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Variation of dose distribution with depth and incident energy using EGSnrc Monte Carlo simulation method

Oluwaseyi MichaelOderinde(1) and Rachel Obed(2)
(1)Department of Medical Physics, University of the Free State, Bloemfontein, South Africa
(2) Department of Physics, University of Ibadan, Ibadan, Nigeria

Abstract:_Developing an accurate Monte Carlo dose calculation engine is of clinical importance.Since it is not convenient to perform such dose calculation after every clinical treatment, MC dose calculation engine is helpful in facilitating radiotherapeutic treatment plan. It is well understandable that to every radiotherapeutic treatment, there will be an absorbed dose.This research work focused on the calculation of dose deposited at each depth with respect to specified energy using the EGSnrc Monte Carlo simulation, which has been considered to be fast and accurate. Incident pencil beam of 1.0 MeV, 2.0 MeV, 6.0 MeV, 8.0 MeV, 10.0 MeV, 12.0 MeV, 14.0 MeV, 16.0 MeV, 18.0 MeV, 20.0 MeV were considered. The phase-space scores were recorded within the first 20.0 cm of the semi-finite water Phantom. Likewise the phantom materials (Tantalum, Silicon, and Sodium Iodide) phantom was changed and the same procedure was taken. The simulation procedure was also utilized to check the effect of energy cutoff for electron transport and energy cutoff for photon transport. It was observed that the depth dose maximum increases with increase in the energy for the cases considered for the water phantom. The materials used varied in terms of their masses, this affect the depth dose at maximum. The least material size has the highest increasing depth dose with increase in energy while the highest material size has the least increasing depth dose with increase in energy. It was observed that, the variation of energy cutoff for electron transport and energy cutoff for photon transport plays a negligible role especially when the incident energy is far higher than the energy cutoff for electron transport and the energy cutoff for photon transport. This simulation method thus serves not only to compliment but as well to stand as a substitute for experimental measurement._

Key words:_Radiotherapeutic treatment, depth dose, energy cutoff_

I. Introduction

In Nigeria, radiotherapy treatments have widely been used conventionally for treatment of tumor, either located on the surface or within the patient. With the use of radiotherapy machines for treatment,it is a function of generated incident energy that interacts with the specific patient. There is a need for accurate dose deposition to the patient at a specific location within the part that is to be treated, which is to reduce the patient's exposure as possible to the minimum, notwithstanding being in compatibility with the medical purposes of the treatment.

Patient's dose is often described on the patient's skin at the centre of the incident beam. An alternative to this is to make the measurement free–in-air without the contribution of the radiation that is backscattered from the patient, and express the result in terms of air kerma.[2] In some cases such simple measurement may be sufficient. This is the case, for example, in quality control measurement which concern the stability of equipment, and where the same exposure conditions are used in each measurements. However, the entrance surface dose is not sufficient for comparison or assessment of patient's doses if the irradiation conditions (the size of the patient, the radiation quality, the exposed body-part, or other factors) are changed. In such cases, the patient dose needs to be characterized by quantities that are more directly related to the detriment caused by radiation.[1-7]

Incident energy interaction with matter can be reflected, deposited and transmitted. These three liable outcomes solely depend on the incident energy. The photon interaction with matter can be materialized into an electron/positron pair in the electromagnetic field of the nuclei and surrounding atomic electrons, incoherent (Compton) scattering with atomic electrons, Photo-electric absorption and coherent (Rayleigh) scattering with the molecules (or atoms) of the medium.

The inception of Monte Carlo simulation system and the computing strength even in spectra simulation which seems to complement and as well serves as substitute for experimental measurements is widely experiencing a giant stride in Medical Physics research. The (Electron Gamma Shower) EGSnrc system designed by National Research Council of Canada (NRCC) which is of computer codes which is also a package of Monte Carlo simulation which simulate the photon and electron transport in the interaction of photon with matter for this stochastic measurement of the transport.

The incident beam simulation that interacts with the skin surface can also be determined via the EGSnrc algorithm codes when the photons are deposited at each position within the patient; it is a function of probability that there will be vast photo-electric absorption of the energy. The energy deposited within the phantom at various depths is taken and use in calculating the dose deposited. This method has been extensively tried and proven to be capable of accounting for the density and atomic number variation within the patient when the simulation of energy deposit and radiation transport is observed.

This present paper is devised to calculate the dose deposited within several depths of a water phantom at specified energies and to determine the percentage depth dose as well as stating the effect of phantom size on the energy deposited, likewise checking the effect of varying the electron/photon cutoff all these will be accomplished using EGSnrc Monte Carlo simulation. This is done to annex the previous methods for dose calculations studied by researchers. Since dose calculation is of great importance in setting a radiotherapy treatment plan. This is done to solve the stress and time taken in calculating dose deposited in a phantom experimentally. Dose calculation is of great importance in a setting radiotherapy treatment plan. It is highly encouraged in order to minimize patient absorbed dose, which may be detrimental to the cells around where the dose is deposited. Monte Carlo simulation is commonly considered the most accurate method due to its capacity to faithfully describe the underlying physical interactions between radiation and matter. This paper is done to facilitate radiotherapy treatment.

II. Materials And Methods

A. Research procedures

EGSnrc Monte Carlo simulation method, which was utilized in studying various incident energy interactions with semi-infinite phantoms. Ten energy values (1MeV, 2MeV, 6MeV, 8MeV, 10MeV, 12MeV, 14MeV, 16MeV, 18MeV, 20MeV) were selected being of interest and widely used in radiotherapeutic treatment in Nigeria.

A semi-infinite slab of material, to be specific, virtual water phantom was also utilized. Water phantom is usually preferred for dose distribution measurement because, it closely approximates the radiation absorption and scattering properties of muscles and other soft tissues, likewise it is universally available with reproducible properties. Notwithstanding, semi- infinite slab of Tantalum (Ta), Silicon (Si) and Sodium Iodide (NaI) phantoms were also included in the simulation. The energy deposited on the surface of the materials and percentage depth dose for the materials was also studied. Likewise EGSnrc Monte Carlo simulation method was also used in checking the variation of the energy deposited and the percentage depth dose when the energy cutoff for electron transport (ECUT) and the energy cutoff for photon transport (PCUT) changes for various incident energy, focusing on a semi-infinite water phantom.

The ten cases of interest representing different depth at an interval of 0.5cm each within the phantom were simulated. Cases differ by their dose distribution curve, Percentage Depth Dose and the absorbed dose on the surface.

An EGSnrc code was written compiled and executed to derive the result for each case. The output gives the energy deposited at each depth. For each energy or case, a user code was built or compiled and ran in the same vein.[8]

Subroutines of the EGSnrc user code were written to provide:

1. HATCH: To establish media data.
2. SHOWER: To initiate the cascade.
3. HOWFAR and HOWNEAR: To specify the geometry
4. AUSGAB: To score and output the results and to control variation reduction.

B. Methods of analysis

EGSnrc user code designed was used to simulate an incident broad parallel beam. This incident beam was focused on the phantoms where the source surface distance considered is 100cm, the procedure is to note the energy deposited when an incident energy interact with matter. It is generally noted that energy will be reflected, deposited and transmitted. A field size of $10 \times 10\, cm^2$ was considered. For this research work, we focused on the energy deposited per interaction. An history of 10^6 electron particles are energized to interact with the matters considered.

Photon cross section, Compton cross section, pair angular sampling and pair cross section were set in place during the interaction. But the triplet production, Radiative Compton corrections, Rayleigh scattering and electron impact ionization were switched off. The photon transport cutoff of 0.01MeV was also set during the interaction; likewise the electron transport cutoff of 0.6MeV was also set. Also the Atomic relaxation, bound Compton scattering, photo electron angular sampling and spin effect were switched on in the interaction. Maximum electron step of 0.1000E+11, maximum fractional energy loss of 0.25, maximum first elastic moment of 0.5 and skin-depth for boundary crossing of 0.3 were all set in the procedure. PRESTRA-II algorithm was utilized; bremsstrahlung cross section and angular sampling were not left out. Rayleigh data used was from the PEGS4 data set. This incident beam was showered on a Phantom whose thickness on the surface is 1mm. The

energy deposited was studied within the first 10.5cm depth of 0.5cm variation (0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, 10.0, and 10.5). The readings were generated in time of seconds. All this parameters where used at all the ten cases considered for Water, Tantalum, Sodium Iodide and Silicon Phantom. But for the variation ECUT and PCUT, incident energy of 1MeV, 6MeV, 10MeV and 20MeV were considered while the variation of ECUT was done at 0.6MeV, 1MeV, 2MeV and 5MeV, also PCUT was varied at 0.01MeV, 0.05MeV, 0.1MeV, 0.5MeV, 1MeV, 5MeV and 10MeV using Water Phantom as its interaction medium. The later was done in order to deduce the effect of ECUT and PCUT variation on the percentage depth dose.
All the ten cases were simulated with variation to depth at which energy is deposited at each Joules by:

$$1Mev = 1.6E - 13J \qquad (1)$$

Therefore, the energy in Joules was utilized in all the ten cases for the energy deposited at each region. A phantom mass of 18E-3kg was used to convert the deposited energy into dose. All these conversions and calculative measures were imposed to get our dose deposited using EGSnrc Monte Carlo simulation.

The dose versus depth curve was as well generated for all the cases consideredwhich we call depth-dose curve or dose distribution in a material curve. Likewise the percentage depth dose curve was generated for the cases considered.(9-10)

III. Results And Discussion

The simulation of an incident beam's interaction with a semi-infinite water phantom using EGSnrc Monte Carlo, dose distribution for the ten cases considered was generated.Figure 1 contains the summary of the simulation for various depths in the water phantom. Likewise the dose deposited on the surface (SD) for the water phantom was deduced in Table 1.

Table 1: Surface dose for various incident energy in a water phantom

Incident energy (MeV)	Surface dose (Gy)
1	1.01E-13
2	7.60E-14
6	4.03E-14
8	3.12E-14
10	3.10E-14
12	3.00E-14
14	2.40E-14
16	2.34E-14
18	1.98E-14
20	1.38E-14

EGSnrc Monte Carlo simulation method was also utilized in studying the energy deposited in a semi-infinite phantom of Tantalum (Ta), Silicon (Si) and Sodium Iodide (NaI) material. The surface energy deposited was noted for all this materials and compared with the semi- infinite water phantom in Table 2, likewise the dose depth at maximum was deduced in Table 3. EGSnrc Monte Carlo simulation method was also used to deduce the variation of the energy deposited and the dose depth at maximum when the energy cutoff for electron transport (ECUT) and the energy cutoff for photon transport (PCUT) changes for various incident energy enclosed in the Appendix 1.

From Table 3 which shows the simulation result depicting the dose depth at maximum which has the reference dose depth for Tantalum (Ta), Silicon (Si), Sodium Iodide (NaI) and Water (H_2O)

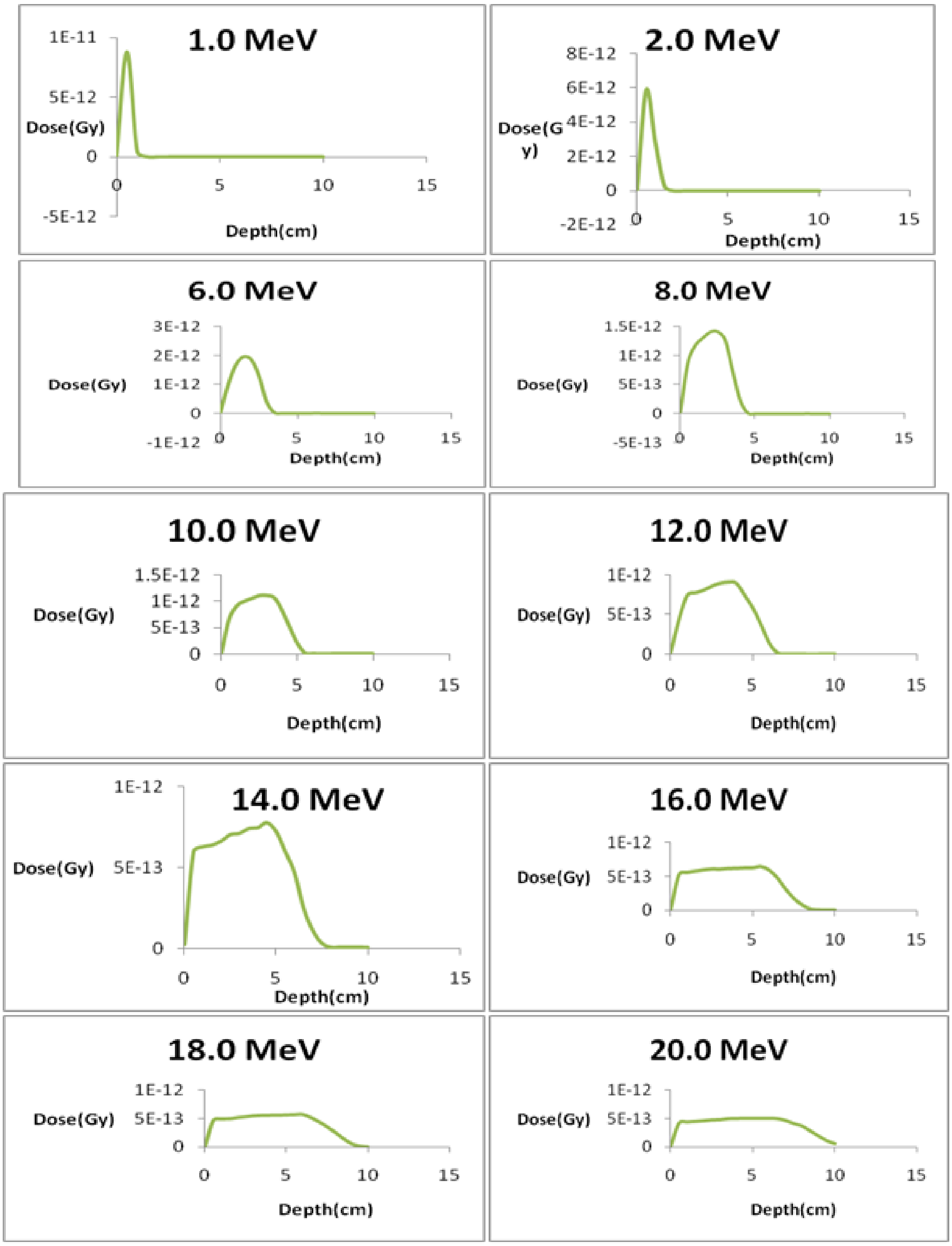

Figure 1: Summary of the simulation for various depths in the water phantom for the ten cases considered

Table 2: Dose depth at maximum for Ta, Si, NaI, and H_2O phantom for various incident energy

Incident energy	Material	1 MeV	2 MeV	6 MeV	8 MeV	10 MeV	12 MeV	14 MeV	16 MeV	18 MeV	20 MeV
Z_{max}	Ta	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Si	0.5	0.5	0.5	1.0	1.0	1.5	2.0	2.0	2.0	2.5
	NaI	0.5	0.5	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0
	H_2O	0.5	0.5	1.5	2.5	3.0	3.5	4.5	5.5	6.0	6.0

Table 3: Surface energy deposited on Ta, Si, NaI and H_2O phantom for various incident energy

Incident energy	Material	1 MeV	2 MeV	6 MeV	8 MeV	10 MeV	12 MeV	14 MeV	16 MeV	18 MeV	20 MeV
Surface energy(MeV)	Ta	0.33202	0.24606	0.12529	0.10385	0.09392	0.07682	0.06872	0.06342	0.05450	0.04866
	Si	0.05920	0.02863	0.01124	0.01166	0.00792	0.00768	0.00723	0.00687	0.00649	0.00483
	NaI	0.22210	0.16003	0.08024	0.05712	0.04869	0.04580	0.03773	0.03018	0.02934	0.02771
	H_2O	0.01114	0.00855	0.00453	0.00351	0.00349	0.00338	0.00270	0.00263	0.00214	0.00157

phantom, it was discovered that the Water phantom has a highest increasing percentage depth dose with increase in incident energy, followed by Silicon phantom, next to Silicon is Sodium Iodide and lastly the Tantalum phantom has the same depth for all the cases considered. This can be explained, that the mass number of Water which is 18g happens to be the least mass number of the phantoms considered. The mass number for Silicon is 28g, that of Sodium Iodide is 150g and that of Tantalum is 181g. The low mass number of Water allows a deeper ejection of electrons since it does not need to break much barrier or needs its speed to be attenuated when tending towards the reference depth which is the maximum depth. It can therefore be stated that the size of the phantom places a great role in the percentage depth dose.

Variation of the energy cutoff for electron transport (ECUT) with the energy cutoff for photon transport (PCUT) for various incident energy, it was discovered that at 1.0 MeV incident energy when the ECUT is 0.6 MeV and 1.0 MeV at all values of PCUT, there was an energy deposited on the phase space. But when the ECUT was increased to 2.0 MeV likewise increased to 5.0MeV, there was no energy deposited on the material. This is also applicable to the incident energy of 6.0MeV, 10.0MeV and 20.0MeV. This can be explained that when ECUT is greater than the incident energy, there will not be an energy deposited since only energy greater than the ECUT can flow through the set parameter and be deposited on the phase space.

It can be deduced that on the surface, increase in the incident energy causes a decrease in the deposited energy. Likewise, as the ECUT increases the energy deposited decreases. The effect of PCUT is variably minimal once the ECUT has been well checked. For the entire incident energy considered it was realized that the change in the energy deposited and the percentage depth dose falls within a close range when the ECUT and PCUT were varied. The variation of ECUT and PCUT plays a negligible role especially when the incident energy is far higher than the ECUT and the PCUT. Though the ECUT and PCUT are generally set to reduce the phantom dose which is detrimental to the phantom it if it was to be a biological material.

In the interaction of incident beam with matter, definitely there will be dose deposited in the Patient or Phantom. The variation of the dose deposited on the surface with incident energy for these cases 1 to 10 depicted on Table 1 shows that the surface dose deposited for incident energy of 1.0MeV is 1.01E-13, which happens to be the highest dose deposited for the cases considered and the surface dose for incident energy of 20.0MeV is 1.40E-14, which is the least dose deposited for the cases considered. It can be stated that increase in incident energy causes a decrease in the surface dose (skin dose). This is as a result of much penetration power possessed when the incident energy is increasing, which decreases the attenuation efficiency of the phantom. Therefore dose deposited on the surface will be decreasing.It also occurs due to the fact that all the energies considered are of Mega-electron Volt, that is the energies pose a fast moving electron. This will definitely reduce the photo absorption or energy deposition occurrence in the interaction. Reason been that at a low energy, photo-electric absorption will be dominant, there will be more energy deposited within the phantom even the phantom may even absorb the entire incident beam. This constitutes more to the Phantom dose. But at higher energy mostly of mega-volt, where Compton scattering or pair production are dominant, much energy will be transmitted rather than deposited within the interactive medium, this reduces the phantom dose especially at the surface.

Table 2 shows the energy deposited on the surface for semi-infinite Ta, Si, NaI, and H_2O phantom for various incident energies. It was observed that the surface energy deposited decreases with increase in incident energy; anomalous is noted in the case of Si phantom for incident energy of 8.0MeV which its energy deposited is higher than the incident energy of 6.0MeV. Likewise, it was discovered that for each incident energy considered, H_2O phantom has the least energy deposited, followed by Si phantom, next to it is NaI phantom, while the Ta phantom has the highest energy deposited. This is as a result of the mass number affecting the energy deposited. Increase in mass number increases the energy deposited because of the attenuating power which is a function of the mass number.

For the result of the semi-infinite water phantom simulation, the reference depth dose which is the dose at the maximum depth of dose deposition, which can be used to deduce our Percentage depth dose (PDD). Percentage depth dose increases with increase in incident energy. That is higher incident energy deposit much speed to the electrons present in the phantom, there will be ejected electrons which will be deposited at a distance away from the ejected origin. This tends to increase the depth at which the maximum dose is deposited. Though reference depth dose is inversely proportional to the PDD. From this research result (Table 2), it was discovered that the reference depth dose for case 1 MeV and 2 MeV are the same which is 0.5cm, likewise for case 18 MeV and 20 MeV the maximum dose is deposited at 6.0cm. These should not be seen as confusion to the inverse law of reference depth dose with Percentage depth dose. It should be noted that the reference depth dose position is of one significant figure, for further research, if the significant is extended to three or four significant figure, it will explicitly be in correlation with the stated inverse law.

IV. Conclusions

The results deduced from the simulated cases were able to determine the Percentage Depth dose for each case and were able to say categorically that the PDD increases with increase in incident energy and the maximum depth dose is located within the few centimeters of the matter considered. Also from the results generated, high energy creates a large range of secondary electron and consequently a high depth dose maximum. Likewise from the variation of incident energy with surface dose, surface dose decreases with increase in incident energy, that is, skin dose decreases with increase in the incident energy. All these facts were generated when an EGSnrc Monte Carlo simulation method was applied for incident energy interaction with matter.

The accuracy and speed of the EGSnrc Monte Carlo in calculating the absorbed dose in Phantom is well appreciated. This method is encouraged in deducing the unlimited research for dose distribution since we know that, calculating the absorb dose is the most integral part of radiotherapeutic treatment because the higher the absorbed dose the greater the chance of killing the cells in the patient. This simulation method thus serves not only to compliment but as well to stand as a substitute for experimental analysis.

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Appendix 1: Summary of variation of ECUT and PCUTfor various incident energy

IE(MeV)	6.0																											
ECUT(MeV)	0.6							1.0							2.0							5.0						
PCUT(MeV)	0.01	0.05	0.1	0.5	1.0	5.0	10.0	0.01	0.05	0.1	0.5	1.0	5.0	10.0	0.01	0.05	0.1	0.5	1.0	5.0	10.0	0.01	0.05	0.1	0.5	1.0	5.0	10.0
DES(MeV)	0.003	0.003	0.004	0.003	0.001	0.002	0.002	0.004	0.005	0.002	0.001	0.001	0.004	0.004	0.002	0.003	0.003	0.002	0.001	0.003	0.003	0.002	0.004	0.003	0	0	0	0
Dmax(cm)	1.5	2.0	1.5	1.5	1.5	1.5	1.5	1.5	2.0	1.5	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0	1.5	2.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

IE(MeV)	1.0																											
ECUT(MeV)	0.6							1.0							2.0							5.0						
PCUT(MeV)	0.01	0.05	0.1	0.5	1.0	5.0	10.0	0.01	0.05	0.1	0.5	1.0	5.0	10.0	0.01	0.05	0.1	0.5	1.0	5.0	10.0	0.01	0.05	0.1	0.5	1.0	5.0	10.0
DES(MeV)	0.011	0.011	0.011	0.010	0.010	0.010	0.010	0.006	0.003	0.004	0.004	0.003	0.003	0.003	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dmax(cm)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

IE(MeV)	10.0																											
ECUT(MeV)	0.6							1.0							2.0							5.0						
PCUT(MeV)	0.01	0.05	0.1	0.5	1.0	5.0	10.0	0.01	0.05	0.1	0.5	1.0	5.0	10.0	0.01	0.05	0.1	0.5	1.0	5.0	10.0	0.01	0.05	0.1	0.5	1.0	5.0	10.0
DES(MeV)	0.002	0.002	0.002	0.002	0.0006	0.0006	0.0008	0.004	0.002	0.002	0.0015	0.0019	0.001	0.0004	0.002	0.003	0.002	0.0002	0.0001	0.0001	0.0004	0.001	0.001	0.002	0.001	0.0001	0	0
Dmax(cm)	3.0	2.5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0

IE(MeV)	20.0																											
ECUT (MeV)	0.6							1.0							2.0							5.0						
PCUT (MeV)	0.01	0.05	0.1	0.5	1.0	5.0	10.0	0.01	0.05	0.1	0.5	1.0	5.0	10.0	0.01	0.05	0.1	0.5	1.0	5.0	10.0	0.01	0.05	0.1	0.5	1.0	5.0	10.0
DES(MeV)	0.001	0.001	0.001	0.0001	0.0003	0.0002	0.0002	0.002	0.001	0.002	0.002	0.001	0.0002	0.0001	0.001	0.001	0.001	0.001	0.0001	0	0	0.001	0.001	0.001	0.001	0.0001	0.0001	0.0001
Dmax(cm)	6.0	5.0	5.5	5.5	5.0	5.5	5.5	4.5	6.0	5.5	5.0	6.0	5.5	4.5	5.5	5.0	5.5	5.5	5.5	6.0	6.0	6.5	6.0	5.5	6.5	5.5	5.5	5.5

IE (MeV): Incident Energy
ECUT (MeV): Energy Cutoff for Electron Transports
PCUT (MeV): Energy Cutoff for Photon Transports
Dmax(cm): Depth for maximum Energy deposited
DES (MeV): Energy Deposited on the Surface