Radiation Issues for the Experimental Area at HIGS
Internal Report: SPIR-117

Jennifer Robb

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Introduction

Radiation can be defined as emitted energy that propagates in the form of waves or particles, and it occurs when unstable atoms become stable. Depending on the type of radiation, it can be capable of traveling through a medium or through space. When radiation travels through a medium, it deposits energy, which can have many effects.

There are two main types of radiation, particulate and electromagnetic. Particulate radiation occurs in the form emitted particles, and electromagnetic radiation occurs as electromagnetic rays, at any position on the electromagnetic spectrum. The emission of radiation by atoms can be broken into 5 major categories:

1. *Alpha Particles* - Alpha particles originate from a disintegrating nucleus, and they are composed of two neutrons and two protons (a helium nucleus). Due to their composition, alpha particles carry a net positive charge of +2 (+2e). Also note that alpha particles are monoenergetic with energies between 4 and 8 MeV.

2. *Beta Particles* - Beta particles also originate from a disintegrating nucleus. They occur in the form of an electron or a positron, and thus have a charge of ± 1. Beta particles are not monoenergetic, with energies in a continuous spectrum between 0.02 and 4.8 MeV.

3. *Neutrons* - The emission of neutrons does not occur in pure nuclear substances. To emit a neutron, a target must be bombarded by alpha particles or high-energy gamma rays. Neutrons have no net charge.

4. *Gamma Rays* - Gamma rays are electromagnetic waves with wavelengths shorter than 10^{-12}m. By nature, in being electromagnetic waves, they have no charge and no mass. They originate within the nucleus and travel at 3.0×10^{10} cm/s. Gamma rays are monoenergetic, with energy between 10 keV and 3 MeV.

5. *X-Rays* - X-Rays are very similar to Gamma rays, except that they are produced external to the nucleus. They are electromagnetic waves with wavelengths between 10^{-8} and 10^{-12}m, and they are also monoenergetic with energies between 10 keV and 3 MeV.

When one of these types of radiation interacts with matter, energy is deposited into that medium. The amount of energy transferred is dependent on the geometry of the collisions between the radiated particles or electromagnetic waves with the atoms in the medium. Depending on how much energy is transferred, there are three main effects on the atoms in the medium:

- **Excitation** - An electron of the target is given enough energy such that it is raised to a higher energy level.
- **Ionization** - An electron of the target is given enough energy such that it is able to leave the atom (it is excited beyond the highest energy level of the atom).
- **Nothing** - The energy received by the target is less than needed to raise an electron to the next energy level.

The most important effect, in the context of this report, is ionization. Radiation due to ionization is called *ionizing radiation.* Ionizing radiation is the cause of biological effects to living tissues, the reason that radiation is shielded, and also the basis on which radiation detection devices operate.
There are three mechanisms of ionization.

1. **Photoelectric Effect** - The photoelectric effect occurs when a beta particle or low energy gamma ray collides with an orbiting electron. This knocks the electron out of its orbit, emitting a photon in the process.
2. **Compton Scattering** - Compton Scattering occurs when a photon strikes an orbiting electron. In this case, the electron is knocked out of its orbit, and a photon of a different energy is emitted.
3. **Pair Production** - When very high energy gamma rays are in the presence of the nuclear forces that are present near a nucleus, a positron and an electron are produced.

It is important to note that all of these ionization processes create free electrons, which cause the dangers of radiation.

1 Dosimetry

One important area in the study of radiation is *dosimetry.* Dosimetry is a field that attempts to quantitatively relate specific radiation measurements to the chemical and biological changes that radiation would produce in matter it interacts with. Studies of these chemical and biological changes as a function of received radiation can be useful for monitoring radiation exposure of people and the environment, and for comparing experiments that involve radiation.

The primary physical quantity involved in dosimetry is the *absorbed dose.* The absorbed dose is an objective property of radiation that expresses the amount of energy transferred per unit mass from ionizing radiation to a target. The SI unit of the absorbed dose is the *gray* (Gy), which is equal to the number of joules of energy that is transferred per kilogram of target material.

It is important to note here that the gray does not depend on the type of radiation, or target material.

$$1gray = 1joule/kilogram \tag{1}$$

The Imperial unit for absorbed dose is the *rad*, and it is equal to the number of ergs per gram of target material.

$$1rad = 100ergs/g \tag{2}$$

The conversion between rads and grays is:

$$1Gy = 100rads \tag{3}$$

NOTE: This report will deal primarily in SI units.

The gray(rad) does not take into account, that chemical and biological damage differs for different types of radiation. Radiation composed of charged particles does more biological cell damage than radiation composed of electromagnetic energy only, for the same amount of absorbed energy. For example, Alpha particle radiation does twenty times more damage than gamma ray radiation. A weighted absorbed dose can be used to account for these differences in biological damage, and it is called the *equivalent dose*.

The equivalent dose takes into account that biological damage that a type of radiation can cause is a function of the ability of the particle/wave to penetrate the material irradiated. An alpha particle can be effectively stopped by a sheet of paper, and it can travel from 2 to 8 cm in air. A beta particle can travel in air from 8 to 10 m, but can be stopped by low atomic weight materials such as plexiglass, lucite, glass or paper. Beta particles can penetrate tissues on the order of several g/cm^3. Neutrons, since they carry no charge, are not influenced by any electric or magnetic fields, and can penetrate very effectively. Neutrons can only be effectively stopped by hydrogen rich materials or thick barriers such as wax, water, and concrete. Electromagnetic radiation like gamma rays and x-rays can be stopped by lead or concrete. Their penetration ability is governed statistically by a probability of interaction per unit distance traveled.

The conversion from absorbed dose to equivalent dose is done using a radiation weighting factor W_R. The radiation weighting factor is selected according to the type and energy of the radiation incident on the target.

Table 1: Radiation Weighting Factor for Various Types of Radiation

Type of Radiation	Weighting Factor W_R
β particles, γ-rays, X-rays	1
Thermal Neutrons	2.3
Neutrons $<$10 keV	5
Neutrons $>$10 keV - 100 keV	10
Neutrons $>$100 keV - 2 MeV	20
Neutrons $>$2 MeV - 20 MeV	10
Neutrons $>$20 MeV	5
Protons	10
α particles	20

Using the appropriate weighting factor the equivalent dose can be found from the absorbed dose as follows:

$$H_T = \sum W_R * D_A \tag{4}$$

Where H_T is the equivalent dose and D_A is the absorbed dose. The units of the equivalent dose are *sieverts* (Sv).

$$1 sievert = 1 joule/kilogram \tag{5}$$

The Imperial unit for equivalent dose is the *rem*, and it is based on the Imperial absorbed dose (rad). The relationship between the sievert and the rem is:

$$1Sv = 100rem \tag{6}$$

While the sievert takes into account the type of radiation, it does not take into account the material being irradiated. It is important to note that chemical and biological damage differs for different media (tissues). The relationship between the probability of biological damage and equivalent dose is found to depend on the organ or tissue irradiated. A weighted equivalent dose can be used to account for these differences in biological damage, and it is called the *effective dose*.

The conversion from equivalent dose to effective dose is done using a tissue weighting factor W_T. The tissue weighting factor represents the relative contribution of that tissue to the total damage resulting from uniform irradiation of the entire body.

Table 2: Tissue Weighting Factors

Tissue or Organ	Weighting Factor W_T
Reproductive Organs	0.20
Bone Marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone Surface	0.01
Remainder	0.05
Total Body	1.00

Using the appropriate conversion factor the effective dose can be found from the equivalent dose as follows:

$$E = \sum W_T * H_T \tag{7}$$

The units of effective dose are the same as the equivalent dose, the sievert (Sv), or the rem.

1.1 Effects of Radiation

Radiation produces its biological effects by altering the function of cells in the body. The excitation or ionization of cells in the body by radiation causes:

- The production of free radicals (neutral atoms or molecules with unpaired electrons).
- The destruction of chemical bonds.
- Production of new chemical bonds.
- Damage to molecules that regulate vital cell processes (DNA, proteins).

Since the body reacts similarly to cell damage, independent of the cause of the damage, radiation produces symptoms that are much like many other illnesses. It is known that high levels of radiation exposure can cause biological effects that are harmful to an organism. The effects (symptoms) of unsafe radiation levels can be classified into three categories, *Genetic effects*, *Teratogenic effects* and *Somatic effects*.

Genetic effects are abnormalities that are passed on from a parent to child as a result of the parent's exposure to radiation. Teratogenic effects are effects that may be observed in children who were exposed during fetal and embryonic stages of development.

Somatic effects can be further divided into two categories, *acute effects* and *delayed effects*. Acute effects are seen immediately after large doses of radiation are experienced over relatively short periods of time (less than 4 days). Table 3 outlines the symptoms that occur due to various acute absorbed dosages of radiation.

Table 3: Acute Radiaiton Effects

Dose (Gy)	Symptoms	Remarks
0 - 0.25	None	No clinically significant effects.
0.25 - 1	A few persons may exhibit nausea and anorexia	Bone marrow damaged, decrease in red and white blood cell and platelet counts.Lymph nodes and spleen injured; lymphocyte count decreases.
1-3	Mild to severe nausea, malaise, anorexia, infection.	Hematologic damage more severe. Recovery probable, though no assured.
3-6	Severe effects as above, plus hemorrhaging, infection, diarrhea, epilation, temporary sterility.	Fatalities will occur in the range 3.5 Gy without treatment.
>6	Above symptoms plus impairment of central nervous system.	Death expected.

Delayed effects may be caused by a single, intense overexposure, or by a continuous long term exposure, and are manifested long after the actual radiation exposure occurs. The most common delayed effects include the formation of cataracts and the induction of cancer.

All of the aforementioned effects are either *deterministic* or *stochastic*. Deterministic effects are those in which the severity of the effect increases as the dose exceeds a certain threshold value. Emphysema and cataracts are examples of deterministic effects. Stochastic effects increase linearly in severity with an increase in dose. Cancer is an example of a stochastic effect.

1.1.1 Benefits of Radiation

It has been proven that there are benefits that stem from low levels of radiation exposure, such as that used in medical treatment and diagnostic procedures. There is also evidence that cells may benefit from receiving radiation, becoming more robust and having a longer lifespan after being exposed to low levels of radiation. It has also been hypothesized that low doses of radiation have a therapeutic effect. This idea is called *hormesis*, and has been found true in paramecia animals and radiation workers.

1.2 Background Radiation

Every person is always exposed to some levels of radiation. Radiation that occurs from both natural and man-made sources, but that is a part of every-day life is called *background radiation*. There are several components to background radiation:

- **Nuclear Power/Fallout** (∼0.02 mSv/year) - The testing of nuclear weapons creates a worldwide occurrence of nuclear fallout materials. Very small residue particles from the weapons and explosion are drawn up into the stratosphere, dispersed by atmospheric winds, and eventually fall back to earth.

- **Cosmic Rays** (∼0.3 mSv/year) - Energetic particles originate in space (many from the sun but also from other sources) and are filtered through atmosphere. Ranging in energy, these particles are always present on the earth's surface, and are more concentrated at higher altitudes.

- **Gamma Rays from Rock & Soil** (∼0.35 mSv/year) - Rocks and soil naturally contain uranium, thorium and potassium, and the decay of these elements can produce radioactive products.

- **Radon Gas in the Air** (∼1.0 mSv/year) - Radon gas is a naturally occurring radioactive gas, that is present in the air due to the decay of isotopes of uranium and thorium which can be present in rocks, soil (as mentioned above) and building materials. Radon gas is made up of radionucleotides that are radioactive. Radon gas is inhaled and deposits on the walls of the lungs.

- **Medical Sources** (∼0.6 mSv/year) - Medical and dental procedures such as x-rays and various treatments (therapeutic and diagnostic) make use of radioactive materials.

- **Internal Sources** (∼0.35 mSv/year) - Internal sources of radiation include radioactive materials inhaled or ingested from various other radiation sources. Food, water, and air all contain small amounts of naturally radioactive materials.

- **Other** ($\sim$0.02 mSv/year) - Household products, daily activities, work-related activities, and many other sources can also contribute to the background radiation experienced.

Overall, the average Canadian receives 1.8 mSv per year of background radiation.

1.2.1 Radiation Experienced Beyond Background

Radiation protection guidelines for levels beyond this background have been created for those who must be exposed to more than the expected radiation. Those who are exposed to more than background amounts of radiation in their occupational setting are classified into two categories, *Nuclear Energy Workers* (*NEW*) and *members of the public*. Table 4 outlines the annual effective dose limits for these groups, as recommended by the Canadian Nuclear Safety Commission (CNSC).

Table 4: Maximum Effective Radiation Dose Limits (beyond background)

Person/Area	Period	Dose
Nuclear Energy Worker	1 year dosimetry	50 mSv
Nuclear Energy Worker	5 year dosimetry	100 mSv
Pregnant NEW	duration of pregnancy	4 mSv
General Public	1 calender year	1 mSv

It is important to note that these are maximum values, the expected values are much lower. It is also important to note that it is not recommended to simply respect these dose limits, but for all efforts to be made to reduce doses as much as possible. Management of radiation doses includes keeping radiation exposure as low as reasonably achievable.

1.2.2 ALARA

The philosophy that exposure to radiation should be kept "*as low as reasonably achievable*" (ALARA) has been adopted by many people involved in dealing with radiation. This concept has been Incorporated in defining radiation regulations, by requiring that all radiation released into the environment, and all doses of radiation to working personnel, be in accordance with ALARA. This means that it is important not just to meet the published regulatory limits, but to stay as far below them as possible. More quantitatively, complying with ALARA should place radiation levels within or below one tenth of the regulatory limits.

2 Room at HIGS

The area in question at HIGS is the gamma detector vault, the adjacent collimator hut, and the surrounding experimental area, where people will be working. See Figures 1 and 3 for a scale drawing of the layout and a picture of the collimator hut during construction. Note that the light grey areas (ie. walls) are cement and the dark grey areas (ie. collimator) are lead.

Figure 1: Top View of Area

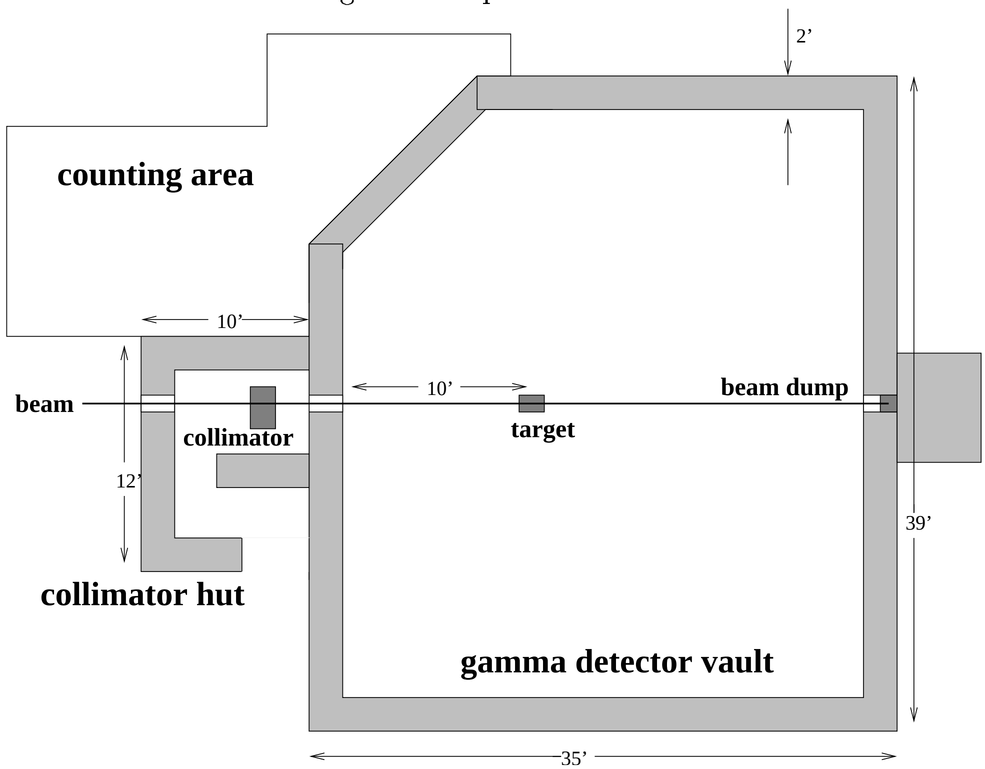
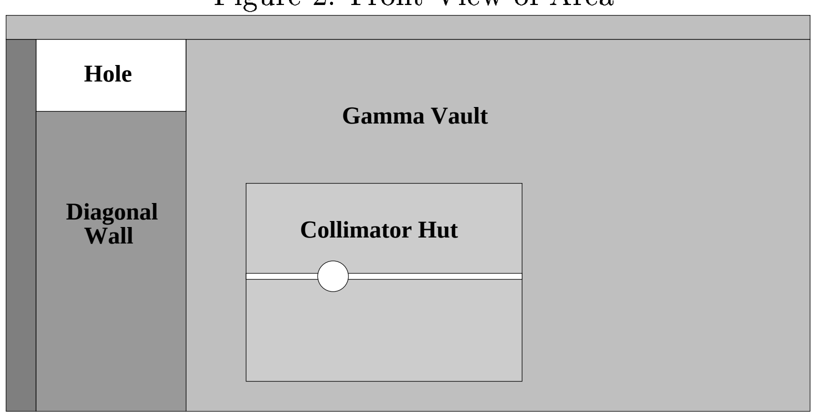


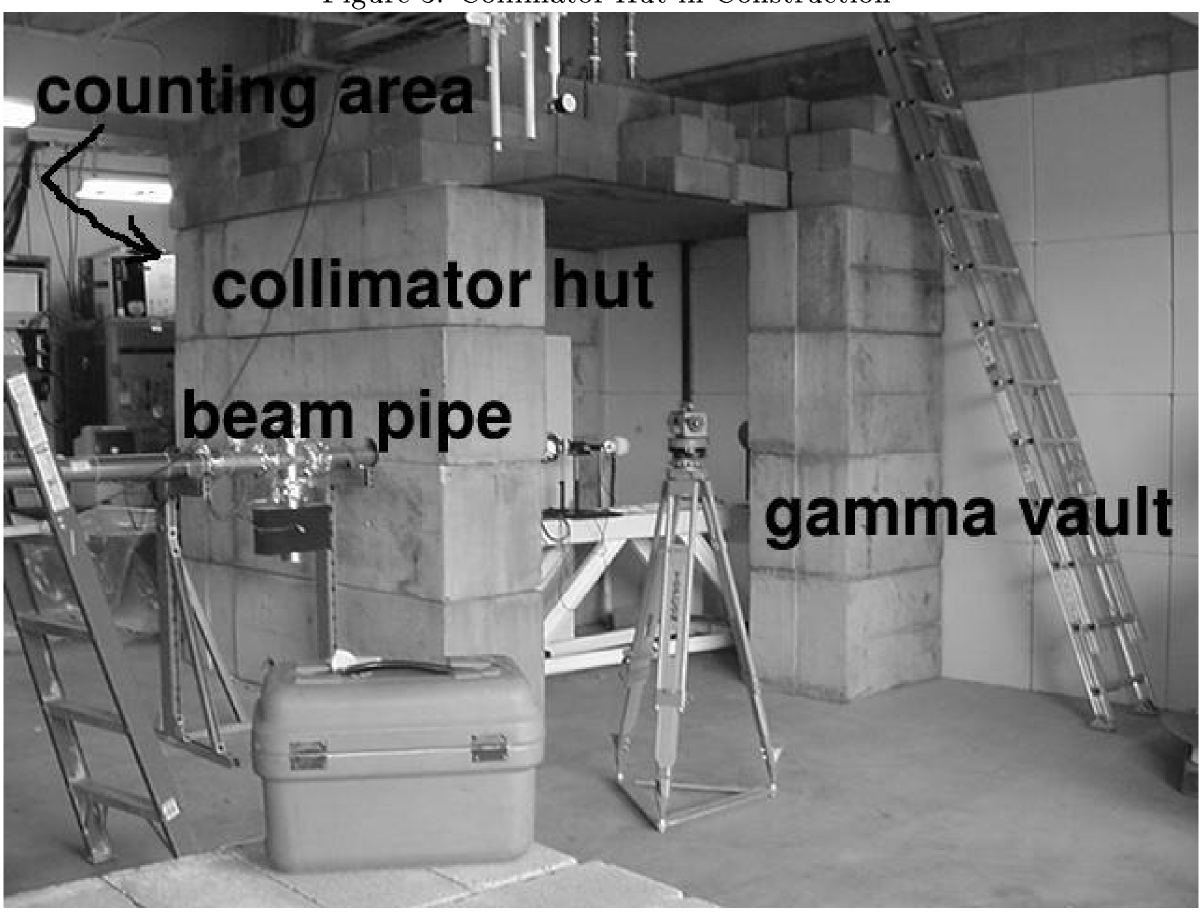
Figure 2: Front View of Area



There are several important things to note about the room:

- The one diagonal wall of the gamma vault is not the same height as the other walls, thus there is a air gap between the top of the diagonal wall and the ceiling.
- There is a crack in the front wall of the collimator hut (the wall facing the direction from which the beam originates). Simulations were done with the crack at sizes 0" and 1" (see spreadsheet data). For the purpose of considering the worst-case scenario, the analysis of the data will be done for the 1" case.
- The 2.5" (Gaussian distribution) beam travels through a 6" hole in the front of the collimator hut before being sized in the 1" collimator. It then travels through a 4" hole in the front of the gamma vault.
- Both rooms also have a hole for alignment purposes that has radius 4", and is positioned at the very base of their front walls.
- There is a hole for dumping the beam in the back of the gamma vault, that is backed by a $1m^3$ box of concrete.

Figure 3: Collimator Hut in Construction



3 Simulation

A simulation of the room discussed in the above section was creating using GEANT 3. GEANT is a program that allows for the tracking of particles through an experimental setup, as well as the graphical representation of that setup and particle trajectories. A beam of varied-energy gamma rays was used on a lead target to find out the radiation that was produced by the setup, and how much of that radiation was escaping the room. More specifically, it was important to find if those working in the experimental area were experiencing an unhealthy amount of radiation. See Appendix A: GEANT Pictures for various views of the GEANT room geometry.

The energy of the beam was varied from 2 to 200 MeV, and the flux of the beam was set at 10^8/s. For various numbers of triggers (gamma ray beam events) the number of escaping gamma rays and neutrons was recorded. Also, the positions in which a person would have any energy due to radiation deposited in them were recorded, along with the amount of energy that was deposited in that spot.

From the collected data it was possible to calculate the radiation doses that would be experienced by the experimenters working in the experimental area. The absorbed dose and equivalent dose were found, as well as the equivalent dose over periods of one day and one year, and the amount of hours in the area that would be needed to reach the maximum dose. See the following spreadsheets (Figure 4) for the data.

For the experimenters, the bulk of the time in the area will be spent in the counting area. This area is right outside the one diagonal wall of the gamma vault. Thus, more detailed simulations were carried out for these positions in the simulation. See the following spreadsheets (Figure 5) for the data.

Figure 4: Spreadsheets of Simulation Data

Table 2: Collimator Hut Crack = 0"

Energy (MeV)	Triggers	Person #	Energy Deposited (GeV)	Absorbed Dose (Grays)	Equivalent Dose (Sieverts)	Dose/Trigger (Siverts/trigger)	Flux (triggers/sec)	Yearly Dose (siverts)	Daily Dose (siverts)
2	1E+06	1	0.0014582	1.37431061E-15	1.37431061E-15	1.37431061E-21	1E+08	4.33402595E-06	1.18740437E-08
		2	0.011777	1.10994761E-14	1.10994761E-14	1.10994761E-20	1E+08	3.50033079E-05	9.58994737E-08
		3	0.040952	3.85960555E-14	3.85960555E-14	3.85960555E-20	1E+08	1.21716521E-04	3.3346992E-07
		4	0.012992	1.22445779E-14	1.22445779E-14	1.22445779E-20	1E+08	3.86145008E-05	1.05793153E-07
		5	0.0358063	3.37463846E-14	3.37463846E-14	3.37463846E-20	1E+08	1.06422599E-04	2.91568763E-07
		6	0.032828	3.09394245E-14	3.09394245E-14	3.09394245E-20	1E+08	9.7570569E-05	2.67316627E-07
		7	0.0063977	6.02964408E-15	6.02964408E-15	6.02964408E-21	1E+08	1.90150856E-05	5.20961249E-08
		8	0.066246	6.24349066E-14	6.24349066E-14	6.24349066E-20	1E+08	1.96894721E-04	5.39437593E-07
		9	0.019751	1.86147366E-14	1.86147366E-14	1.86147366E-20	1E+08	5.87034333E-05	1.60831324E-07
		10	0.0112952	1.06453938E-14	1.06453938E-14	1.06453938E-20	1E+08	3.35713139E-05	9.19762023E-08
10	1E+06	1	0.0017469	1.64640187E-15	1.64640187E-15	1.64640187E-21	1E+08	5.19209294E-06	1.42249122E-08
		2	0.0900577	8.48767335E-14	8.48767335E-14	8.48767335E-20	1E+08	2.67667267E-04	7.33334977E-07
		3	0.411813	3.8812164E-13	3.8812164E-13	3.8812164E-19	1E+08	1.22398041E-03	3.35337097E-06
		4	0.0259748	2.4480485E-14	2.4480485E-14	2.4480485E-20	1E+08	7.72016576E-05	2.11511391E-07
		5	0.351673	3.31441459E-13	3.31441459E-13	3.31441459E-19	1E+08	1.04523379E-03	2.86365421E-06
		6	0.437603	4.12427957E-13	4.12427957E-13	4.12427957E-19	1E+08	1.3006328E-03	3.56337755E-06
		7	0.0098098	9.24544798E-15	9.24544798E-15	9.24544798E-21	1E+08	2.91564447E-05	7.98806705E-08
		8	0.5354689	5.04663689E-13	5.04663689E-13	5.04663689E-19	1E+08	1.59150741E-03	4.36029427E-06
		9	0.0125135	1.17936057E-14	1.17936057E-14	1.17936057E-20	1E+08	3.7192315E-05	1.01896753E-07
		10	0.00928617	8.7519421E-15	8.7519421E-15	8.7519421E-21	1E+08	2.76001246E-05	7.56167798E-08
20	1E+06	1	0.019358	1.82443456E-14	1.82443456E-14	1.82443456E-20	1E+08	5.75353684E-05	1.57631146E-07
		2	0.274999	2.59178469E-13	2.59178469E-13	2.59178469E-19	1E+08	8.17345221E-04	2.23930197E-06
		3	0.899029	8.4730839E-13	8.4730839E-13	8.4730839E-19	1E+08	2.67207174E-03	7.32074449E-06
		4	0.061172	5.76528108E-14	5.76528108E-14	5.76528108E-20	1E+08	1.81813904E-04	4.98120286E-07
		5	0.763193	7.19286956E-13	7.19286956E-13	7.19286956E-19	1E+08	2.26834334E-03	6.2146393E-06
		6	0.856387	8.0711956E-13	8.0711956E-13	8.0711956E-19	1E+08	2.54533224E-03	6.973513E-06
		7	0.01569	1.47873635E-14	1.47873635E-14	1.47873635E-20	1E+08	4.66334296E-05	1.27762821E-07
		8	0.0244798	2.30714915E-14	2.30714915E-14	2.30714915E-20	1E+08	7.27582556E-05	1.99337687E-07
		9	0.0160555	1.51318365E-14	1.51318365E-14	1.51318365E-20	1E+08	4.77197597E-05	1.30739068E-07
		10	0.0140167	1.32103275E-14	1.32103275E-14	1.32103275E-20	1E+08	4.16600888E-05	1.1413723E-07
50	1E+06	1	0.028277	2.66502408E-14	2.66502408E-14	2.66502408E-20	1E+08	8.40441995E-05	2.30258081E-07
		2	0.381841	3.59873912E-13	3.59873912E-13	3.59873912E-19	1E+08	1.13489837E-03	3.1093106E-06
		3	1.700718	1.60287669E-12	1.60287669E-12	1.60287669E-18	1E+08	5.05483194E-03	1.38488546E-05
		4	0.0966533	9.10928925E-14	9.10928925E-14	9.10928925E-20	1E+08	2.87270546E-04	7.87042591E-07
		5	1.482623	1.39732857E-12	1.39732857E-12	1.39732857E-18	1E+08	4.40661538E-03	1.20729189E-05
		6	1.623898	1.5304761E-12	1.5304761E-12	1.5304761E-18	1E+08	4.82650944E-03	1.32233135E-05
		7	0.0266643	2.51303185E-14	2.51303185E-14	2.51303185E-20	1E+08	7.92509724E-05	2.17125952E-07
		8	0.0240755	2.26904506E-14	2.26904506E-14	2.26904506E-20	1E+08	7.15566052E-05	1.96045494E-07
		9	0.00888017	8.36929904E-15	8.36929904E-15	8.36929904E-21	1E+08	2.63934215E-05	7.23107437E-08
		10	0.0140633	1.32542466E-14	1.32542466E-14	1.32542466E-20	1E+08	4.17985922E-05	1.14516691E-07
150	1E+06	1	0.081732	7.70300061E-14	7.70300061E-14	7.70300061E-20	1E+08	2.42921827E-04	6.65539253E-07
		2	1.07037	1.00879224E-12	1.00879224E-12	1.00879224E-18	1E+08	3.18132722E-03	8.71596498E-06
		3	3.410201	3.21401414E-12	3.21401414E-12	3.21401414E-18	1E+08	1.0135715E-02	2.77690822E-05
		4	0.241519	2.27624554E-13	2.27624554E-13	2.27624554E-19	1E+08	7.17836793E-04	1.96667615E-06
		5	2.93582	2.766924E-12	2.766924E-12	2.766924E-18	1E+08	8.72577153E-03	2.39062234E-05
		6	3.08803	2.91037745E-12	2.91037745E-12	2.91037745E-18	1E+08	9.17816633E-03	2.51456612E-05
		7	0.050107	4.72243738E-14	4.72243738E-14	4.72243738E-20	1E+08	1.48926785E-04	4.08018589E-07
		8	0.021229	2.00077081E-14	2.00077081E-14	2.00077081E-20	1E+08	6.30963083E-05	1.72866598E-07
		9	0.189585	1.78678286E-13	1.78678286E-13	1.78678286E-19	1E+08	5.63479844E-04	1.5437804E-06
		10	0.0453332	4.27252077E-14	4.27252077E-14	4.27252077E-20	1E+08	1.34738215E-04	3.69145794E-07

Table 1: Collimator Hut Crack = 1"

Energy (MeV)	Triggers	Person #	Energy Deposited (GeV)	Absorbed Dose (Grays)	Equivalent Dose (Sieverts)	Dose/Trigger (Siverts/trigger)	Flux (triggers/sec)	Yearly Dose (siverts)	Daily Dose (siverts)
2	1E+06	1	0.002463	2.32130506E-15	2.32130506E-15	2.32130506E-21	1E+08	7.32046763E-06	2.00560757E-08
		2	0.01205	1.13567706E-14	1.13567706E-14	1.13567706E-20	1E+08	3.58147117E-05	9.81224979E-08
		3	0.045264	4.26599887E-14	4.26599887E-14	4.26599887E-20	1E+08	1.3453254E-04	3.68582302E-07
		4	0.0094212	8.87920391E-15	8.87920391E-15	8.87920391E-21	1E+08	2.80014574E-05	7.67163217E-08
		5	0.030632	2.88697591E-14	2.88697591E-14	2.88697591E-20	1E+08	9.10436722E-05	2.49434718E-07
		6	0.043298	4.08070915E-14	4.08070915E-14	4.08070915E-20	1E+08	1.28689244E-04	3.52573271E-07
		7	0.00774497	7.29940643E-15	7.29940643E-15	7.29940643E-21	1E+08	2.30194081E-05	6.30668716E-08
		8	0.076011	7.16381319E-14	7.16381319E-14	7.16381319E-20	1E+08	2.25918013E-04	6.18953459E-07
		9	0.01383	1.30343682E-14	1.30343682E-14	1.30343682E-20	1E+08	4.11051837E-05	1.12616942E-07
		10	0.011403	1.07469921E-14	1.07469921E-14	1.07469921E-20	1E+08	3.38917143E-05	9.28540119E-08
10	1E+06	1	0.0049892	4.70217426E-15	4.70217426E-15	4.70217426E-21	1E+08	1.48287767E-05	4.06267856E-08
		2	0.08186	7.71506424E-14	7.71506424E-14	7.71506424E-20	1E+08	2.43302266E-04	6.6658155E-07
		3	0.444952	4.19354173E-13	4.19354173E-13	4.19354173E-19	1E+08	1.32247532E-03	3.62322006E-06
		4	0.024355	2.29538712E-14	2.29538712E-14	2.29538712E-20	1E+08	7.23873281E-05	1.98321447E-07
		5	0.390039	3.67600286E-13	3.67600286E-13	3.67600286E-19	1E+08	1.15926426E-03	3.17606647E-06
		6	0.413529	3.8973892E-13	3.8973892E-13	3.8973892E-19	1E+08	1.22908066E-03	3.36734427E-06
		7	0.0057981	5.46453872E-15	5.46453872E-15	5.46453872E-21	1E+08	1.72329693E-05	4.72136145E-08
		8	0.0433596	4.08651477E-14	4.08651477E-14	4.08651477E-20	1E+08	1.2887233E-04	3.53074876E-07
		9	0.012973	1.22266709E-14	1.22266709E-14	1.22266709E-20	1E+08	3.85580295E-05	1.05638437E-07
		10	0.012973	1.22266709E-14	1.22266709E-14	1.22266709E-20	1E+08	3.85580295E-05	1.05638437E-07
20	1E+06	1	0.0151206	1.42507208E-14	1.42507208E-14	1.42507208E-20	1E+08	4.4941073E-05	1.23126228E-07
		2	0.215831	2.0341437E-13	2.0341437E-13	2.0341437E-19	1E+08	6.41487556E-04	1.75750015E-06
		3	0.9362115	8.82351803E-13	8.82351803E-13	8.82351803E-19	1E+08	2.78258465E-03	7.62351958E-06
		4	0.0654421	6.16772545E-14	6.16772545E-14	6.16772545E-20	1E+08	1.9450539E-04	5.32891479E-07
		5	0.748189	7.05146127E-13	7.05146127E-13	7.05146127E-19	1E+08	2.22374883E-03	6.09246254E-06
		6	0.96796118	9.12274943E-13	9.12274943E-13	9.12274943E-19	1E+08	2.87695026E-03	7.8820555E-06
		7	0.0191398	1.80386986E-14	1.80386986E-14	1.80386986E-20	1E+08	5.68868398E-05	1.55854356E-07
		8	0.0232756	2.19365684E-14	2.19365684E-14	2.19365684E-20	1E+08	6.91791622E-05	1.89531951E-07
		9	0.0146139	1.37731709E-14	1.37731709E-14	1.37731709E-20	1E+08	4.34350718E-05	1.19000197E-07
		10	0.0198159	1.86759029E-14	1.86759029E-14	1.86759029E-20	1E+08	5.88963275E-05	1.61359801E-07
50	1E+06	1	0.0252317	2.37801351E-14	2.37801351E-14	2.37801351E-20	1E+08	7.49930342E-05	2.05460368E-07
		2	0.443178	4.1768223E-13	4.1768223E-13	4.1768223E-19	1E+08	1.31720268E-03	3.60877447E-06
		3	1.745174	1.64477517E-12	1.64477517E-12	1.64477517E-18	1E+08	5.18696296E-03	1.42108574E-05
		4	0.1161398	1.09458346E-13	1.09458346E-13	1.09458346E-19	1E+08	3.45187839E-04	9.45720106E-07
		5	1.377402	1.29816087E-12	1.29816087E-12	1.29816087E-18	1E+08	4.09388013E-03	1.12161099E-05
		6	1.59967	1.50764193E-12	1.50764193E-12	1.50764193E-18	1E+08	4.75449958E-03	1.30260262E-05
		7	0.0255718	2.41006694E-14	2.41006694E-14	2.41006694E-20	1E+08	7.6003871E-05	2.08229784E-07
		8	0.0202914	1.91240477E-14	1.91240477E-14	1.91240477E-20	1E+08	6.03095968E-05	1.65231772E-07
		9	0.021342	2.01142073E-14	2.01142073E-14	2.01142073E-20	1E+08	6.34321641E-05	1.73786751E-07
		10	0.0269941	2.54411453E-14	2.54411453E-14	2.54411453E-20	1E+08	8.02311958E-05	2.19811495E-07
150	1E+06	1	0.095391	8.99032119E-14	8.99032119E-14	8.99032119E-20	1E+08	2.83518769E-04	7.76763751E-07
		2	1.081306	1.0190991E-12	1.0190991E-12	1.0190991E-18	1E+08	3.21383093E-03	8.80501624E-06
		3	3.417633	3.22101858E-12	3.22101858E-12	3.22101858E-18	1E+08	1.01578042E-02	2.78296006E-05
		4	0.251979	2.37482796E-13	2.37482796E-13	2.37482796E-19	1E+08	7.48925747E-04	2.05185136E-06
		5	2.833502	2.6704923E-12	2.6704923E-12	2.6704923E-18	1E+08	8.42166451E-03	2.30730534E-05
		6	3.253227	3.06607076E-12	3.06607076E-12	3.06607076E-18	1E+08	9.66916076E-03	2.64908514E-05
		7	0.069938	6.5914508E-14	6.5914508E-14	6.5914508E-20	1E+08	2.07867992E-04	5.69501349E-07
		8	0.028652	2.70036673E-14	2.70036673E-14	2.70036673E-20	1E+08	8.51587652E-05	2.33311685E-07
		9	0.0212894	2.00646333E-14	2.00646333E-14	2.00646333E-20	1E+08	6.32758277E-05	1.73358432E-07
		10	0.0476725	4.49299291E-14	4.49299291E-14	4.49299291E-20	1E+08	1.41691024E-04	3.88194588E-07

Figure 5: Spreadsheets of Simulation Data

Table 3: People in Counting Area - Collimator Hut Crack = 0"

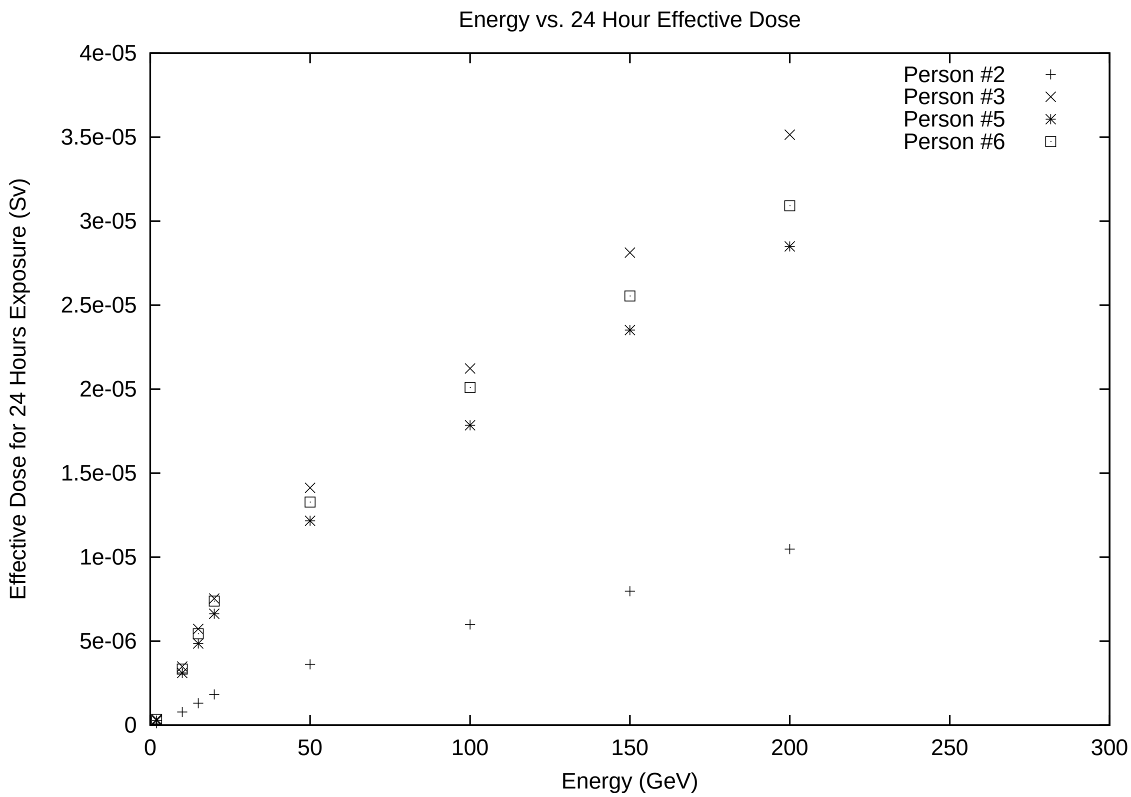
Energy (MeV)	Triggers	Person #	Energy Deposited (GeV)	Absorbed Dose (Grays)	Dose/Trigger (Siverts/trigger)	Yearly Dose (siverts)	Daily Dose (siverts)
2	1E+07	2	0.13562	1.27817861E-13	1.27817861E-20	4.03086407E-05	1.10434632E-07
		3	0.4418	4.16383506E-13	4.16383506E-20	1.31310702E-04	3.59755349E-07
		5	0.35001	3.29874131E-13	3.29874131E-20	1.04029106E-04	2.85011249E-07
		6	0.40348	3.80268033E-13	3.80268033E-20	1.19921327E-04	3.2855158E-07
10	1E+07	2	0.977999	9.21735293E-13	9.21735293E-20	2.90678442E-04	7.96379293E-07
		3	4.20166	3.95994097E-12	3.95994097E-19	1.24880698E-03	3.421389E-06
		5	3.66856	3.4575099E-12	3.4575099E-19	1.09036032E-03	2.98728855E-06
		6	4.18203	3.94144027E-12	3.94144027E-19	1.2429726E-03	3.4054044E-06
15	1E+07	2	1.62063	1.52739611E-12	1.52739611E-19	4.81679637E-04	1.31967024E-06
		3	6.99664	6.59412742E-12	6.59412742E-19	2.07952402E-03	5.69732609E-06
		5	5.90889	5.56895503E-12	5.56895503E-19	1.75622566E-03	4.81157715E-06
		6	6.82947	6.43657461E-12	6.43657461E-19	2.02983817E-03	5.56120046E-06
20	1E+07	2	2.16249	2.03808322E-12	2.03808322E-19	6.42729925E-04	1.7609039E-06
		3	9.43528	8.89247389E-12	8.89247389E-19	2.80433057E-03	7.68309744E-06
		5	7.90566	7.45085203E-12	7.45085203E-19	2.3497007E-03	6.43753615E-06
		6	8.64636	8.14894E-12	8.14894E-19	2.56984972E-03	7.04068416E-06
50	1E+07	2	4.42441	4.1698763E-12	4.1698763E-19	1.31501219E-03	3.60277312E-06
		3	17.2698	1.62762786E-11	1.62762786E-18	5.13288721E-03	1.40627047E-05
		5	14.87778	1.40218701E-11	1.40218701E-18	4.42193694E-03	1.21148957E-05
		6	16.51369	1.55636671E-11	1.55636671E-18	4.90815807E-03	1.34470084E-05
100	1E+07	2	7.17975	6.76670321E-12	6.76670321E-19	2.13394752E-03	5.84643157E-06
		3	25.9318	2.44399588E-11	2.44399588E-18	7.70738541E-03	2.11161244E-05
		5	21.75914	2.05073495E-11	2.05073495E-18	6.46719773E-03	1.77183499E-05
		6	24.43513	2.30293913E-11	2.30293913E-18	7.26254885E-03	1.98973941E-05
150	1E+07	2	9.86063	9.29335376E-12	9.29335376E-19	2.93075204E-03	8.02945765E-06
		3	34.8647	3.28589543E-11	3.28589543E-18	1.03623998E-02	2.83901365E-05
		5	28.3538	2.67226226E-11	2.67226226E-18	8.42724625E-03	2.30883459E-05
		6	31.31046	2.95091877E-11	2.95091877E-18	9.30601742E-03	2.54959381E-05
200	1E+07	2	12.5499	1.18279116E-11	1.18279116E-18	3.73005021E-03	1.02193157E-05
		3	42.2104	3.97820605E-11	3.97820605E-18	1.25456706E-02	3.43717003E-05
		5	34.5488	3.25612279E-11	3.25612279E-18	1.02685088E-02	2.81329009E-05
		6	37.92878	3.57467596E-11	3.57467596E-18	1.12730981E-02	3.08852003E-05

Table 4: People in Counting Area - Collimator Hut Crack = 1"

Energy (MeV)	Triggers	Person #	Energy Deposited (GeV)	Absorbed Dose (Grays)	Dose/Trigger (Siverts/trigger)	Yearly Dose (siverts)	Daily Dose (siverts)
2	1E+07	2	0.13724	1.29344664E-13	1.29344664E-20	4.07901331E-05	1.11753789E-07
		3	0.42139	3.97147681E-13	3.97147681E-20	1.25244493E-04	3.43135597E-07
		5	0.32912	3.1018592E-13	3.1018592E-20	9.78202317E-05	2.68000635E-07
		6	0.42656	4.02020254E-13	4.02020254E-20	1.26781107E-04	3.473455E-07
10	1E+07	2	0.96069	9.05422069E-13	9.05422069E-20	2.85533904E-04	7.82284668E-07
		3	4.28316	4.03675232E-12	4.03675232E-19	1.27303021E-03	3.48775401E-06
		5	3.80824	3.58915419E-12	3.58915419E-19	1.13187567E-03	3.10102922E-06
		6	4.09407	3.85854056E-12	3.85854056E-19	1.21682935E-03	3.33377904E-06
15	1E+07	2	1.60465	1.51233543E-12	1.51233543E-19	4.76930101E-04	1.30665781E-06
		3	7.032883	6.62828538E-12	6.62828538E-19	2.09029608E-03	5.72683857E-06
		5	5.961032	5.61809734E-12	5.61809734E-19	1.77172318E-03	4.8540361E-06
		6	6.67539	6.29135874E-12	6.29135874E-19	1.98404289E-03	5.43573395E-06
20	1E+07	2	2.24174	2.11277402E-12	2.11277402E-19	6.66284414E-04	1.82543675E-06
		3	9.24799	8.71595858E-12	8.71595858E-19	2.7486647E-03	7.53058821E-06
		5	8.14475	7.67618732E-12	7.67618732E-19	2.42076243E-03	6.63222585E-06
		6	9.06365	8.54222355E-12	8.54222355E-19	2.69387562E-03	7.38048114E-06
50	1E+07	2	4.44336	4.18773611E-12	4.18773611E-19	1.32064446E-03	3.618204E-06
		3	17.33412	1.63368983E-11	1.63368983E-18	5.15200424E-03	1.41150801E-05
		5	14.9371	1.40777774E-11	1.40777774E-18	4.43956789E-03	1.21631997E-05
		6	16.30536	1.53673222E-11	1.53673222E-18	4.84623874E-03	1.32773664E-05
100	1E+07	2	7.35994	6.93652698E-12	6.93652698E-19	2.18750315E-03	5.99315931E-06
		3	26.06717	2.4567541E-11	2.4567541E-18	7.74761974E-03	2.12263555E-05
		5	21.91556	2.06547707E-11	2.06547707E-18	6.5136885E-03	1.78457219E-05
		6	24.68634	2.32661494E-11	2.32661494E-18	7.33721287E-03	2.01019531E-05
150	1E+07	2	9.78787	9.2247796E-12	9.2247796E-19	2.90912649E-03	7.97020957E-06
		3	34.52855	3.25421428E-11	3.25421428E-18	1.02624902E-02	2.81164114E-05
		5	28.87036	2.72094652E-11	2.72094652E-18	8.58077694E-03	2.35089779E-05
		6	31.36898	2.9564341E-11	2.9564341E-18	9.32341059E-03	2.55435907E-05
200	1E+07	2	12.87375	1.21331307E-11	1.21331307E-18	3.82630411E-03	1.0483025E-05
		3	43.15267	4.06701223E-11	4.06701223E-18	1.28257298E-02	3.51389856E-05
		5	34.9965	3.29831719E-11	3.29831719E-18	1.04015731E-02	2.84974606E-05
		6	37.95326	3.57698313E-11	3.57698313E-18	1.1280374E-02	3.09051342E-05

From the data it is apparent that the absorbed and effective dose for people working in the counting area is dependent on the energy of the beam. Figure 6 below shows the relationship between beam energy and effective daily dose. The 24 hour effective dose appears to increase logarithmically with an increase in energy.

Figure 6: Effective Dose for 24 Hour Exposure



It is also apparent that for all the cases tested, those working in the experimental area should not receive their maximum radiation dosage. Some important facts about the simulation results include:

- The dose for spending 24 hours in the experimental area ranged from approximately 20 nSv to 35 μSv.
- The worst case in the simulation was for person #3, with a 1" crack in the collimator hut, and a beam energy of 200 MeV. Over a 24 hour period the person received approximately 35 μSv of radiation.
- To provide a perspective for these dose, a flight from Toronto to Vancouver would provide someone with a 500 μSv full-body dose of radiation. The doses that are created by the simulation are less than an order of magnitude below that value.
- The recommended maximum effective dose for members of the general public is 1 mSv. To receive this a person would have to spend between 800 and 200,000 hours in the experimental area within a year. Since there is about 8760 hours in a year, in some cases you

could spend an entire year in the experimental area, with an experiment running, and still not exceed the recommended maximum dose limit.

4 Why no Neutrons?

Because of both the lead collimator and the lead target being bombarded with photons, it is expected that a significant number of neutrons should be produced in the simulation. These neutrons are important because they will have a much more detrimental biological effect upon any person they interact with. In the simulations described above, it was found that no neutrons were detected interacting with any of the people in the simulation. This raised questions about the validity of the simulation because incident neutrons were expected. Several adjustments were made to the simulation to examine this lack of neutrons.

4.1 Neutron Cutoff

The neutron cutoff energy in GEANT was questionable, and since there may be lower-energy neutrons produced (ie. thermal neutrons), the neutron cutoff energy for the simulation was changed to 1e-4 eV. Without changing anything else in the simulation, several of the trials were repeated. The data from the simulation runs with the original cutoff energy were identical to the data from the simulation runs with a lower cutoff energy. This indicates that the lack of neutrons in the simulations is not because of energy cutoff considerations.

4.2 Person Positioning

Another explanation for the lack of neutron hits is that the positions of the person markers are positions that are not reached by a lot of neutrons. To test this, one of the people was moved to a position directly outside of the collimator hut's crack. See Appendix A: GEANT Pictures for the new positioning. Several trials were repeated with this positioning, and the results can be found in the following spreadsheet (Figure 7).

4.3 Beam Thickness

The beam has a 2.5" radius, is a Gaussian distribution, and is sized by a 1" collimator. It is possible that less of the beam is being dumped into the lead collimator that is intuitively expected, namely because of the Gaussian distribution. Several trials were repeated with the collimator hole having a 0" diameter. The results can be found in the following spreadsheet (Figure 7).

From these results we can become suspicious of the handling of neutrons in the simulation. Neutrons should be produced by the beam incident on a lead target. This is a problem with the simulation that should be investigated further.

Figure 7: Spreadsheets of Simulation Data with Neutron Test Changes

Table 5: Changes to Simulation

Energy (MeV)	Triggers	Person #	Energy Deposited (GeV)	Equivalent Dose (Sieverts)	Dose/Trigger (Siverts/trigger)	Flux (triggers/sec)	Yearly Dose (siverts)	Daily Dose (siverts)
Moved Person #8 Directly Outside Collimator Hut - Crack 1"								
20 MeV	1E+07	8	1.46549	1.38118122E-12	1.38118122E-19	1E+08	4.3556931E-04	1.19334058E-06
50 MeV	1E+07	8	1.501767	1.41537123E-12	1.41537123E-19	1E+08	4.4635147E-04	1.22288074E-06
Made Collimator Hole 0" - Crack 1"								
50 MeV	1E+06	1	0.135183	1.27406002E-13	1.27406002E-19	1E+08	4.01787566E-04	1.10078785E-06
		2	0.0005675	5.34852059E-16	5.34852059E-22	1E+08	1.68670945E-06	4.62112179E-09
		3	0.0031409	2.96020587E-15	2.96020587E-21	1E+08	9.33530523E-06	2.55761787E-08
		4	0.0061632	5.80863473E-15	5.80863473E-21	1E+08	1.83181105E-05	5.01866041E-08
		5	0.0048225	4.54506441E-15	4.54506441E-21	1E+08	1.43333151E-05	3.92693565E-08
		6	0.0062986	5.93624525E-15	5.93624525E-21	1E+08	1.8720543E-05	5.12891589E-08
		7	0.0170084	1.60299168E-14	1.60299168E-20	1E+08	5.05519455E-05	1.38498481E-07
		8	0.0375608	3.53999493E-14	3.53999493E-20	1E+08	1.1163728E-04	3.05855562E-07
		9	0.01747354	1.64682975E-14	1.64682975E-20	1E+08	5.19344231E-05	1.42286091E-07
		10	0.03291999	3.10261223E-14	3.10261223E-20	1E+08	9.78439794E-05	2.68065697E-07
Made Collimator Hole 0" - Crack 36"								
50 MeV	1E+06	1	0.110642	1.04276831E-13	1.04276831E-19	1E+08	3.28847414E-04	9.00951818E-07
		2	0.0041618	3.92237409E-15	3.92237409E-21	1E+08	1.23695989E-05	3.38893122E-08
		3	0.00141618	1.334708E-15	1.334708E-21	1E+08	4.20913514E-06	1.15318771E-08
		4	0.0103389	9.74410916E-15	9.74410916E-21	1E+08	3.07290227E-05	8.41891032E-08
		5	0.00014288	1.34660198E-16	1.34660198E-22	1E+08	4.24664399E-07	1.16346411E-09
		6	0.00371632	3.5025223E-15	3.5025223E-21	1E+08	1.10455543E-05	3.02617926E-08
		7	0.0209456	1.9740612E-14	1.9740612E-20	1E+08	6.22539939E-05	1.70558887E-07
		8	0.0725147	6.8342972E-14	6.8342972E-20	1E+08	2.15526396E-04	5.90483278E-07
		9	0.157023	1.47989559E-13	1.47989559E-19	1E+08	4.66699874E-04	1.27862979E-06
		10	0.0338698	3.19212903E-14	3.19212903E-20	1E+08	1.00666981E-04	2.75799948E-07

References

[1] University of Saskatchewan. *Radiation Safety Training Course Manual*. May 2002.

[2] Dalhousie University. *Radiation Safety Training Manual*. Feb 2001. http://is.dal.ca/ ehs/radtr.htm, July 24, 2003.

[3] *Radiation and Life*. July 2002. http://www.uic.com.au/ral.htm, July 24, 2003.

[4] Duke University and Duke Medical Center. *Laboratory Radiation Safety*. March 1995.