3), again below r of 1 mm, the VARSKIN results differ more significantly from EGSnrc, and sharply decrease. The relevant range for brachytherapy dose delivery falls within 3 – 5 mm of the source. In this range, VARSKIN results are highly consistent with EGSnrc, at 1 – 2 MeV and about 15 percent lower at 0.5 MeV.

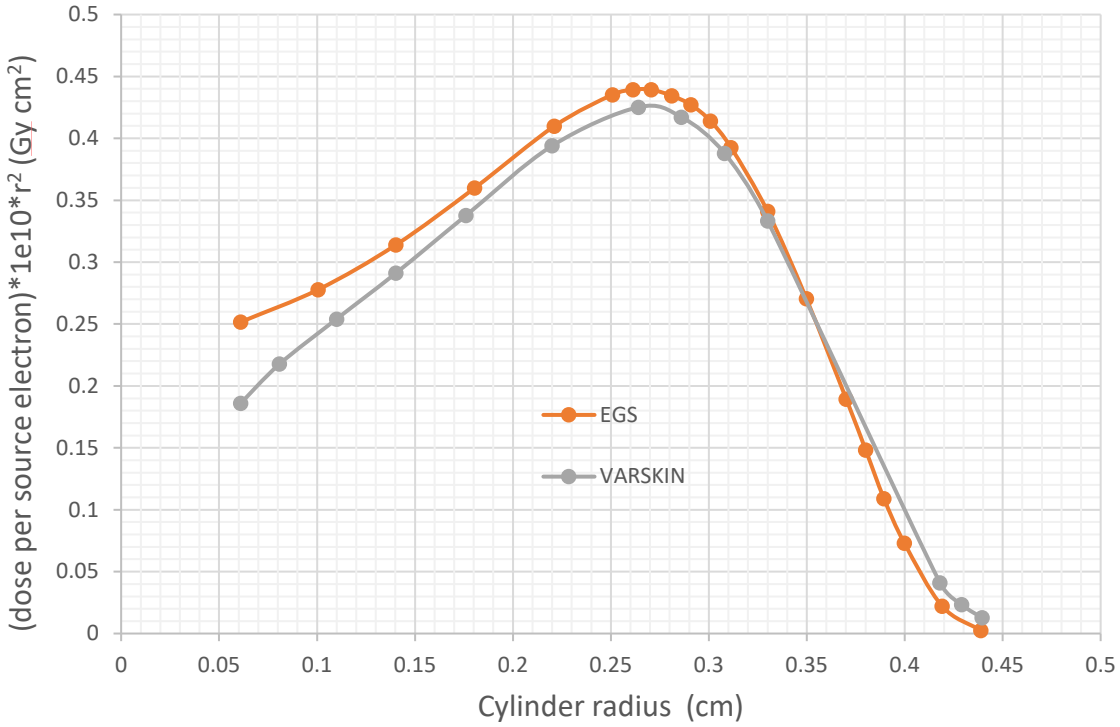

Figure 4-2 Dose Distribution around a 1 MeV Mono-Energetic Beta Source, VARSKIN Versus EGSnrc

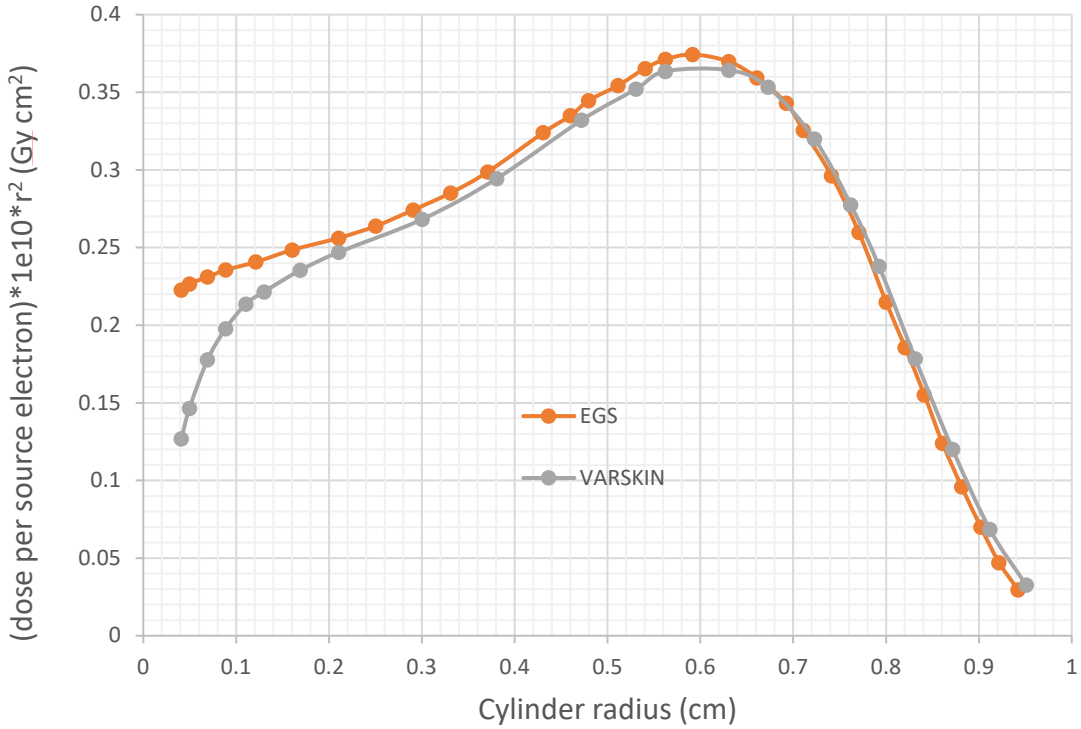

Figure 4-3 Dose Distribution around a 2 MeV Mono-Energetic Beta Source, VARSKIN Versus. EGSnrc

4.1.3 Sr-90/Y-90 Point and Realistic Source

In Figure 4-4 the dose distributions around Sr-90/Y-90 point source, along the electron range, are shown, calculated with VARSKIN and compared with the EGSnrc results from [19]. Again, VARSKIN is very close to EGSnrc along most of the electron's range, but starts to differentiate significantly at distances lower than 1 mm.

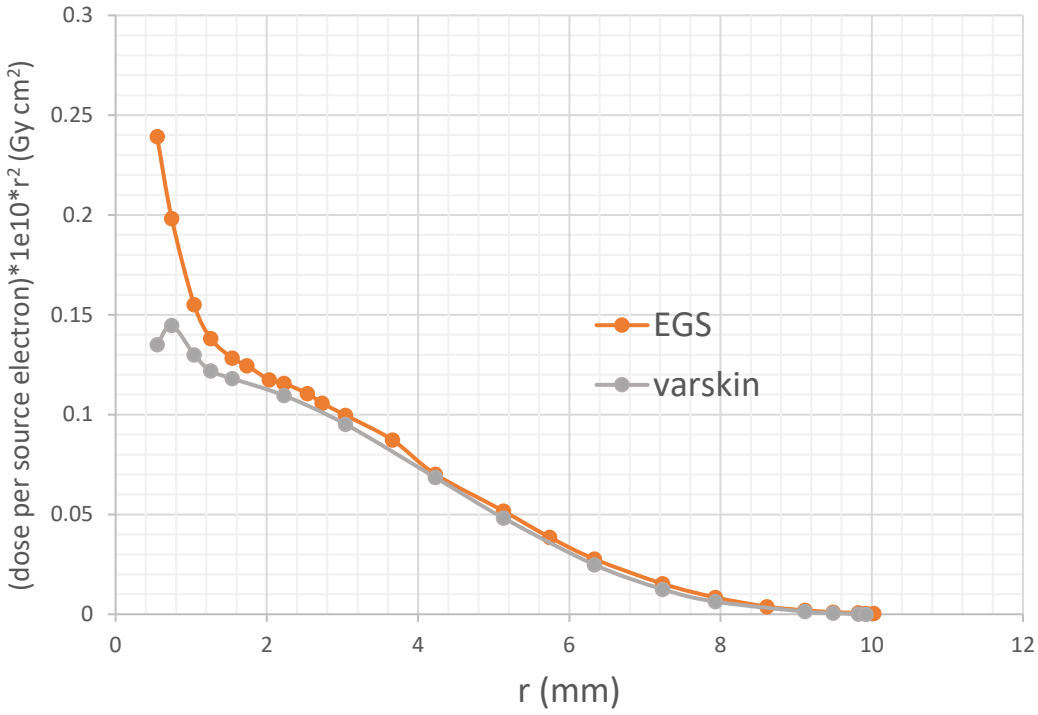

Figure 4-4 Dose Distribution around Sr-90/Y-90 Point Sources, VARSKIN Versus EGSnrc

The last comparison was done between a realistic Sr-90/Y-90 brachytherapy source, produces by Novoste which its characteristic was described in [19] and include:

1. Ceramic cylinder core composition SiO_2 encapsulated by SS304 stainless steel. The radioactive material is distributed uniformly in its core.
2. The diameter and height of the core are 0.56 and 2.5 mm, respectively. The thickness of the steel capsule was taken as 0.04 mm.
3. Material densities of the cores and capsules were taken as 3.0 g/cm^3 for SiO_2 and 8.02 g/cm^3 for steel cover.

The VARSKIN model was prepared as describe in Section 3.2 and the following points were also considered:

1. The dose from a cylindrical source type in VARSKIN is calculated for an averaging area located in front of the cylindrical base, while in this case the distributing needed is in the middle of the cylinder axis. For that reason, an equivalent slab source geometry was chosen, with length of 2.5 mm and edges of 0.5 mm.
2. SiO_2 effective atomic number was calculated according to Equation 3-2 in Section 3.3.1 and was found to be 11.56.
3. The steel capsule inserted as a 0.04 mm cover.

The results for a volumetric source capsule, shown in Figure 4-5, are significantly different from

the point source results. In this case VARSKIN differ significantly from EGSnrc, 30 percent, along most of the range.

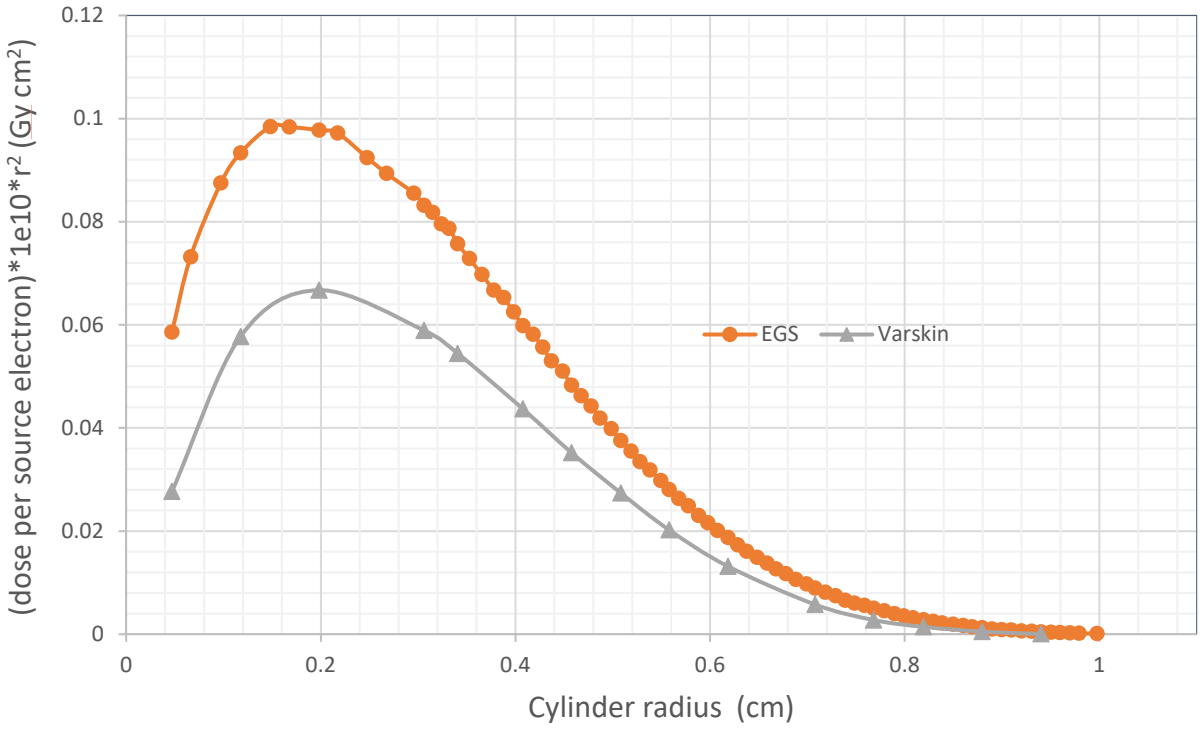

Figure 4-5 Dose Distribution around Sr-90/Y-90 Realistic Sources, VARSKIN Versus EGSnrc

4.2 Conclusions

VARSKIN gives good dose evaluation compared to the Monte-Carlo codes MCNP 6.2 and EGSnrc, when calculating a point brachytherapy dose distribution in cylindrical geometry as describe above, for distances above 1 mm from the source.

That might be significant for brachytherapy dose evaluation since the significant range there is 3 – 5 mm. Above 1 mm, the VARSKIN doses calculation for the higher energies (1 – 2 MeV) seems to be identical or within few percent from the EGSnrc doses. For lower energy (0.5 MeV) the results are between identical to 15 percent lower from the other codes. Below 1 mm, VARSKIN results decline sharply and differ significantly from EGSnrc.

Considering the Sr-90/Y-90 source, VARSKIN is accurate for Sr-90/Y-90, again down to the 1 mm distance from the source. However, when a realistic source was considered, the results are significantly lower (30 percent) from EGSnrc.

5 CONCLUSIONS

VARSKIN was benchmarked against MCNP calculations and the Dounreay report data [1] to evaluate whether VARSKIN could be used for the calculation of beta doses to the digestive tracts in the case of hot particles ingestion. A method was developed to perform the rectosigmoid dose calculation with VARSKIN which included modification of the code to calculate the dose in a homogeneous water environment, and a method to set the averaging area according to the maximum energy deposition. At the first stage the case of a hot particle located on the luminal surface of the rectosigmoid i.e., constantly in the closest position to the tissue, was evaluated. In this case VARSKIN results can be interpolated in two ways. Averaged over the whole rectosigmoid surface area, creating dose evolution for the case of a particle moving along the rectosigmoid but maintain contact with the rectosigmoid wall. Or averaged on a small local area, creating peak dose evolution for the unlikely case in which a particle will with be fixed, or slightly move, in a certain area along the rectosigmoid wall.

The Dounreay report [1] has referred to the first scenario (particle moving along the whole rectosigmoid but maintained contact with the wall) as the maximum dose scenario for hot particles ingestion. The result of VARSKIN dose calculations for Y-90 and Sr-90 with a 3 μm in diameter hot particle were compared to the MCNP results from [1] and there were found in alignment, within 1 percent of each other for Y-90 and 5 percent for Sr-90. The dependence of the results on the electron energy was further investigated based on a comparison of VARSKIN results to a designated MCNP 6.2 model. It was found that VARSKIN calculation agrees, within 1 percent from MCNP, for most of the electron energies between 0.2 MeV and 2.5 MeV, which means that it has the potential to give a reasonable dose assessment for most of the beta emitters radionuclides.

For sources with very low energy distribution, below 0.2 MeV, certain discrepancy might occur, as seen in the previous section where the VARSKIN calculation for Y-90, with high average beta energy (mean beta energy: 933.7 keV) was closer to MCNP than Sr-90 (mean beta energy: 195.8 keV). The reason for the larger discrepancy at lower energies might be related to the decrease in VARSKIN accuracy as the electron reaches its maximum depth, which is discussed in [14] and [15]. In this case the deviation increases for the lower energy electrons, with the target cells closer to their maximum depth.

The effect of the hot particle size on the results was also examined. VARSKIN calculation was done also for hot particles with diameters between 67 and 1300 μm and compared with Dounreay [1] report results. VARSKIN gave similar results, within 10 percent discrepancy from MCNP, for hot particles in the size of few μm to few hundred μm. For higher diameter hot particles, the discrepancy is larger and VARSKIN results are significantly higher, up to 66 percent higher at 1300 μm and could be consider conservative.

Finally, examining the capability of VARSKIN for the evolution of the realistic average hot particle dose, for hot particles located in various depth inside the rectosigmoid content, revealed significant discrepancy between VARSKIN and MCNP. The differences grow sharply in deeper locations, about 40 percent discrepancy when the depth is about half of the electrons range. This difference might be attributed to the fact that MCNP calculates the dose to an actual cylinder representing the rectosigmoid target cells where VARSKIN only can calculate the dose

to a plane tangent to the cylinder. As the hot particle location becomes deeper, the solid angle for the cylinder become significantly larger than the solid angle to the VARSKIN tangent plane.

VARSKIN was found to large extent in alignment with MCNP for the calculation of the maximum dose from ingested hot particles. VARSKIN results were found close (within 10 percent) to the MCNP calculations, for most of the electron energies and hot particle sizes (up to few hundred micrometers in diameter). Such calculation can estimate the worst case for the hot particle exposure, mainly related to the local dose for ulceration risk, when the hot particle is held stationary against the organ tissues surface for a long period of time, or the average dose for cancer risk, when the hot particle is moving in contact with the tissue surface throughout the transit.

The case of brachytherapy sources, VARSKIN gave good dose evaluation compared to the Monte-Carlo codes MCNP 6.2 and EGSnrc, when calculating a point dose distribution in cylindrical geometry for distances above 1 mm from the source. That might be significant for brachytherapy dose evaluation since the significant range there is 3 – 5 mm. Above approximately 1 mm, the VARSKIN doses calculation for the higher energies (1 – 2 MeV) seems to be identical or within few percent from the EGSnrc doses. For lower energies (less than 0.5 MeV) the results are between identical to 15 percent lower than the other codes. Below 1 mm, VARSKIN results decline sharply and differ significantly from EGSnrc.

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11. ABSTRACT (200 words or less)
VARSKIN was benchmarked against Monte Carlo N-Particle (MCNP) simulations and data from the literature, to evaluate its ability to be used for the calculation of beta doses to the digestive tracts in the case of hot particles ingestion. VARSKIN was found to a large extent in alignment with the calculation of the maximum dose from ingested hot particles. The VARSKIN code results were found to be within approximately 10 percent of those from MCNP, for electron energies between 0.2 to 2.5 megaelectronvolts (MeV) and hot particle sizes no larger than a few hundred micrometers in diameter. However, to perform such calculation in VARSKIN, it was found that few enhanced parameters must be included in the calculation. The first is to cancel the backscatter correction. Second an appropriate volume averaging parameter according to the International Commission on Radiological Protection (ICRP) organ model must air be included. Third, the user must set the averaging area to give the maximum Dose Area Product (DAP). With these enhanced parameters, the dosimetry from VARSKIN will be able to estimate the worst case for the hot particle exposure which will mainly relate to the local dose for a potential ulceration risk or the average dose for cancer risk.

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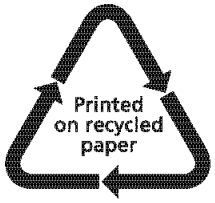

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