

## **ACCELERATOR FACILITY SHIELDING DESIGN**

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## **1. INTRODUCTION TO ACCELERATOR FACILITIES**

Several new research facilities will soon be constructed as part of the creation of a new engineering complex on the campus of the University of Tennessee, Knoxville. The complex will combine the Estabrook and Pasqua buildings, and will house the departments that currently occupy the two buildings [1]. The new nuclear engineering building will introduce the following upgrades: a critical experiment facility, graphite pile, and modular high-energy X-ray (electron accelerator) source. Considering that the new facilities in the new nuclear engineering building will be located in close proximity to Neyland Stadium and surrounded by other buildings, it is first and foremost a priority that the facilities meet the regulatory shielding requirements. The new facility's vicinity to Neyland brings heightened attention to the design project. Therefore, the Nuclear Engineering Department and the College of Engineering are motivated to pursue an in-depth and thorough accelerator shielding analysis to ease public apprehension.

This report will reflect the project planning and design of the aforementioned accelerator shielding analysis. The end design places an accelerator into a well-shielded room, and directs the x-ray beam through a collimating hole in the shielding wall into the next room. The x-ray beam is to be used as a part of a materials irradiation laboratory in the adjoining room. The modular high-energy X-ray source under consideration is assumed to operate at a maximum of 22 MV in order to conservatively estimate the shielding requirements. If an accelerator of lesser energy is initially installed, efforts to upgrade the facility in the future will be made easier by the relatively high level of shielding required by the higher energy machine. The rating of 22 MV represents the energy of the x-rays produced by the accelerator and then exit in a beam. The beam exits the accelerator in a direction chosen by the orientation of the accelerator itself. It is important to note that all the shielding calculations and design will be specific to a single orientation of the beam. No change in the beam direction can be made without further calculations and additional shielding.

## **2. ACCELERATOR SHIELDING BACKGROUND**

### **2.1 ACCELERATOR HISTORY**

Research on the effects and uses of radiation with regards to materials can only be done with access to radiation. In a laboratory environment, that radiation must be created. This can be done in many ways and with many sources to model radiation fields that may be encountered or created outside of the lab. One way to produce an x-ray beam, for example, is through the use of a particle accelerator. The NCRP defines a particle accelerator as, "a device that imparts sufficient kinetic energy to charged particles to initiate nuclear reactions," [2]. There are many types of particle accelerators, and they are classified and referred to by one or more of their distinguishing qualities. One feature is the technology by which acceleration is achieved; this can be referring to either the power source of acceleration or the acceleration path geometry (linear accelerators). The type of accelerated particle and its maximum energy are two factors most commonly used to classify accelerators. The particles created and their energies are the essential descriptive parameters that dictate the characteristics of health physics. The type of particle accelerated does not necessarily represent the type of particle in the useful beam. Electrons are accelerated in electron accelerators, but an x-ray beam is the result of those electrons colliding with a tungsten target within the accelerator. Other important accelerator characteristics are maximum intensity, duty factor, and the media in the vicinity of where the beam strikes the target. [2]

The first devices that can be classified as particle accelerators are cathode ray tubes, and they existed by the end of the nineteenth century. Accelerators as they are today were not invented until 1932 [2]. Both Cockcroft and Walton at Cambridge, and Lawrence and his colleagues at Berkeley are independently cited for the design, construction, and operation of accelerators in 1932. The first high-energy medical

accelerator that did not rely on the production of extremely high voltages was the betatron developed by Kerst in 1941 [3]. Particle accelerators have since developed to higher energies, higher intensities, and larger duty factors. In general, these accelerators work by using electromagnetic forces to place particles in a particular energy, location and with a desired direction. In the case of electron accelerators, the electron beam is stopped in a target made of high-Z material. Through the interaction of the electrons with the target material, photons are emitted in all directions from the target. As electron energy increases, the photon distribution becomes increasingly more forward-peaked, and thus forms the X-ray beam. Furthermore, if the incident electron energy is greater than 10 MeV, neutrons are isotropically released.

## **2.2 CURRENT ACCELERATOR FACILITIES**

Accelerators began as research instruments, but have expanded in functionality to many practical industry applications. Accelerators are now manufactured commercially in energies ranges up to 50 MeV for uses in applied science, in industry, and in medicine. “In addition to their (accelerators) continued application to fundamental research in cosmology and particle physics, they are now widely applied in e.g., medicine (diagnosis, therapy, radiopharmaceutical production), materials science and solid-state physics (ion implantation, radiation damage studies, microlithography), polymerization of plastics, sterilization of toxic biological wastes, and food preservation,” [2]. Electron accelerators are used by industry in radiography and radiation processing. Intensity modulated radiation therapy and total body irradiation techniques also use electron accelerators to provide photon doses to patients receiving cancer treatment. Operating facilities already encompass the full spectrum of accelerator uses. The Provision Center for Proton Therapy operates in Knoxville, providing proton treatment techniques for cancer patients as an alternative to photon treatment. Georgia Tech houses a medical accelerator that is used to treat patients with photons rather than protons [4]. On UTK’s campus, the College of Veterinary Medicine uses a linear electron accelerator to perform photon radiation therapy on animals. Research accelerators are located in cargo bay scanners in Las Vegas, high energy CT scanners at the Hill Air Force Bay, and on academic campuses and national labs across the United States [5].

The proposed facility in the new nuclear engineering building will be most like the cargo bay scanners in Las Vegas. Although the accelerator will have many users and uses, the planning of the facility was centered on the needs of one of the primary users. Dr. Hayward, a Nuclear Engineering Department Associate Professor, intends to set up a cargo scanning bay for radiation interrogation of shipping containers. In this case, a 9 MeV x-ray beam is used to irradiate the cargo container in search of special nuclear material or other prohibited items, “such as weapons, explosives, and explosive devices,” [5, 6]. The assessment of the special nuclear material is reliant on the response of the cargo to the x-ray beam in the form of prompt and delayed neutrons and delayed gamma rays and is collected by a setup of detector panels surrounding the cargo. This is known as active interrogation. “In active cargo interrogation an external source is directed into the cargo to induce fission, if nuclear material is present,” [7]. The general setup will be installed initially with a Varian M9 Linatron. Varian is a manufacturer of medical devices and software [5]. Varian “gives users the power to inspect everything from automotive parts and castings to rockets and aerospace products,” [6].

## **3. ACCELERATOR FACILITY RADIATION CONSIDERATIONS**

### **3.1 SHIELDING DESIGN**

Along with the understanding of radiation, accelerator physics and their potential benefits, their potential harm became evident. Acute radiation syndrome (ARS) is an illness caused by irradiation of the body by a high dose of penetrating radiation. The first acknowledged case of ARS was due to radiation exposure from an accelerator. It has since been learned that reducing the time of exposure, distance to

source, or increasing the material between the target and the source will decrease the radiation exposure to a person or object. This report will focus on the third method of reducing the exposure: shielding. “The term shielding analysis can be used in a narrow sense to refer to the quantification of how a system of shields near a source of radiation affects the radiation field at some point of interest,” [8]. The study involves how radiation is created, migrates from its source, interacts with matter, creates microscopic changes in the medium it traverses, and how these changes affect the medium. This requires a thorough understanding of radiation source characteristics, protection criteria, the special dosimetric units, and the fundamental physics of the interaction of radiation with matter [8]. The NCRP defines “shields” as “a physical entity interposed between a source of ionizing radiation and an object to be protected such that the radiation level at the position of that object will be reduced,” [9]. It is important to design shielding that restricts radiation exposures to both members of the public and to radiation workers to be within their respective dose limits.

The accelerated beam of electrons produces radiation as a consequence of an interaction between the incident particle beam and the target material. Radiation of many is produced by these interactions. “In general, the higher the kinetic energy of the incident particle, the greater yield and number of types of secondary radiations,” [9]. When considering electron accelerators, bremsstrahlung photons dominate the secondary radiation field for all incident electron energies. The field of photons produced can change phase space in five different ways as it exits the accelerator and interacts with materials in the accelerator room. Phase spaces denotes a radiation field of specific particles, energy, direction, and position, and can be altered through collisions, uniform translations, continuous slowing down, decay or the introduction of new particles [9]. In addition to bremsstrahlung and characteristic x-ray radiation, prompt and delayed photons add additional gamma spectra to the field. Neutron, charge particles, ions, and nuclear fragments are generated as well if the electrons or gammas have high enough energy. For an accelerator operating at 22 MV, only neutron production is a concern.

The radiation produced by these nuclear interactions can be grouped and classified, like accelerators, in differing ways by their characteristics. For example, radiation created within the accelerator room is either prompt or induced residual radiation. Prompt radiation exists only when the accelerator is operation, and ceases when the accelerator is turned off. This type of radiation directly originates from the beam by either beam loss or the normal utilization of the beam. Prompt radiation is made up of direct and scattered radiation. “The characteristics of the prompt radiation field are determined by the energy and type of particle accelerated, the beam duty factor, the target material, and shielding around the accelerator,” [9]. Induced radioactivity is a result of the activation in the accelerator structure, its ancillary components, or in shielding. The activated components decay and give rise to the residual radiation field that remains for some time even after the accelerator is turned off. Sodium-24 produced in the shielding, for example, is often a major contributor to the residual radiation levels. A second and important classification of radiation denotes the difference between directly and indirectly ionizing radiation. Neutrons, x-rays, and gamma ray are not charged, and are therefore radiations that indirectly ionize the material through which they pass. This takes place through the emission of energetic secondary charged particles, which cause the ionization. “Directly ionizing radiation interacts very strongly with shielding media and is therefore easily stopped,” [9]. Indirectly ionizing radiation, like that produced from electron accelerators requires more extensive shielding. Ionization is the reason for the importance of shielding because the significant biological effects from radiation exposure are intimately related to the ionization of atoms in the body.

### **3.2 REGULATING ORGANIZATIONS**

Several governing bodies, regulatory organizations, and advisory boards are involved in the licensing and operations surrounding an accelerator installation. “In the United States, the regulation of the manufacturing, distribution and operation of particle accelerators in a manner that does not jeopardize public health and safety is a complex matter shared by several government agencies,” [9]. The U.S. Food

and Drug Administration (FDA) has the authority to adopt performance standards for accelerators under the provision of the Radiation Control for Health and Safety Act of 1968. The U.S. Department of Energy (DOE) holds the authority over radiological safety, which includes particle accelerators. The U.S. Environmental Protection Agency (EPA) is responsible for the set of guidelines that federal agencies use for radiological protection. The Nuclear Regulatory Commission (NRC) has the authority to exercise federal regulation over the use, transportation, and disposal of radioactive materials.

In addition to the governing regulatory agencies, there are several organizations that offer advice, yet hold no direct governing authority. The International Atomic Energy Agency (IAEA), the International Commission of Radiological Protection (ICRP), the International Commission of Radiation Units and Measurements, and the National Council of Radiological Protection (NCRP) are national or international agencies respectively, which are involved in the uses, effects, and safety of radiation and the radiation sources. The NCRP and ICRP are most concerned with the standards for protection. In contrast, the Committee on the Biological Effects of Ionizing Radiation works on the evaluation and interpretation of scientific research in the field. Similarly, the IAEA has as its principal objective: “to accelerate and enlarge, the contribution of atomic energy to peace, health, and prosperity throughout the world,” [9]. The list of related organizations continues with the Radiation Safety Information computational Center (RSICC) located at Oak Ridge National Laboratory. RSICC maintains a comprehensive set of literature, computer programs, and data libraries for shielding and radiation calculations. RSICC is also the distributor of U.S. export controlled radiation transport codes. National organizations that have issued reports on the installation, operation, and use of accelerator facilities are: the American National Standards Institute, the American Society for Testing Materials, the Institute of Electrical and Electronic Engineers, the American Nuclear Society, and the American Association of Physicists in Medicine.

The interrelationship of the various organizations is complex and ever changing as the scope and authority of each entity fluctuates. There is, however, a typical pattern of operation. For example, the NCRP or ICRP will issue a series of recommendations that initially is in no mandatory. Then the EPA may choose to adopt the recommendations in part or in their entirety as regulations. Finally, the NRC is responsible for the issuance and enforcement of the now mandatory regulations. Since 1959 the NRC has been permitted to delegate to the individual states the responsibility and licensing authority for all regulator activity excluding reactors States that operate in this manner are called agreement states and must maintain protection standards at least as strict and comprehensive as the federal standards. The local authorities may choose to adopt more restrictive policies, and is it important to follow both the federal and the state regulations. It is also possible that limitations be ascribed to a facility by the facility administration or owner [10].

The principle of As Low As Reasonably Achievable (ALARA) is in place on the federal, state, and facility levels. ALARA represents a change from the previous thought: maximum permissible exposure. Instead, it is now the goal to optimize the economic and social factors with a dose as low as possible and at least as low as the prescribed limit. Facility justification and regulatory dose limits accompany considerations of radiation protection. A radiation facility or exposure is considered justified if it can be shown that there is approximate net benefit.

### **3.3 RADIATION REGULATIONS**

The organizations and principles discussed in Section 3.2 combine a series of regulations that restrict the allowable radiation exposure emitted by the accelerator facility. These radiation limits dictate the shielding goals at points in and near the facility where various levels of access are permitted. The recommended radiation protection quantity for the limitation of exposure to people from sources of radiation is effective dose (E). Effective dose is defined as the sum of the weighted equivalent doses to specific organs and tissues. However, it is not practical to base shielding design directly on effective dose because it is dependent on the energy spectra of the photons and neutrons, as well as on the posture of the recipient. Instead, shielding design goals (P) are more practical values based on dose equivalent (H)

values of a single radiation source. Dose equivalent is defined as the product of the quality factor (Q) and the absorbed dose (D). Dose equivalent and shielding goals are given in units of Sieverts, which are equivalent to Joules per kilogram. Shielding goals are given in Sieverts over unit of time.

Any location where the public or personnel are permitted should be considered in radiation protection. Possible areas of exposure include laboratories, offices, and other areas routinely occupied by workers and the general public. Because Tennessee is an agreement state, the Division of Radiological Health of the Tennessee Department of Environment and Conservation was established to maintain compatibility with federal radiation regulations in all of these exposure areas. This is accomplished by dividing the areas into two types of space: controlled and uncontrolled [11]. A controlled area is a limited-access area in which the occupational exposure of personnel is under the supervision of an individual in charge of the radiation protection. Workers in these areas are trained specifically in radiation work and safety. Uncontrolled areas are all other spaces in the facility. These areas are not access controlled, and the dose delivered to individuals in these areas is not monitored on an individual basis. Regulations followed by the state of Tennessee, as an agreement state, are taken from NCRP recommendations. The recommendation for controlled areas is 0.1 mSv/week or 5 mSv/year in dose equivalent [11]. The recommendation for uncontrolled areas is 0.02 mSv/week or 1 mSv/year in dose equivalent. It has been shown that the reduction from a yearly dose to an average weekly dose over the course of 50 weeks is an acceptable simplification. However, any further reduction in the time cannot be made by dividing the dose into the smaller time interval [11]. The NRC instead specifies that the dose equivalent in any unrestricted area from external sources may not exceed 0.02 mSv in any one hour. Other dose limits exist for special situation and should be considered, as these are situations that may occur on campus. Measures are to be taken to ensure that the radiation dose received by a fetus/embryo over the entire course of a declared pregnancy dose not exceed 0.5 mSv. Furthermore, the occupational dose limits for minors are 10 percent of the dose limits (annual) for adult workers. All of these regulations are validated through measurement of calculation that the individual likely to receive the highest dose by operation does not receive a total effective dose equivalent exceeding the annual dose limit.

#### **4. PRELIMINARY DESIGN FEATURES**

All current facilities have radiation shielding in place; these and many others represent the various methods that can be put into place to limit the dose equivalent. A few of the most common are discussed below. One important characteristic of the shielding is its material. Cost and convenience are the driving factors when considering shielding materials. Construction materials such as concrete, steel and earth are the most commonly used materials for shielding applications. Neutron shielding requires materials that contain hydrogen, while x-ray shielding materials need high mass and atomic number. Materials that cater to one or both of these requirements are concrete, lead, steel, polyethylene, earth, and wood. However, all of these materials have pros and cons.

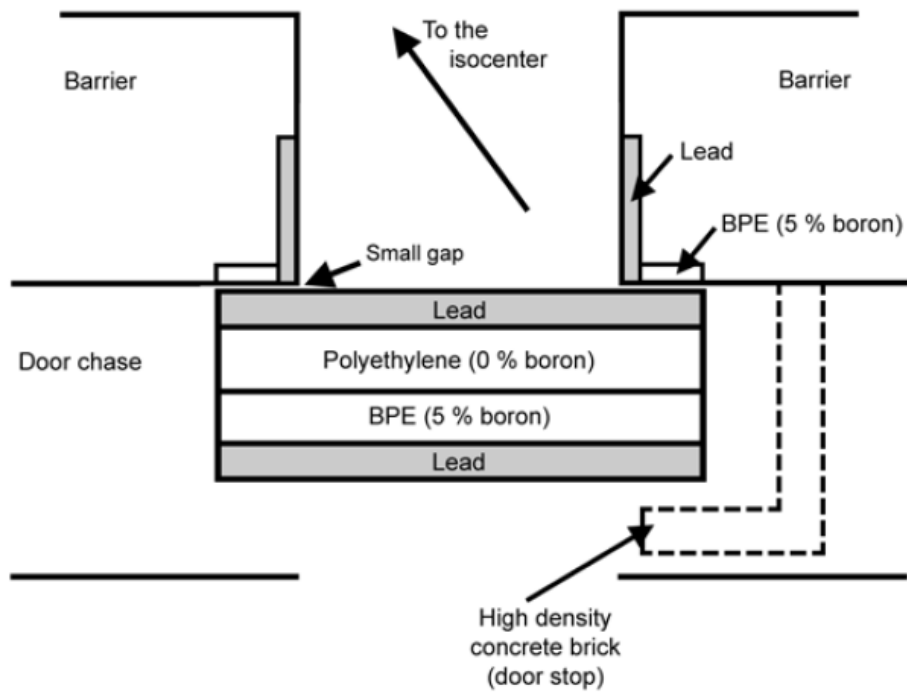
Concrete has many advantages and is the most commonly used shielding material [11]. It can be poured in almost any configuration; it also provides reasonable x-ray shielding and structural strength. Concrete is a relatively good neutron shield as well, and is inexpensive compared to other structural materials. Heavy concrete can replace lower density concretes to reduce the thickness required in concrete shields. By adding various higher density aggregates, the overall density of the concrete mixture increases, and thereby increases photon attenuation. Heavy concrete is not necessarily better for neutron shielding because the neutron shielding is reliant on the density of hydrogenous material and not the overall density of the mixture. Lead has a very high density, and is a fantastic photon shield. However, lead is not able to support its own weight, is nearly transparent to neutrons, and must also be enclosed because of its toxicity. Steel is not as dense as lead, but it is structurally sound and non-toxic. Polyethylene is perhaps the best neutron shielding material available. Polyethylene is most often used to

fill the voids where shielding has been removed (HVAC, wiring, etc.) or where weight or size of shielding is a factor (doors). Wood, water, and paraffin are other shielding materials commonly used.

The location, shape, and order of these materials determine the required thickness and effectiveness of the shielding. Beam stops, tapered barriers, directly shielded doors, and mazes are all physical features that comprise a complete shielding design. By definition, a beam stop is a slab of material that attenuates the primary beam by a factor of  $10^{-3}$  so that surfaces that would otherwise be primary barriers are made secondary barriers [11]. Beam stops can be built out of water, iron, concrete, graphite, or earth. However, few beam stops are installed in facilities today. A beam stop accounts for the difference in shielding required between primary and secondary shielding. Another way to selectively increase shielding is by tapering the wall and increasing the effective slant thickness. While this decreases the amount concrete needed, it may not decrease the price. The formwork is well over half of the total cost of pouring concrete, so it is often cheaper to use more concrete than to construct elaborate forms [11]. Concrete can be poured in modular, and possibly interlocking blocks that can be purchased and set up as needed.

Typically, the most complex portion of the shielding is the shielding required over and around the entrance. Door shielding by nature is complicated because access to the facility necessitates an opening in the shielding. The door must be comprised of shielding that is equivalent to the shielding that would be removed by the door opening. The door may not be placed in the primary barrier. This means that the door should be shielded for leakage and scattering radiation plus 1 half value layer (HVL) for conservatism. A HVL is the thickness of a given material required to reduce the radiation field quality to half of its original value. The additional HVL is required because the door is made of lead and steel laminate with the addition of borated polyethylene (BPE) if photo-neutrons are present and not made of concrete. The gamma rays produced from neutron capture in the door need additional shielding. These doors are very heavy, but there are practical limitations. A four foot wide swinging door can weigh up to 8,000 to 9,000 kg before the use of a motor is necessary to move the door open and closed. The shielding must be changed around the opening as well as in the opening. Gamma rays passing at an angle through the door and the concrete barrier are only partially shielded.

The issue of partially shielded radiation is fixed by constructing a door that is larger than the opening or by inserting a shielded door stop as shown in Fig. 1.



**Fig. 1. Directly shielded door: large overlap alternative [11]**

A well-designed maze reduces the amount of shielding required for a specific dose limit outside of the barrier walls and doorway. Mazes are additional wall structures strategically placed within the accelerator room to attenuate radiation in a specific direction. The optimum place to insert a maze is between the accelerator and the accelerator room doorway, and this placement of the maze essentially creates an additional hallway between the entrance to the accelerator room and the accelerator itself. Incorporating a maze into the design of the accelerator facility allows the shielding of the entrance door to be less extensive. The use of a maze eliminates the need for a motorized shielding door, and is the more economical option when considering entrance or doorway shielding. An example maze can be seen with maze parameters in Fig. 2.

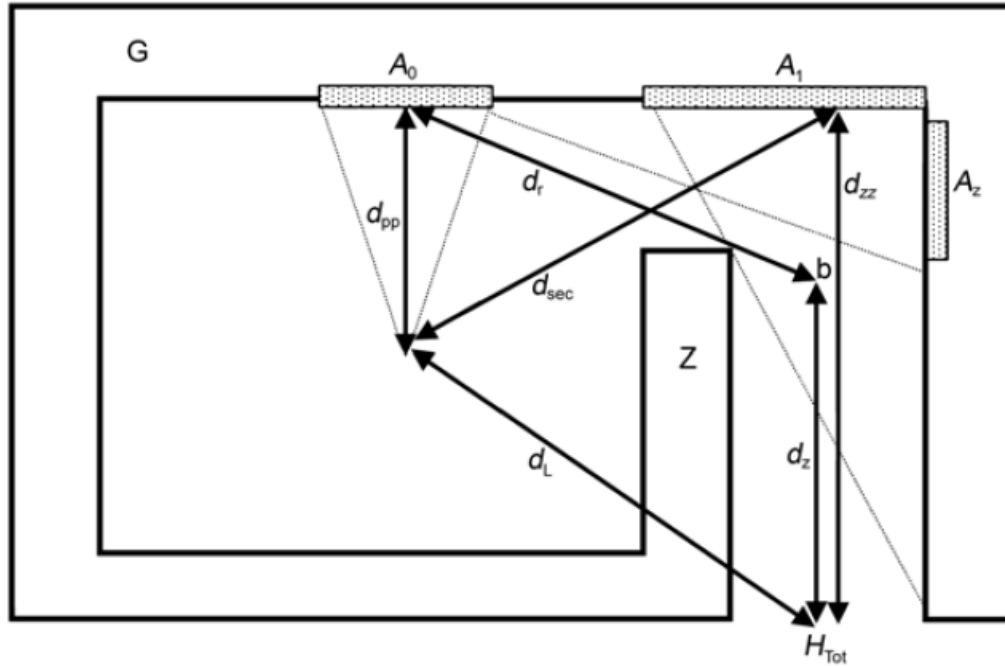
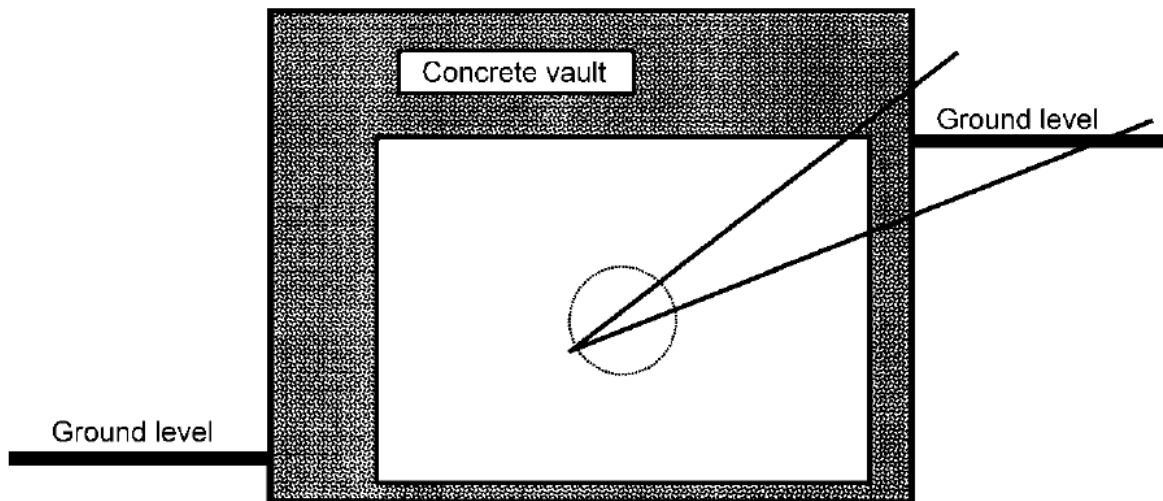


Fig. 2. Maze design [11]

An alternative to many of the previously discussed shielding features is to place the facility underground where the surrounding earth becomes the shielding. Earth is not a well-defined material and its density can considerably vary. However, it has been shown that in most cases, its composition is comparable enough to concrete that it can be treated as a concrete equivalent with lower density [11]. Constructing the facility entirely or partially underground can be the most cost effective form of shielding. The principle constituent of dry earth is silicon dioxide, making it an effective shielding material for both photons and neutrons. Neutron shielding is enhanced in wet earth compared to dry earth, and photon attenuation increases if the earth is compressed. If the earth is compressed, the shield is also free from cracks and voids that would allow neutron streaming. Furthermore, during the construction of a large accelerator facility, earth will be readily available and costs can be minimized by placing the accelerator room at an optimum depth such that the volume of earth excavated equals that required for overhead shielding [9].

Fig. 3 shows a diagram comparing a facility wall shielded with concrete on the left and shielded by being placed underground on the right. “When the vault is below ground level, the projection of the beam through the wall at the level of the ground surface shall be given special consideration to ensure that the upper edge of the largest projected beam will be far enough below the surface to prevent significant scattered radiation from reaching the surface,” [11]. As shown in Fig. 18 and in Appendix B, this is later addressed with an additional six feet of earth surrounding the first floor of the facility. The other rooms in the building will sit on top of the elevated ground surface.



**Fig. 3. Comparison of concrete to earth shielding [11]**

## **5. PRELIMINARY TASKS**

The NCRP reports 144 and 151 outline an approved procedure for the calculation of primary and secondary barrier thicknesses, as well as providing guidance on other shielding features [9, 11]. These practices have been accepted on the federal level and applied as the industry standard, but will again be validated in this report through simulation.

Because of the decision to calculate the shielding using two different and independent methods, there are many steps to the shielding analysis process. Consequently, there is a need to organize and assign these tasks across the members of the accelerator team. One visual method to presenting this information is a Gantt chart. Gantt charts are bar graph timelines that can be color-coded to signify “who is doing what.” The vertical axis is a series of tasks to be completed. The horizontal axis is time. For any section where a bar appears, a task is to take place at that time by the person denoted according to bar color. The team has constructed the following Gantt chart for the remainder of the project timeline.

The Gantt chart was setup with several factors in mind. After the first few meetings a group dynamic developed and personal preferences appeared. When possible, each member of the team was given tasks throughout the project according to his or her skill set or choice. The overall order of tasks to be completed was another major influence to the team assignments. The team worked to spread out the assignments among the members in such a way that everyone was nearly always working on some component of the project without ever working on too many things at once. The last feature of the chart is the checking function performed at the end of each task. In the final week of every task performed, the color of the corresponding task bar changes from the member of the team primarily responsible for the task to another member of team. In order for everything to be verified by at least two persons, a second team member was assigned to review the work of the first team member. The preliminary Gantt chart is found in Appendix A.

Due to design changes and other delays, the original Gantt chart was not followed directly, and the updated Gantt chart is also given in Appendix A.

## 6. NCRP ACCELERATOR FACILITY SHIELDING CALCULATION

### 6.1 OVERVIEW OF NCRP METHOD

The NCRP has published a series of hand calculation methods in Reports No. 144 and No. 151 [9, 11]. These methods have been validated and applied in shielding design reports that are currently in use [3, 4]. A radiation facility that utilizes the shielding goals (P) listed above would produce effective dose values (E) lower than the recommendations for effective dose. This is the result of the conservatively safe nature of the shielding design methodology recommended by the NCRP. The following list of conservative factors will give a “significant measure of assurance to the shielding designer that the actual dose equivalent transmitted through a barrier designed with the methodology given will be much less than the applicable shielding design goal,” [11].

- Attenuation of the primary beam by the target is ignored.
- The calculations of recommended barrier thickness often assume perpendicular incidence.
- Leakage radiation from radiotherapy equipment is assumed to be at the maximum value recommended by IEC.
- The recommended occupancy factors for uncontrolled areas are conservatively high.
- The particles that make up the primary beam are assumed to reach the barrier at their maximum energy.

In general, the shielding calculated by this method is divided into two categories: primary and secondary barriers. Primary barriers are designed to contain the useful beam; secondary barriers only receive secondary radiations in the form of accelerator head leakage and scattered radiation [11]. The size of the primary barrier is defined by “the area on the outer surface of the shield that is illuminated by the useful bremsstrahlung beam with the beam collimator fully opened,” [9]. A barrier schematic is given in Fig. 4. According to Varian, the area the beam can be contained in a 30° cone such that the projection of the beam on the primary barrier can be found as shown in Fig. 5 [12]. An adequate margin should be provided around the area for conservatism.

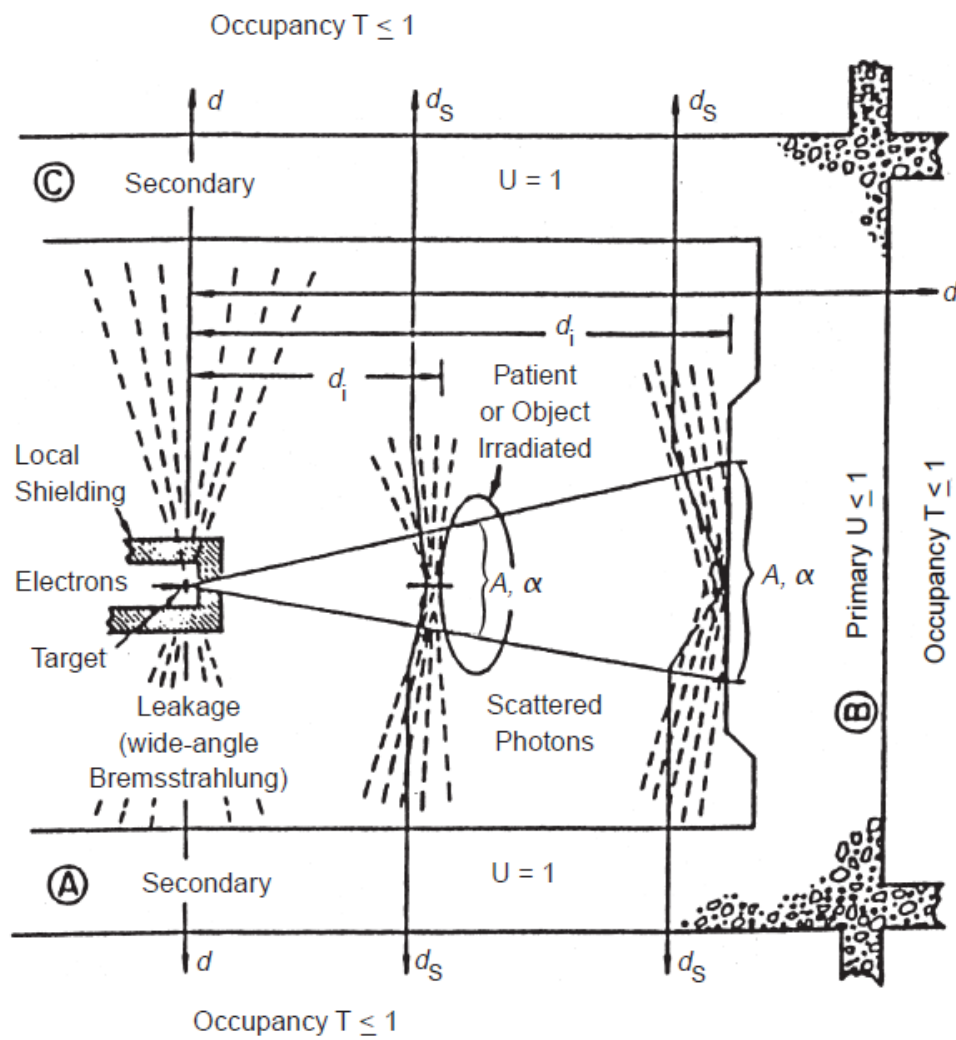


Fig. 4. Barrier definition schematic [9]

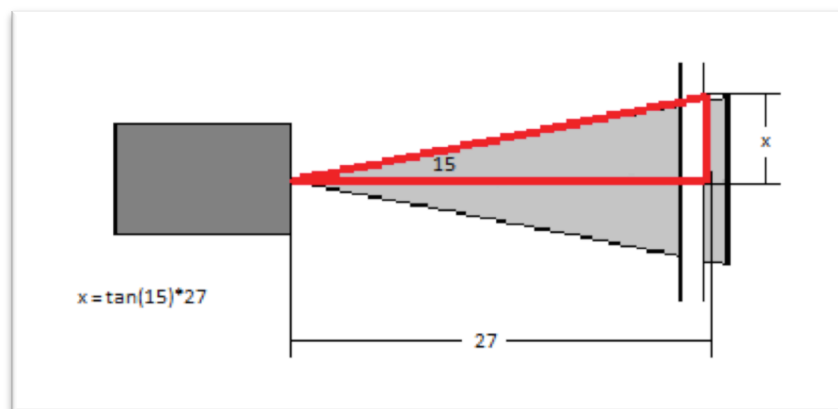


Fig. 5. Primary barrier area calculation

The following methods represent the shielding thickness required for the shielding of bremsstrahlung photons. For energies below 30 MV, it has been found that “photon radiation controls the shielding requirements,” [9]. If adequate shielding is provided for the primary and secondary photon radiation, the direct and scattered electrons will be completely stopped and need not be considered further for radiation protection [9]. Furthermore, neutrons are created through photonuclear reactions starting at energies around 10 MeV. The giant resonance region between 13 and 23 MeV is then the most important source of neutrons for electron accelerators operating below 100 MV. The production of photo-neutrons is nearly isotropic. However, the energy spectrum and intensity of the neutrons in the primary photon beam is unaltered whereas the neutrons outside of the beam are somewhat slowed down by the accelerator head shielding [11]. Regardless, the accompanying neutrons will also be adequately shielded [9].

Accelerators that operate at energies greater than 10 MV expose personnel to radionuclides created by neutron and gamma-ray activation of materials within the radiation area. However, research in this area has shown that at energies comparable to the accelerator under analysis (22 MV) the radiation doses due to materials activation were reduced to background levels within two days of irradiation [11].

## 6.2 BARRIER CALCULATIONS: 22 MV ACCELERATOR

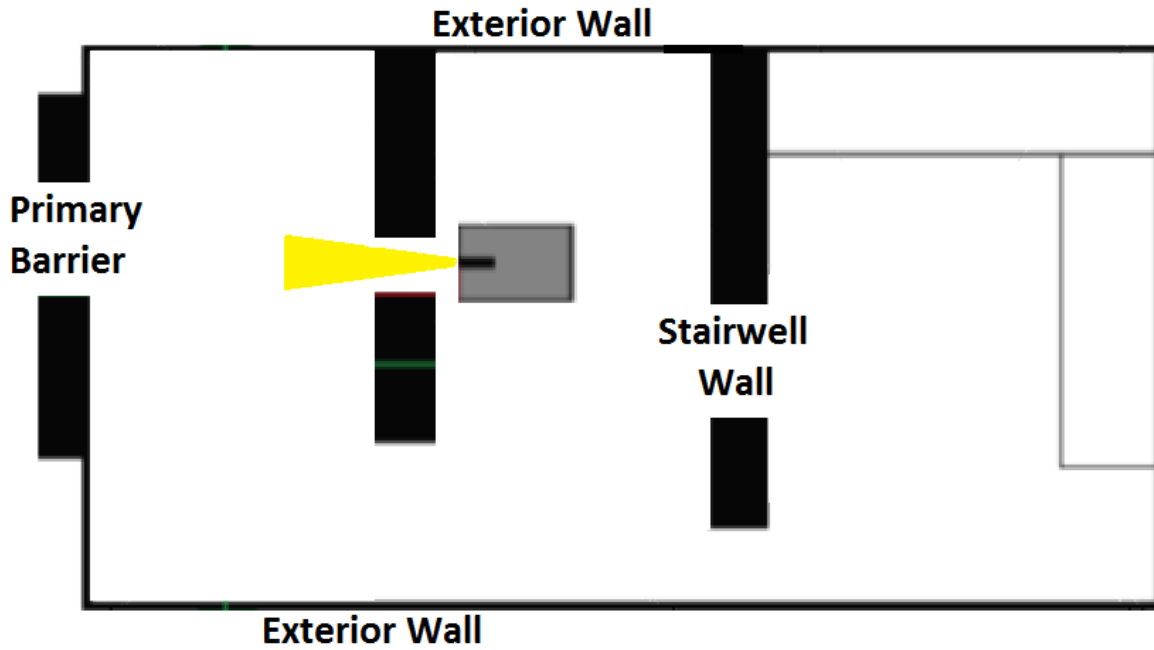
The primary barrier is designed to attenuate the photon beam from the accelerator unit directly incident on the barrier, and thus attenuating the dose equivalent beyond the barrier. The first step to finding the thickness required for the primary barrier is to find the transmission factor  $B_{pri}$ . The number of tenth value layers of any shielding material is found by the manipulation of the transmission factor. A tenth value layer (TVL) is the thickness of a given material required to reduce the radiation field quality to a tenth of its original value. TVLs are specific to material and particle energy and type and have been reported by Varian as summarized in Appendix D [13]. The relevant equations are given in Fig. 6. Appendix D also contains a detailed explanation of the barrier calculations, assumptions, and variables used to achieve a final primary barrier thickness of 2.0 ft. of concrete and 6.12 ft. of earth. These barriers are labeled for clarity in Fig. 7. Preliminary floorplan The factors affecting this result include type of occupants in the area opposite the barrier, occupancy rate, distance between the accelerator primary barrier, the stationary nature of the accelerator setup, and the workload of the accelerator.

$$B_{pri} = \frac{Pd_{pri}^2}{WUT}$$

$$n = -\log (B_{pri})$$

$$t_{pri} = TVL_1 + (n - 1)TVL_e$$

**Fig. 6. Primary barrier equations from NCRP method [11]**



**Fig. 7. Preliminary floorplan**

Secondary barriers are designed to attenuate the wide-angle bremsstrahlung radiation, called leakage, the scattered radiation, and any secondary particles produced through the interaction of materials in the room. In the case of secondary barriers, the required shielding thicknesses for each source of radiation is calculated using the equations found in Fig. 8; Table 1 is list of the relevant variables. The barrier thickness is then equal to the higher of the two values with an additional HVL of thickness. The results of these calculations, also outlined in Appendix D, are a ceiling/floor barrier above the radiation facility of 4.42 ft. of concrete, a dividing stairwell wall of 2.87 ft., and exterior walls requiring 6.0 ft. of earth surrounding. In addition to the previously mentioned contributing factors, the beam area incident on the target, reflective properties of the target, and distance from the target to the barrier in question effect the outcome of these results.

$$\begin{aligned}
 B_s &= \frac{P}{\alpha AWT} d_{sca}^2 d_{sec}^2 & B_l &= \frac{Pd^2}{10^{-3}WT} \\
 n &= -\log(B_s) & n &= -\log(B_l) \\
 t_s &= TVL_1 + (n - 1)TVL_e & t_l &= TVL_1 + (n - 1)TVL_e
 \end{aligned}$$

**Fig. 8. Secondary barrier equations from NCRP method [11]**

**Table 1: NCRP Method Variable Definitions**

---

|                    |                                                                                 |
|--------------------|---------------------------------------------------------------------------------|
| B:                 | Transmission factor from primary, scattered, or leakage barrier calculation     |
| P:                 | Shielding goal in mSv/wk                                                        |
| W:                 | Accelerator workload in Gy/wk                                                   |
| U:                 | Use factor as a fraction of the time spent with beam in a given orientation     |
| T:                 | Occupancy factor as a fraction of the time the area to be protected is occupied |
| $d_{pri}$ :        | Distance between target and primary barrier in meters                           |
| $d_{sec}$ :        | Distance between target and closest point to be protected for a given barrier   |
| $d_{sca}$ :        | Distance between accelerator and target in meters                               |
| d:                 | Distance between accelerator and closest point to be protected                  |
| $\alpha$ :         | The differential dose albedo (reflection coefficient)                           |
| A:                 | The area of the beam at the scattering surface in meters squared                |
| TVL <sub>1</sub> : | The first tenth value layer thickness in centimeters                            |
| TVL <sub>c</sub> : | All subsequent TVL thicknesses in centimeters                                   |

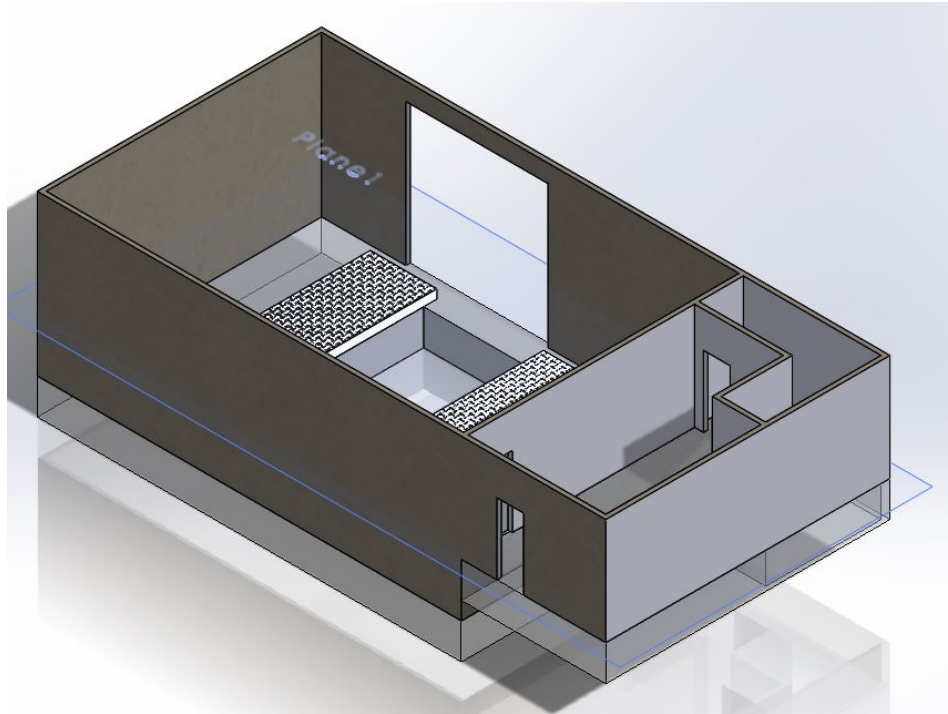
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Although the floor of the facility is technically a secondary barrier as well, it has been shown in other analyses that a floor at grade level requires no additional shielding and is limited only by structural constraints [14].

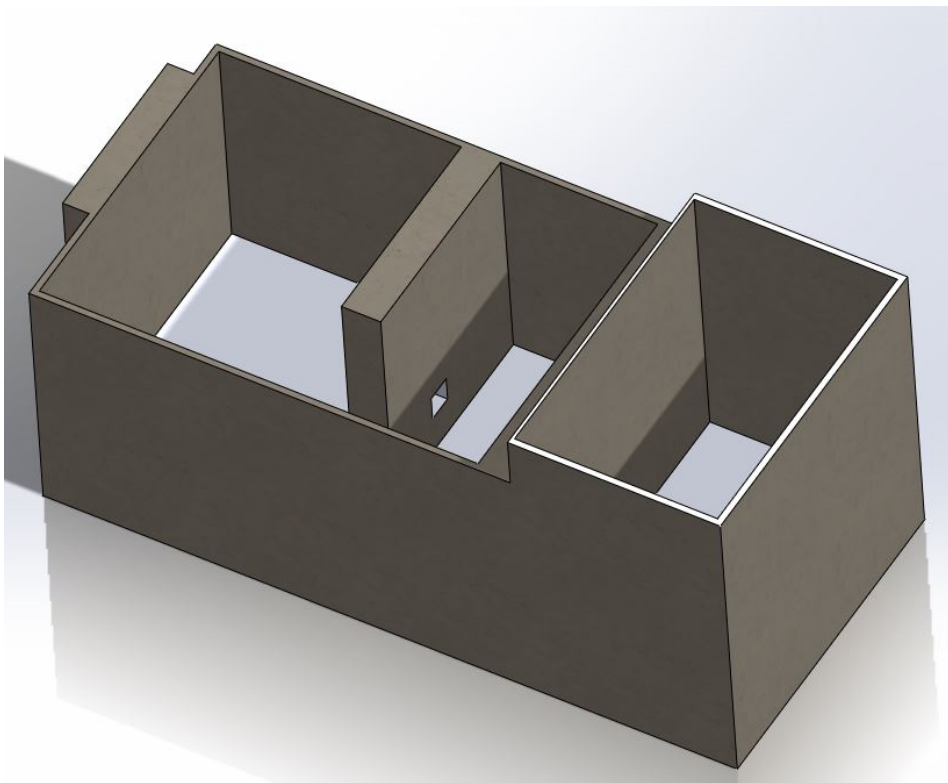
### 6.3 METHOD RESULTS: PRELIMINARY FLOORPLAN

The key design feature of the facility's shielding suggested by this report is the two-floor layout. This setup allows for the accelerator to be operated in the basement level of the facility, and provides an entire floor for storage and staging of the experiments. The two-floor layout, while more extensive to build than a single-floor facility, offers many other advantages. The proposed layout eliminates the need for any directly shielded doors and limits the number of access controlled doors to one. Both directly shielded doors and access control doors complicate the design and operation of a facility as well as increase the facility costs. The personnel access door is located within the control room such that those operating the accelerator can monitor access in and out of the radiation area. The experimental setup is brought back and forth from the basement to the staging area on the first floor with a custom lift (See Section 8.2).

The remainder of the facility details is given graphically in Fig. 9 and Fig. 10. The first floor includes outside traffic access via a 16 ft. x 14 ft. door. Other features to note are the portable shielding slabs for the covering of the lift opening and the control room on the right side of the Fig. 9. The control room is situated 6 ft. above the staging area. This results in 18 ft. ceilings in the staging room and 12 ft. ceilings in the control room. The tall rooms and outdoor access are features required for the transport and setup of cargo container active interrogation as described in Section 2.2. The basement floor directly beneath the first floor is setup to house the accelerator. All the walls of the basement are shielding barriers (Shown Fig. 7). The inside wall separates the accelerator from the target and contains a 2ft. x 2 ft. opening for the placement of various collimating devices. The room on the far right side of Fig. 10 is the stairwell area for personnel access. Detailed drawings of the facility are located in Appendix B.



**Fig. 9. First floor floorplan**



**Fig. 10. Basement floor floorplan**

## 7. MCNP ACCELERATOR FACILITY SIMULATION

### 7.1 OVERVIEW OF THE MONTE CARLO N-PARTICLE CODE

MCNP (Monte Carlo N-Particle Code) is a general-purpose Monte Carlo code developed at Los Alamos National Laboratory (LANL) that is used to track various particle types through a general geometry over a broad range of energies [15]. MCNP6 is the culmination of efforts by the MCNP5 and MCNPX teams at LANL where MCNP6 combines the two codes and provides many additional features that extend beyond simply merging the two codes [15]. Some highlights of the new features in MCNP6 are the updates to some of the high-energy physics models (CEM, INCL, etc.), the ability to create and import unstructured meshes, and the ability to set heavy-ion isotopes as source particles [15]. Historically, MCNP has been heavily used in the nuclear engineering industry for particle transport in a wide range of applications; from critical assemblies to accelerator facilities, and has been well validated by many in the industry [16].

### 7.2 22 MV ACCELERATOR SOURCE DEVELOPMENT

### 7.3 METHOD

The model of the accelerator source was constructed for the purpose of simulating a 22 MV x-ray linear accelerator in the most general sense. Generality was required due to the lack of details of the construction of the accelerator from the manufacturer. The accelerator source model conservatively simulates the source particles generated by a 22 MV x-ray linear accelerator. The accelerator source model consists of a uniform beam of 22 MeV electrons with a radius of 0.25 cm irradiating a 0.2 cm thick tungsten cylinder with a radius perpendicular to the beam of 10 cm. Void space, two nearly infinite planes that are both parallel with each other and the faces of the tungsten cylinder, and a 6000 cm radius sphere make up the rest of the model. These parallel planes are located 10 cm away from the ends of the tungsten cylinder. The geometry of the accelerator source development can be seen in Fig. 11.

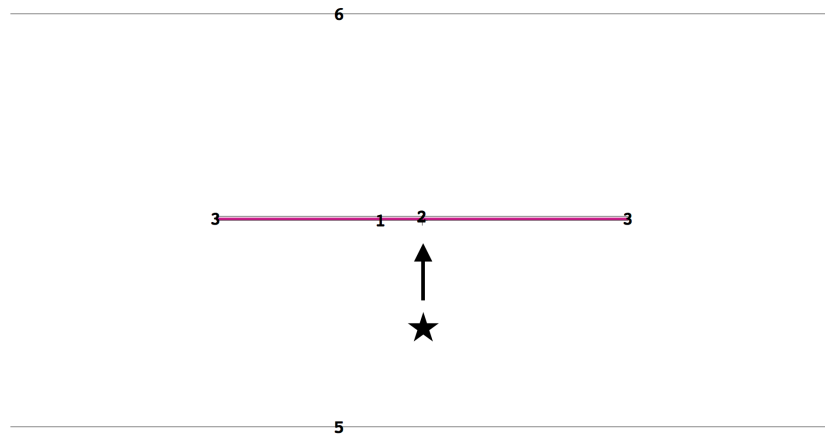
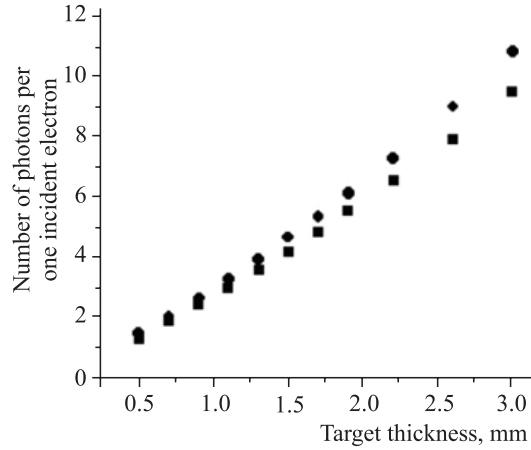


Fig. 11. Geometry of accelerator source term in the XZ plane

The star and arrow in Fig. 11 nominally demonstrate where the 22 MeV electrons originated and the direction of the electron beam. In Fig. 11, the two parallel planes are labeled 5 and 6. The larger sphere could not be pictured in Fig. 11 due to its size.

A 2.0 mm thickness for the tungsten target was chosen due to the average product yield of bremsstrahlung photons per incident electron, shown in Fig. 12 [17]. The photon yield from a 2.0 mm thick tungsten target provides the most general scenario for the accelerator model.



**Fig. 12.** Product yield of bremsstrahlung photons of a 100 MeV (squares) and 200 MeV (circles) electron beams incident on varying thicknesses of tungsten [17]

Natural tungsten is used in the model due to the unknown manufacturer specifics. Fig. 13 shows the composition of tungsten used in the model.

| Abundance,<br>%          |
|--------------------------|
| $^{186}\text{W}$ (28.60) |
| $^{184}\text{W}$ (30.70) |
| $^{183}\text{W}$ (14.28) |
| $^{182}\text{W}$ (26.30) |
| $^{180}\text{W}$ (0.12)  |

**Fig. 13.** Natural abundance of tungsten [17]

Energy limits for the physics cards were set to a maximum energy of 22 MeV for the electrons, neutrons, and photons. The default values were used for the physics cards with the addition of the photonuclear physics option enabled.

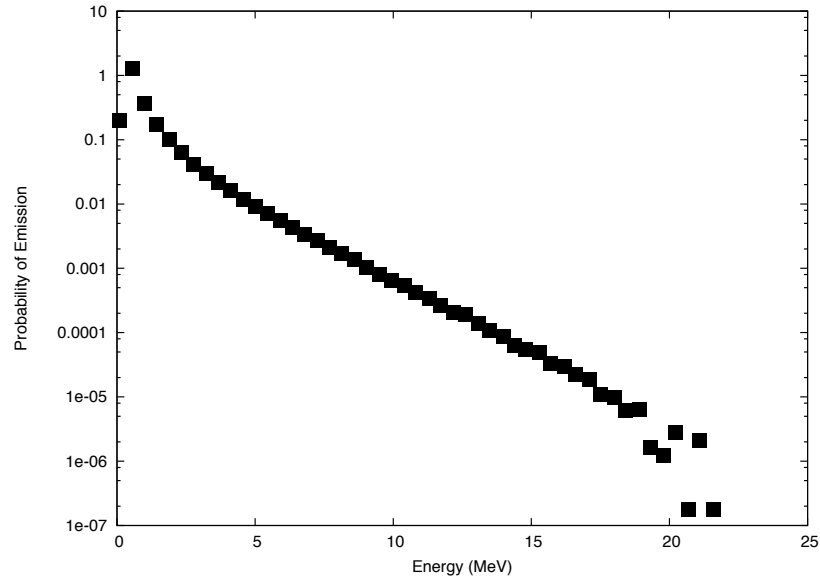
Tallies were constructed on the two parallel planes (shown in Fig. 11) in order to acquire the energy and angular dependence of the neutrons and photons generated by the electron beam incident on the tungsten target. In order to acquire the angular dependence of the source particles, the source particles were tallied with 1-degree bins from 0 to 180 degrees with respect to the angle of the source particle's intersection with either of the parallel planes. Plane 5 in Fig. 11 was tallied from 90 to 180 degrees and Plane 6 was tallied from 0 to 90 degrees while setting 0 degrees to be parallel with the incident electron beam headed in the original direction as the electron beam. Once the source particles cross one of the parallel planes, it is assumed that it will not intersect again due to the void space in the geometry. In each of the 1-degree bins, the energies of the source particles are then binned to 0.44 MeV bins from 0 to 22.0 MeV, resulting in 50 energy bins.

The accelerator source model was executed on 9 nodes with 72 CPUs consisting of a mixture of 2.80 GHz Intel Core i7 860 processors with 8 GB RAM and 3.40 GHz Intel Core i7 2600 processors with 16 GB RAM [18]. The model was executed with MCNP6 and 8 TASKS per node.

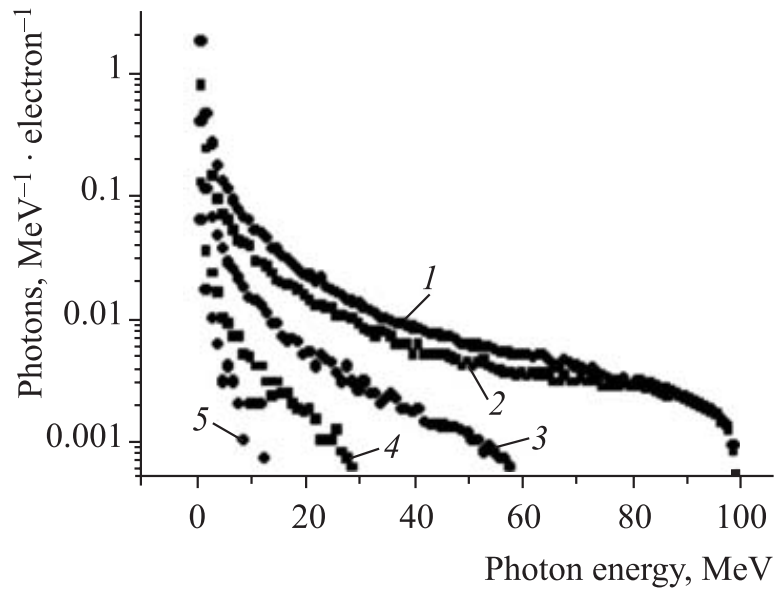
With the angular and energy dependence of the source particles tallied, a PERL script was developed to process the MCTAL file generated by the accelerator source, and compile a point source for use in further simulations. The PERL script reads the MCTAL file and produces an output file consisting of a SDEF card with all of the supporting source distributions.

### 7.3.1 Results

Fig. 14 shows the probability of emission for the photon source with respect to energy in the 0 to 5 degrees range with respect to the direction of the nominal photon beam. The shape of Fig. 14 compares well with the 0 to 5 degree spectrum shown in Fig. 15 in terms of the shape. However, the main difference between Fig. 14 and Fig. 15 are the range of data and this can be attributed to comparing the photon fluence and probability of emission, and how Fig. 15 shows the spectrum for a 100 MeV electron beam and Fig. 14 shows the spectrum for a 22 MeV electron beam.



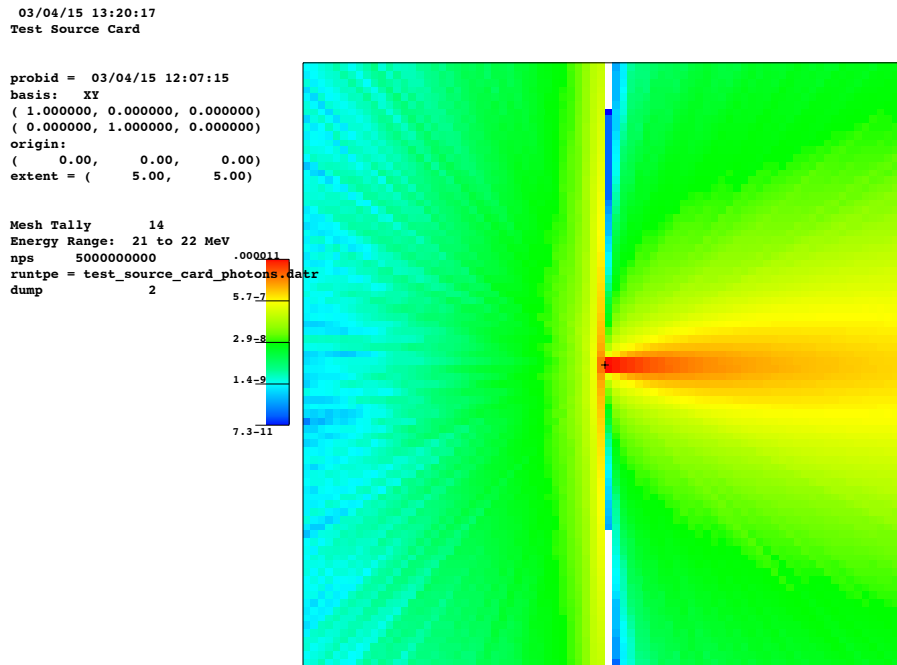
**Fig. 14. Photon source distribution from 0 to 5 degrees**



**Fig. 15. Bremsstrahlung emission at different angles for the case of using the 100 MeV electron beam: 1 – total spectrum; 2 – from 0 to 5 degrees; 3 – from 5 to 10 degrees; 4 – from 10 to 15 degrees; 5 from 15 to 20 degrees [17]**

Fig. 16 shows the XY spatial distribution with Z at the origin of 21 to 22 MeV photons emitted from the accelerator source with the figure of merit being photon fluence per source photon emitted. Fig. 16 has discrepancies towards the center of the figure, and these discrepancies can be attributed to the planes in the source development geometry (Fig. 11) not being completely infinite. There is a strong bias in the positive X direction showing the “photon beam.”

Fig. 17 shows the XY spatial distribution with Z at the origin of 13 to 14 MeV neutrons emitted from the accelerator source with the figure of merit being neutron fluence per source neutron emitted. Much like Fig. 16, Fig. 17 has discrepancies towards the center of the figure, and these discrepancies can be attributed to the planes in the source development geometry (Fig. 11) not being completely infinite. Other than the center discrepancies, Fig. 17 shows an isotropic distribution of neutron fluence.



**Fig. 16. 21 to 22 MeV photon source spatial distribution in the XY plane (photon fluence per source photon)**

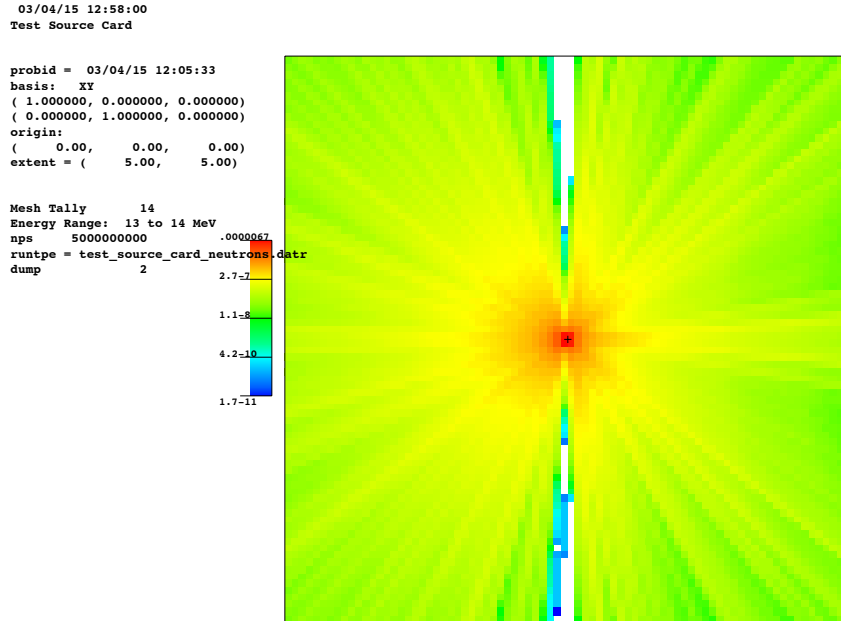


Fig. 17. 13 to 14 MeV neutron spatial source distribution in the XY plane

## 7.4 FULL ACCELERATOR FACILITY MODEL

### 7.4.1 MCNP Geometry

The CAD model that is described in other sections of this report is modeled in Constructive Solid Geometry (CSG) as the input geometry for simulations using MCNP6. Fig. 18 shows an overview of the accelerator facility in the XZ plane. The colors in Fig. 18 show the various materials that were used in the model: air as yellow, concrete as blue, wood as red, earth as green, etc.

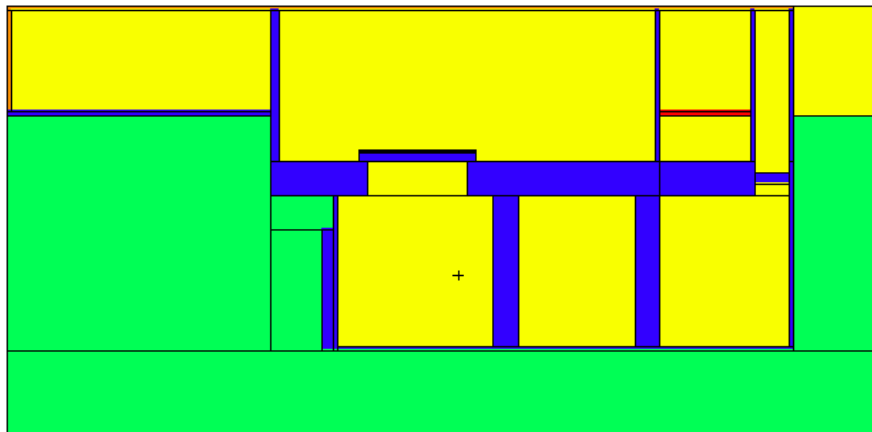
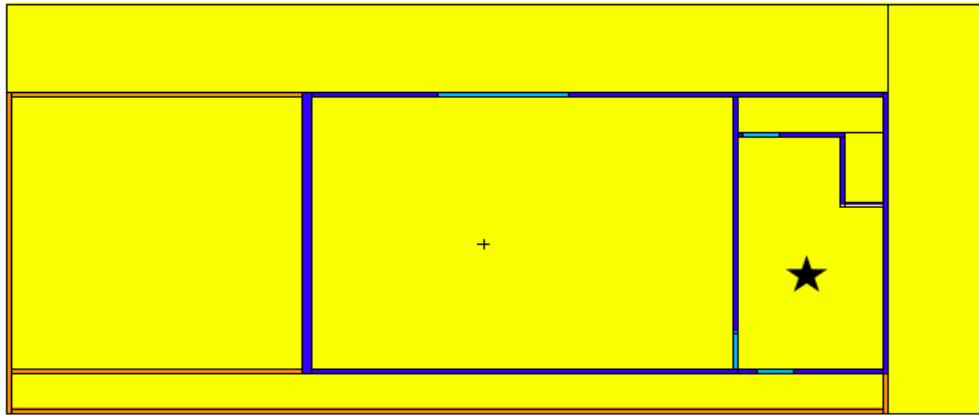


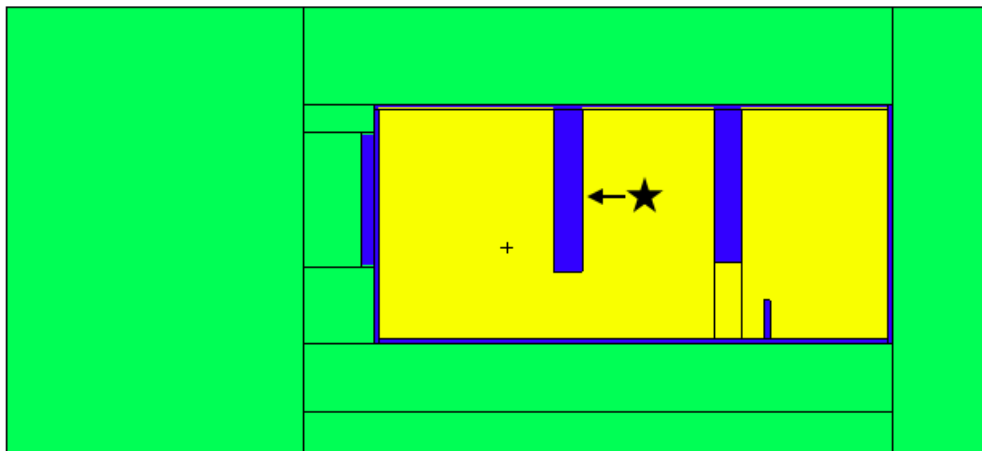
Fig. 18. Accelerator facility MCNP geometry overview XZ plane

Fig. 19 shows a top view of the first floor of the accelerator facility MCNP geometry. The operator room is shown in Fig. 19 with a star inside the room and the stairwell is also depicted in the upper right corner of the operator room. In the concrete (blue) walls shown in Fig. 19, the rolling steel door is depicted as the dark green rectangle in the center of the figure, and the large room in the center is where the loading zone would be for the facility. The leftmost room in Fig. 19 is the critical facility room and the long room at the bottom of the figure is the hallway connecting the critical facility, accelerator facility, and the SKIF room.

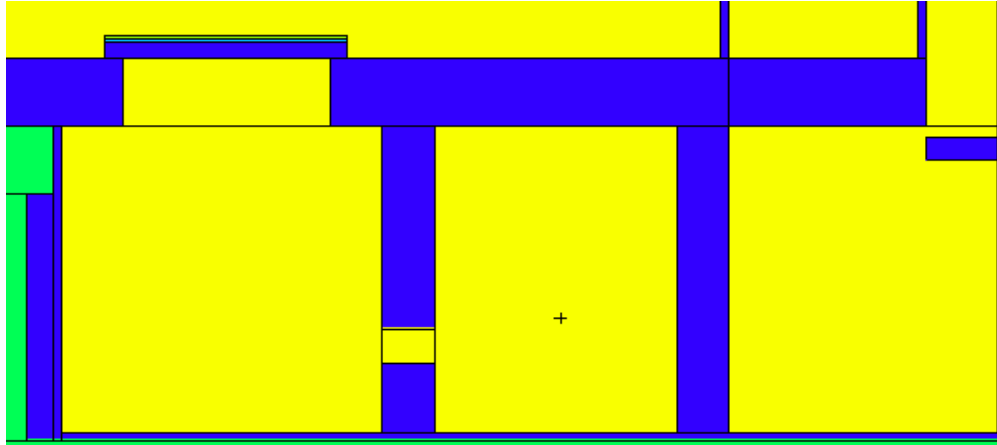


**Fig. 19. Accelerator facility first floor MCNP geometry XY plane**

Fig. 20 shows the top view of the basement where the accelerator is placed at the starred position and pointed in the direction of the arrow. There is a hole in the centermost wall, shown in the XZ cross-section in Fig. 21 that allows collimating apertures to be added to the beam to allow for beam shaping. Fig. 20 shows the primary barrier on the left along with a considerable amount of earth behind the barrier. Another attribute of the basement shown in Fig. 20 is that there is an air void where the backscattering wall ends.



**Fig. 20. Accelerator facility basement MCNP geometry XY plane**



**Fig. 21. Accelerator facility basement MCNP geometry showing collimating hole XZ plane**

#### **7.4.2 Computation of MCNP Model**

The accelerator facility MCNP model was executed on 6 nodes using OpenMPI with 48 CPUs consisting of a mixture of 2.80 GHz Intel Core i7 860 processors with 8 GB RAM and 3.40 GHz Intel Core i7 2600 processors with 16 GB RAM [18]. The model was executed with MCNP6 using 48 MPI tasks.

A series of rectangular tally meshes were employed to tally the neutron and photon dose rate in the overall model with a resolution of 10 cm, the operator room with 4 cm resolution, and the movable sliding door with 2 cm resolution. Dose rate conversion factors from ICRP-21 were intrinsically applied to the tallied flux to produce dose rate values in the MCTAL and MDATA files in the units of Sieverts per hour [19].

#### **7.4.3 Post-processing Data Analysis**

The MDATA file from the MCNP run of the full accelerator facility model containing the mesh tally dose rate information was post-processed with multiple scripts to produce a VTK file for visualizing the data [20]. The ReadMData MATLAB script package was used to convert the binary MDATA file into a MATLAB structure [21, 22]. The mesh tally MATLAB data structure was then converted to a VTK file format using a MATLAB script from the Wave Analysis for Fatigue and Oceanography (WAFO) toolbox for visualization using VisIt [23, 24].

#### **7.4.4 Dose Rate Map Results**

Fig. 22 shows the dose rate of the slice of the accelerator facility on the XZ plane centered at the accelerator source. The view shown in Fig. 22 is the same as the view in Fig. 18, including all of the earth, first floor, basement, classroom (top far left), control room (top far right) and the stairway. Fig. 22 shows that the dose rate  $0.1 \text{ mSv wk}^{-1}$  and higher is contained in the basement level of the facility;

making the basement a controlled area by the standards set by the state of Tennessee. By successfully containing the dose rate of  $0.1 \text{ mSv wk}^{-1}$  to the basement, the first floor in its entirety is able to be an uncontrolled area ( $0.02 \text{ mSv wk}^{-1}$  or lower). Fig. 22 also shows that the barriers incorporated into the floorplan design adequately shield the outside of the facility from the radiation produced by the accelerator. The dose rates in the control room are well below the uncontrolled area limits. Fig. 23 shows the relative error associated with the dose rate shown in Fig. 22. The relative errors are high on the first level because of the low dose rates. However, the areas in the model that would be classified as a controlled area have relative errors of less than 9.0 percent.

Fig. 24 shows the dose rate map of the accelerator facility on the XY plane centered at the accelerator source and shows the same view as Fig. 20; complete with the basement floor and the surrounding earth. Fig. 24 shows the X-ray beam passing through the hole in the collimating wall in the direction towards the primary barrier, and that the basement wall design adequately shields the outside of the facility. Fig. 25 shows the relative error associated with the dose rates in Fig. 24. The relative errors are high where the dose rates are low, and the controlled areas in the basement are below 9 percent error.

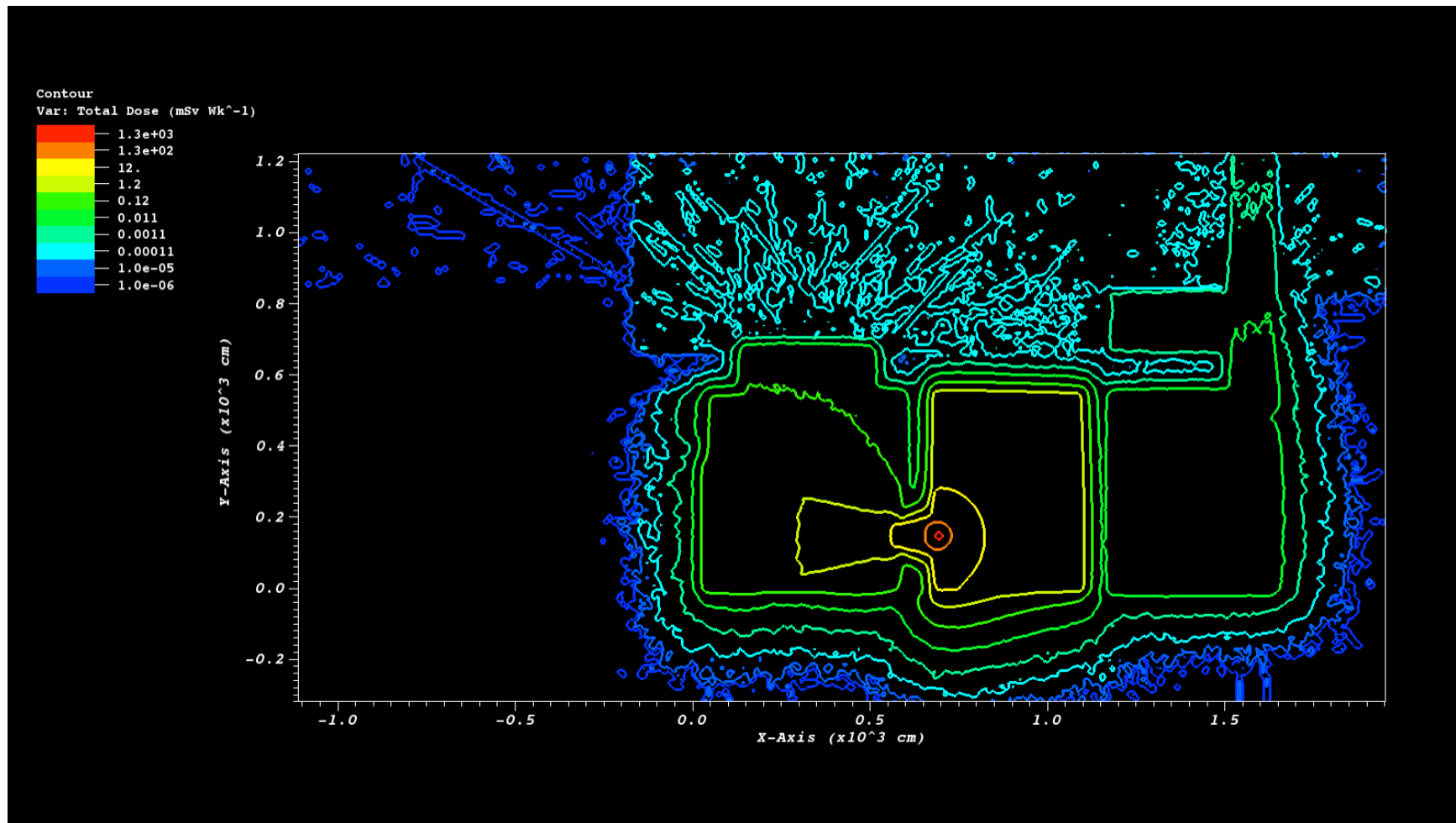


Fig. 22. Accelerator facility overview total dose rate map XZ plane

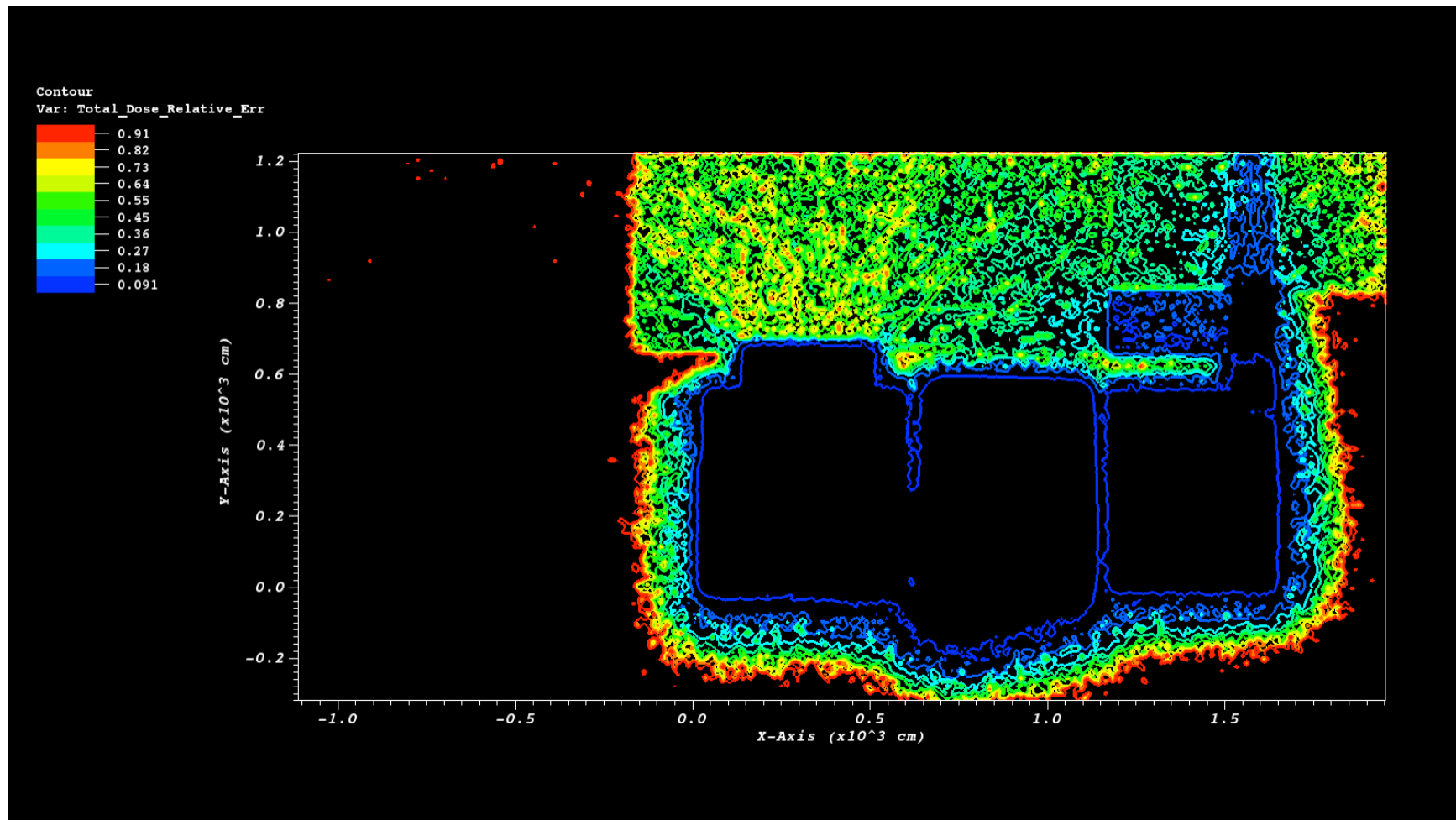


Fig. 23. Accelerator facility overview total dose rate map relative error XZ plane

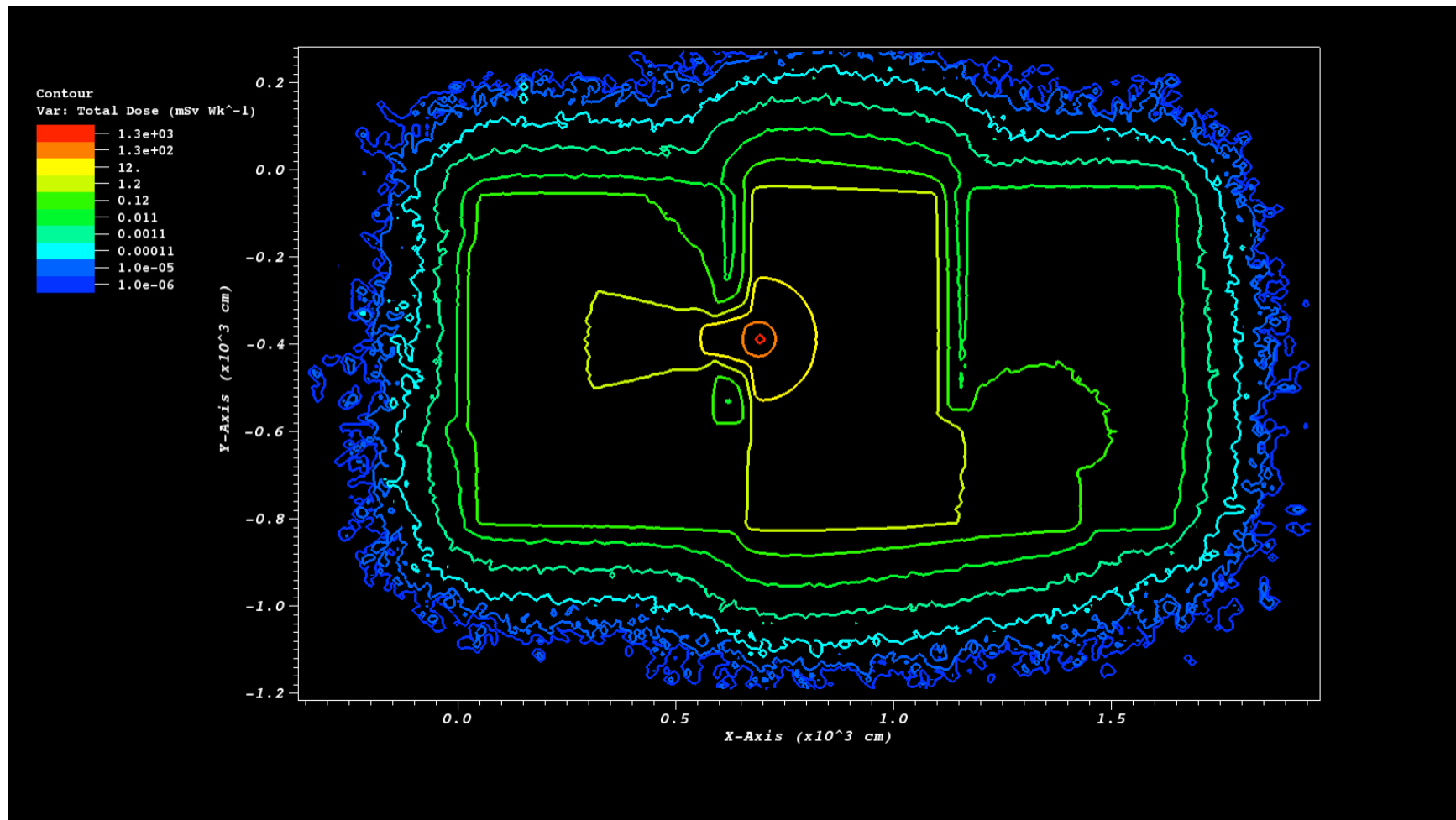


Fig. 24. Accelerator facility overview total dose rate map XY plane

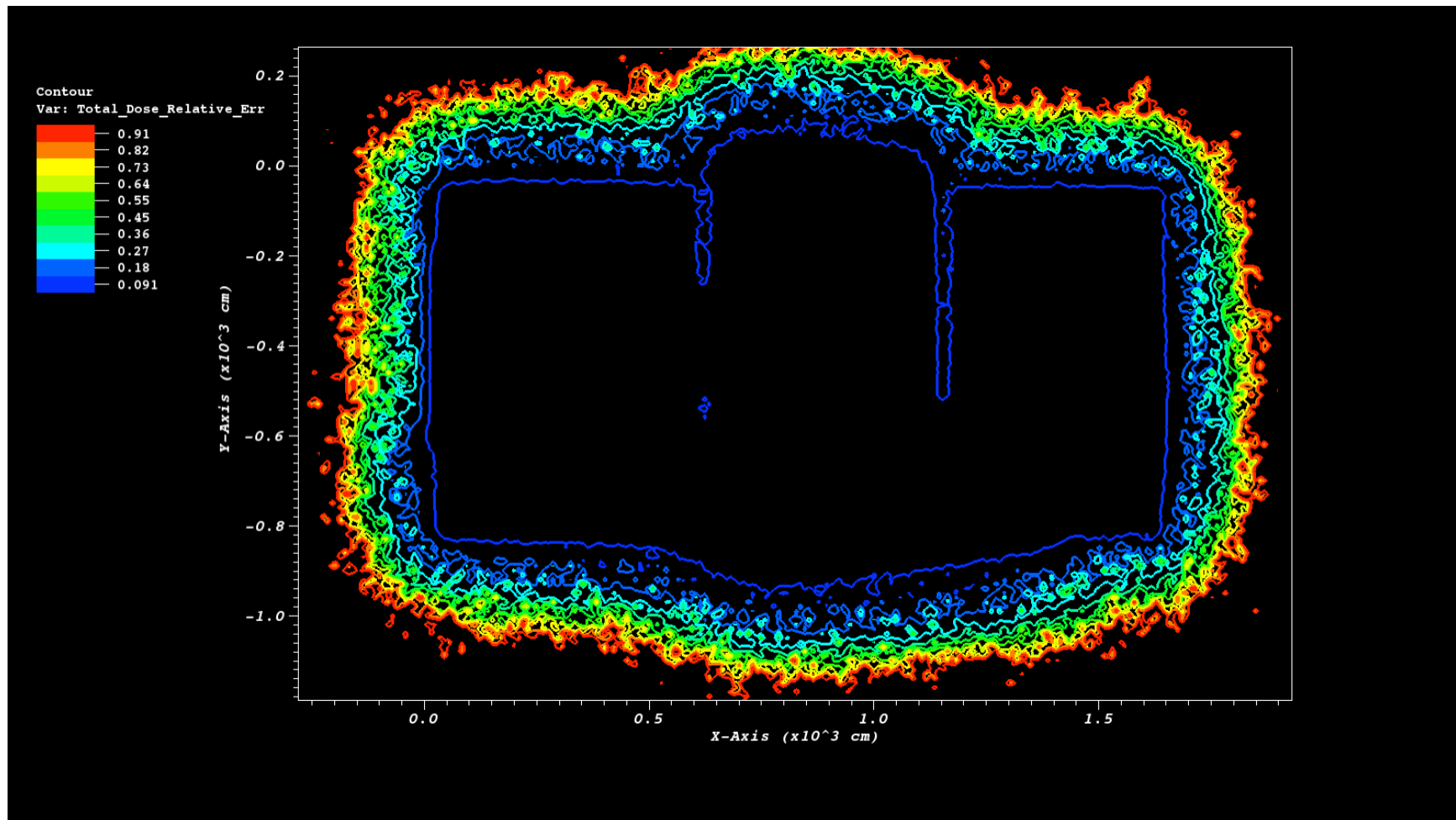
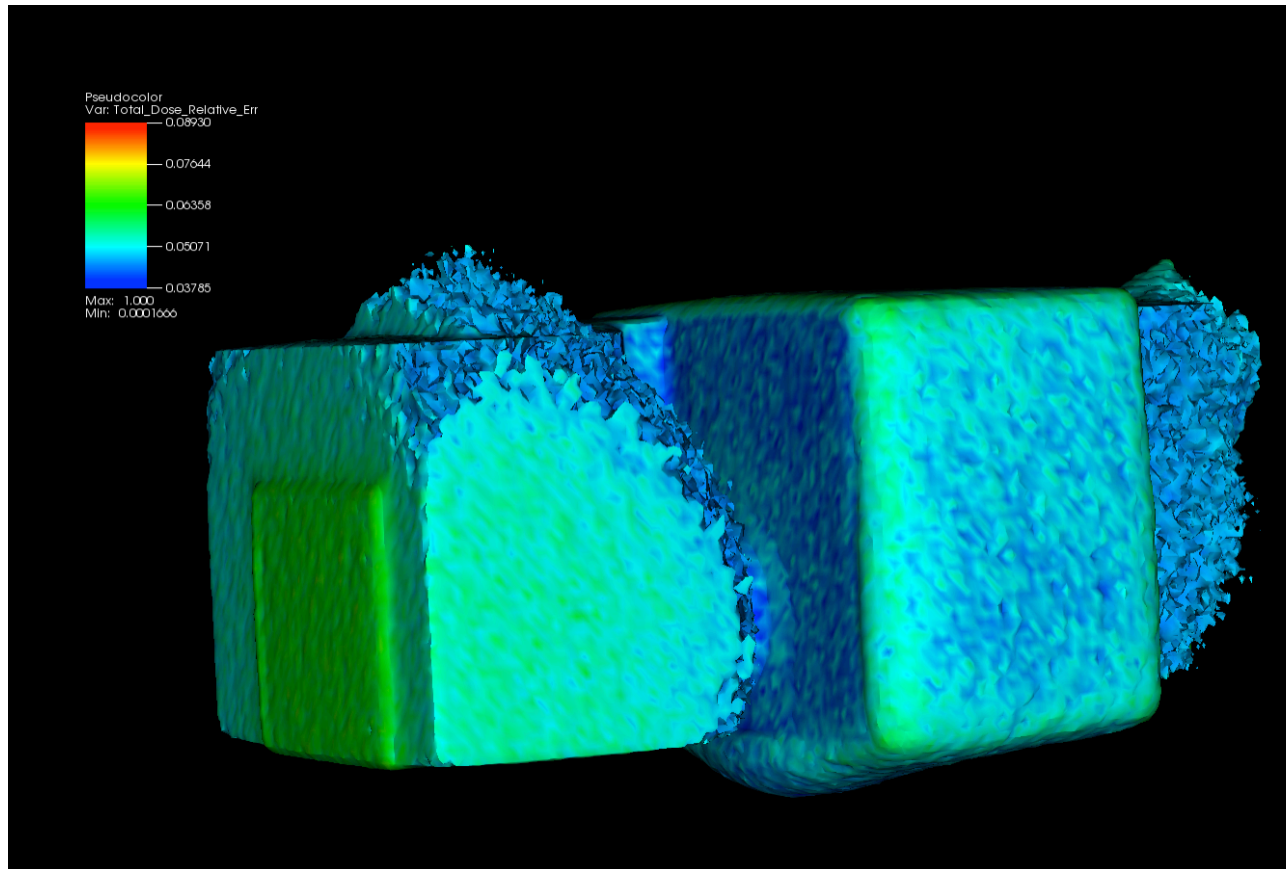
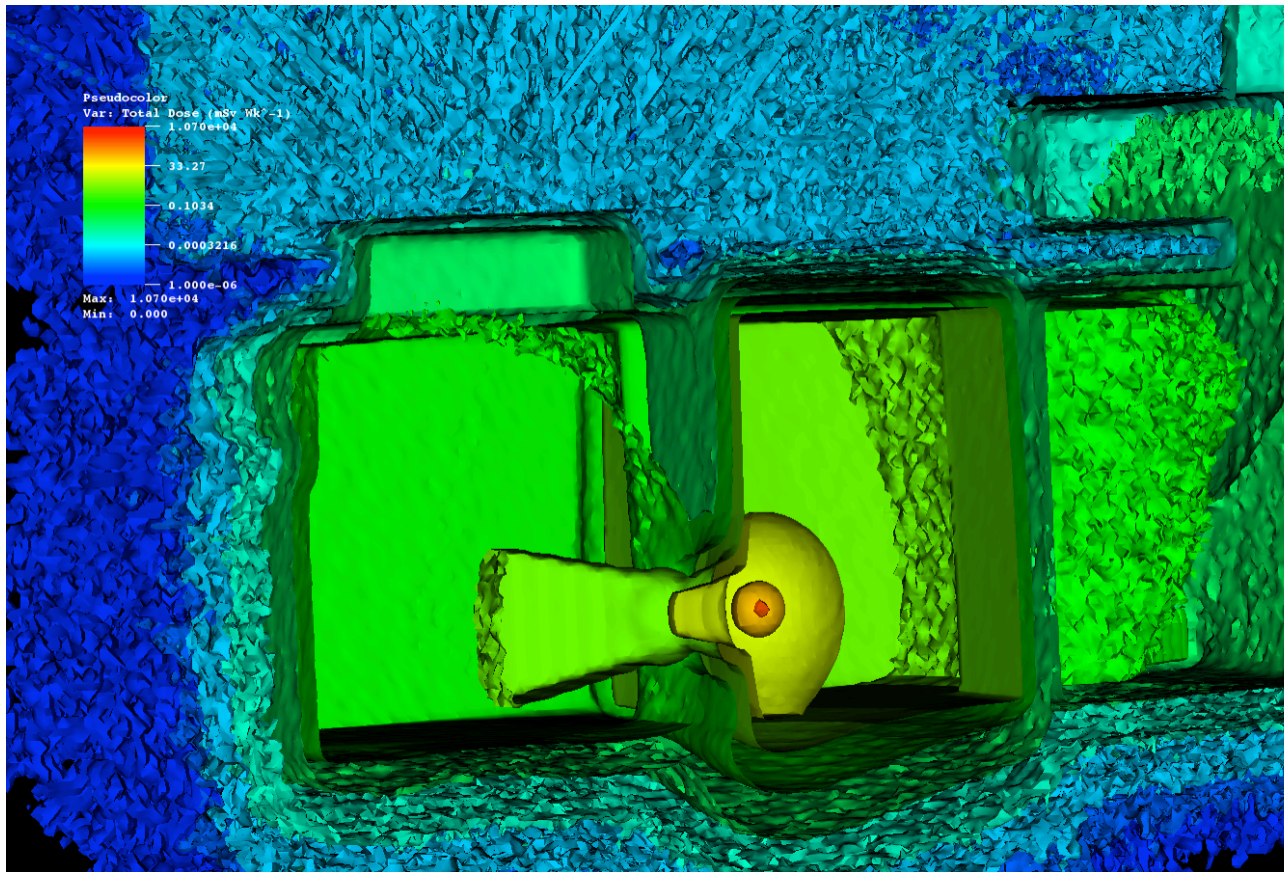


Fig. 25. Accelerator facility overview total dose rate map relative error XY plane

Fig. 26 shows a  $0.1 \text{ mSv wk}^{-1}$  isosurface of the entire accelerator facility model and Fig. 27 gives a reference to the orientation of Fig. 26 with the primary barrier on the left and the staircase on the far right. All of the  $0.1 \text{ mSv wk}^{-1}$  isosurface is located in the basement of the facility, whereas the entire first floor of the facility could be considered an uncontrolled area. The coloring of Fig. 26 shows the level of uncertainty in the isosurface, but the highest uncertainty of 9 percent is not pictured in Fig. 26 and is located in the bottom corner of the stairwell.



**Fig. 26.       $0.1 \text{ mSv}$  per week in the accelerator facility model with relative error coloring**



**Fig. 27. Orientation reference for Fig. 26 showing the total dose rate map**

## **8. FACILITY QUOTES CONTACTS AND COST ANALYSIS**

### **8.1 ACCESS DOOR QUOTE**

Due to the potential size of the sample to be imaged by the accelerator, a relatively large access door was needed to allow these samples to be off-loaded and transported to the irradiation area. The requirements set for the door were that it needed to be 14 feet wide and 16 feet high. A quote for a rolling access door was acquired from the Dynaco Armor Door Company and can be found in Appendix E. This quote details the final cost analysis of the access door with a final cost of \$19,000.00.

### **8.2 PHANTOM LIFT QUOTE**

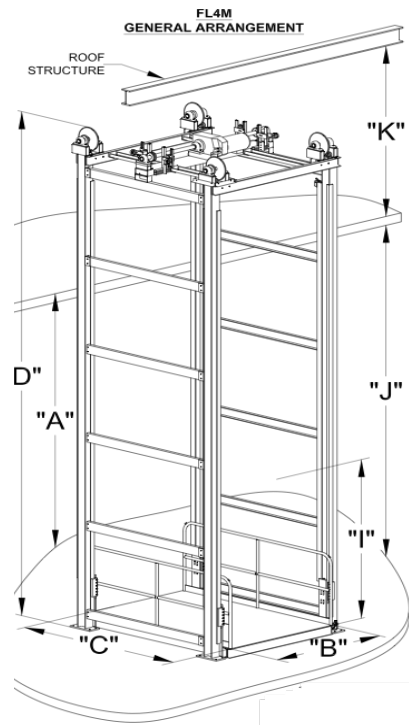
Several challenges were presented with a two level design, one being how the material or object being irradiated would be transported down into the basement where experiments will take place. A decision was made to have a mechanically operated freight lift installed granting the ability to transport heavy objects from the first floor to the basement. Since the lift will need to raise and lower heavy objects a large distance, the selection process required months of searching.

While the lift selection process was underway, much discussion with NE faculty was taking place to determine what type of material was going to be used during experimental activities. Several ideas were

expressed which ultimately resulted in the need for a lift that could lift and lower diverse sized objects. As a group we decided to look for a lift that possessed the ability to lift and lower a maximum capacity of 10,000 pounds, a height of 22 feet. After much research for a lift that would meet our experimental requirements was performed, a company based out of Folsom, California was chosen [25].

The lift company, American Custom Lift, is located in Folsom, California which is approximately 20 miles northeast of Sacramento, California. ACL was founded in 1998 and specialized in parallelogram lifts as well as column lifts [25]. Since then ACL has diversified towards designing parking, vehicle, four-post, trailer, material handling equipment, and custom lifts. ACL has experience in providing custom lift solutions, service and installation for government agencies, major automobile manufactures, and other industries such as aerospace, food and drug stores, museums, paper mills, steel mills, and many more.

The lift that was chosen for experimental use is a mechanical operated freight lift that is capable of lifting 10,000 pounds, with a maximum vertical travel of 22 inches. The travel speed of the lift is approximately 25 feet per minute. Due to the lifting capacity and the traveling speed ability, the quote for the lift itself was \$48,268.50. The quote does not include taxes, duties, freight installation (electrical or mechanical), and unloading fees. A drawing of the lift is shown in Fig. 28. The quote acquired from ACL can be found in Appendix E.



**Fig. 28. Phantom lift schematic [25]**

In regards to the platform size and design, ACL will provide a platform that is 12 feet in width and 12 feet in length. The material of the platform itself is made up of a smooth steel plate. Safety handrails will be installed on the platform, which are 4 feet high and provides secondary fall protection to the object being transported. A high kick that is 4 feet will also be installed on inaccessible sides with a safety snap chain across operating sides to accommodate a z-style loading pattern.

When the lift is being operated, safety is the highest priority. In order to provide workers and operators a safe work environment, backup safety systems were an important piece during the lift

selection process. The lift that has been chosen will be installed with numerous safety features such as an overload or jam protection mechanism, a slack chain safety stop, four safety-locking cams for free-fall arrest that will initiate during an unlikely event of a chain failure, automatic carriage-jam sensing and protection, high tension rollers for smooth platform travel, and many more. All of the safety systems that will be available are guaranteed to provide a reliable and safe work environment.

### 8.3 LAND EXCAVATION QUOTE

In the early stages of constructing the building, the area of interest must be cleared and leveled. Several steps must be performed before building foundations can be placed and the lay of concrete can begin. Before construction of the accelerator facility can begin, costs such as direct labor, planning, excavating equipment, debris disposal, etc. need to be determined. Using an online source that produces an approximate quote for land excavation cost based on your area, a quote of \$328,706.26 was determined [26]. The quote was based on an area of interest of 3,433 cubic yards, which is just for the LINAC room dimensions. A breakdown of the costs, along with what is and is not included in the quote, are given in Table 2 and Table 3. The quote can be found in Appendix E.

| Table 2: Cost to Excavate Land [26]                                                                                                                                                                   |               |              |              |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|--------------|--------------|
|                                                                                                                                                                                                       | Quantity(hrs) | Low          | High         |
| <b>Land Excavation Labor</b><br>Direct labor expenses to excavate land, which includes planning, job equipment and material acquisition, area preparation, setup and cleanup                          | 4,784.6       | \$125,508.70 | \$300,944.61 |
| <b>Land Excavation Debris Disposal Costs</b><br>Costs to load and haul away old materials and installation waste.                                                                                     | -             | \$109,491.42 | \$121,077.79 |
| <b>Land Excavation Equipment Allowance</b><br>Job related costs of specialty equipment used for job quality and efficiency, including: skid loader with excavation   demolition   loading attachment. | -             | \$161.25     | \$228.75     |
| <b>Totals - Cost to Excavate Land - 3433 cubic yards</b>                                                                                                                                              | -             | \$235,161.36 | \$422,251.15 |
| <b>Average Cost Per Cubic Yard</b>                                                                                                                                                                    | -             | \$68.50      | \$123.00     |
| <b>Total Average For All Costs</b>                                                                                                                                                                    | -             | \$328,706.26 |              |

**Table 3: Land Excavation Quote Include vs. Not Included**

| Included                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Not Included                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"><li>• Costs for local material / equipment delivery to and service provider transportation to and from the job site.</li><li>• Costs to prepare the worksite for Land Excavation, including costs to protect existing structure(s), finishes, materials and components.</li><li>• Costs for job cleanup and debris removal at project completion.</li><li>• Labor setup time, mobilization time and minimum hourly charges that are commonly included for small Land Excavation jobs.</li></ul> | <ul style="list-style-type: none"><li>• Unless explicitly noted in the description of work, this Land Excavation estimate does NOT include costs for relocating, repairing, modifying or enhancing existing structural, HVAC, electrical, ventilation and plumbing systems - or bringing those systems into compliance with current building codes.</li><li>• General contractor overhead and markup for organizing and supervising the Land Excavation. Add 11% to 19% to the total cost above if a general contractor will supervise this project.</li><li>• Sales tax on materials and supplies.</li><li>• Permit or inspection fees (or portion thereof) required by your local building department for your overall project.</li></ul> |

## 8.4 CONCRETE QUOTE

Shielding radiation that could potentially cause harm to the public is undoubtedly the most important objective of this project. The selection process for which contractor to hire during the lay of concrete is very important towards having a strong and safe foundation. When laying concrete for a structure that will house a radiological area, the process becomes more significant than laying for your standard office or business building. Crack deficiency reduction also becomes a high priority due to the potential for particle release. In efforts to accomplish all of these objectives, we have chosen a company located in Monroe, OH to perform our construction needs [27].

Baker Concrete Construction is a company based out of Monroe, OH [27]. Ranked among *Engineering News Record's* Top 3 specialty concrete contractors for the past 20 years, Baker is built on the principles of excellence, hard work, service, and integrity [27]. Baker has experience in every type of concrete project imaginable, from commercial office buildings to heavy industrial facilities such as nuclear power plants. Currently, Baker Concrete is the lead concrete contractor for the new Proton Therapy Center being constructed in Knoxville, TN, which was a large attraction.

After contacting Baker Concrete and requesting a quote in March, we received a quote for \$575,000. The quote includes the installation and stripping of formwork, installation of reinforcing steel, installation of embedded metals (materials are furnished by external vendor), and the placement and curing of the concrete. Most projects involving linear accelerator rooms, according to Baker Construction, range from \$550,000 to \$600,000. After researching past quotes for similar projects, this quote was near average and determined accurate. The quote can be found in Appendix E.

## 8.5 LICENSING QUOTE

Licensing is a state-regulated means of registering radiation producing sources and equipment. It is a mandatory step in getting an accelerator facility operational. Licensing is directly dependent on the accelerator and its uses. The Tennessee Division of Radiological Health (DRH) requires that accelerators used for the production of x-rays greater than 0.9 MeV register as Class VII equipment. Equipment of this

type requires \$2,600 per tube per year for licensing and an additional \$375 per MeV upon initial installation [28].

## **9. ACCELERATOR FACILITY FUTURE WORK**

### **9.1 ENVIRONMENTAL IMPACT OF FACILITY**

The effects of a radiation facility on the surrounding environment are important to consider. “In order of importance, the magnitude of exposure from induced activity to the general public is (1) air-activation, (2) groundwater activation, and (3) activated accelerator components,” [9]. Shielding analysis of a facility first addresses the interaction between the beam radiation and the solid or liquid barrier. Before the beam arrives at this barrier, it has already traveled through several feet of air. Thorough analysis accounts for the beam’s interaction with the surround air because the air is activated by the radiation. The principal source of radioactivity in air is due to interactions between the primary and secondary particles and the constituent nuclei of the air. If air is confined in the accelerator facility, this activated air will be maintained in the room boundaries and no release of radioactivity to the general environment will occur. Under these circumstances, a rather high concentration of radioactive gases may accumulate. Before any personal are able to enter a room, the activated air should be purged or given enough time for the activated nuclei in the air to decay. Air activation is minimized if the air is circulated in the irradiation room through an HVAC system. In this case, the residence time of the air in the accelerator enclosure is short enough that high concentrations of radioactive gases with long half-lives is minimal [9]. Radionuclides with short half-lives decay significantly between discharge and the time it takes for the air to reach inhabited regions of space.

Radioactivity induced in the structural shields and accelerator components is relatively immobile. However, if the shield material is porous and is contiguous with the environment, such as earth, there is the potential for the migration of radioactivity. Radioactivity in groundwater is regulated in terms of activity per unit mass or volume [9]. To date, no significant contamination of groundwater systems due to accelerator operations has been observed [9]. It is also unlikely that food will be grown at accelerator sites in contaminated soil. Especially if measures are taken to prevent the disturbance of irradiated soil, radiation migration in this manner may also be ignored. A secondary source of airborne radioactivity is dust, which may be stirred up during maintenance on or around the activated accelerator components. “The experience at several large accelerators tend to show that the potential exposure to radioactive dust for maintenance crews working in the accelerator vault is negligible,” [9]. Further calculations suggest that inhalation and ingestion of accelerator-produced radionuclides common to accelerator facilities do not pose any serious potential for exposure [9].

### **9.2 FACILITY PROCEDURES AND RECOMMENDATIONS**

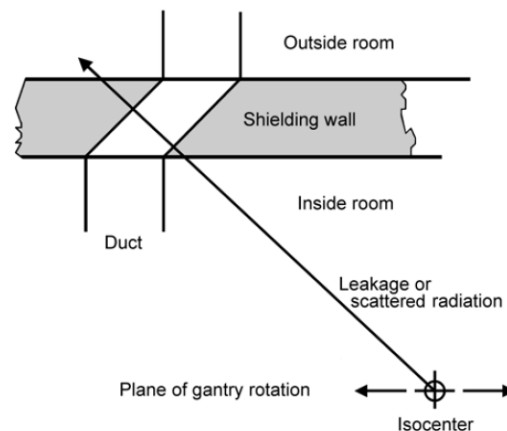
#### **9.2.1 Construction**

Before construction begins, a qualified radiological physicist must review final drawings for the accelerator facility. It is also important that authorities responsible for the facility review the assumptions used to calculate the required shielding features. If actual conditions are expected to vary from the assumptions used, the barriers must be recalculated [14]. Periodic inspections by a qualified expert should also be carried out throughout construction due to the sensitive nature of shielding and the possibility of radiation streaming. Shielding is comprised of subsequent changes that would ordinarily be allowable on construction sites. It has been shown that although the shielding characteristics of concrete are determined without rebar, the steel rebar and fiberglass form ties inserted for structural support do not negatively affect the shielding. If care is taken that the rebar does not run parallel to the useful beam, theoretical

examination shows that shielding is actually improved for both photons and neutrons [11]. The inspection should include an evaluation of the thickness and density of concrete, any neutron shielding materials, thickness of additional metal shielding, location of electrical cabling, and overall verification that the shielding design has been followed. A summary document of the findings is required and is to be forwarded to the owner of the facility, architectural firm, and governing regulatory agency [11]. Immediately after the accelerator facility has been made operational, a preliminary survey is carried out to ensure that radiation exposures do not exceed the shielding design goals. Special care should be taken to identify possible voids, cracks or other defects in the shielding. Measurements must encompass both controlled and uncontrolled areas. These are subsequent validation measurements are important because of the variability in concrete and construction [9]. For example, levels of induced activity and shielding attenuation are directly dependent on the composition of the concrete aggregates and the water content of concrete which may change with time and temperature [9]. The shielding design report, construction documents, post-construction survey reports, and any recent reevaluations of the shielding are all documents that are to be maintained on a permanent basis at the facility.

### 9.2.2 Additional Considerations

In addition to the shielding features discussed above, there are accelerator auxiliary systems, which are usually inserted into the shielding barriers. Often these systems have to completely pass through the shielding walls, and there are guidelines that address the removal of shielding for these purposes. Machine cables are usually placed at floor level or below the floor inside the accelerator room. The machine cables generally do not require additional shielding and may either angle up to the control area outside or pass directly outside. If, however, the conduits are larger than 2.5 cm in diameter, a lead casing should be considered in order to compensate for the missing concrete [11]. A larger portion of concrete has to be removed for the ductwork of the HVAC system. The ducts should be strategically placed so that the least amount of concrete is displaced in the direction of the radiation beam, and such that the direct radiation passing through the aperture is minimized as shown in **Error! Reference source not found.** Ducts should never be placed in



**Fig. 29. Duct schematic [11]**

the primary barrier. Furthermore, ducts that are placed as high as possible within the facility walls will reduce the amount of downward scattered radiation. Lead or BPE can be used around ducts to account for

the removal of concrete. If recesses are made in the walls for other reasons, they too should be backed by steel or lead to retain the recommended shielding value [14]. In general, the goal is to ensure that joints or openings passing through the barriers or systems embedded in the barriers do not compromise protection.

### **9.2.3 Radiation Safety**

It is the responsibility of the facility owner and operator to develop and maintain a thorough radiological safety program. This program should consist of at least the characterization of prompt and residual radiation fields created by the accelerator use, shielding of these sources, radiation monitoring, determination of short term and long term environmental impact, and operational radiation requirements. Other elements as identified by the NCRP are the application of ALARA, personnel orientation and training, control of radioactive waste, and radiation emergency planning. Access control is one proponent of safety that comes with additional regulations. By definition, the controlled areas within the facility are to only be accessible to those with radiation monitoring and prior training. Interlocks and warning lights shall be provided so that the radiation beam status is observable from the control console and the radiation area entrances. The action of opening the door to the radiation area shall be set up to shut off the accelerator beam line. Emergency off switches as well as instructions to follow in an emergency should also be posted in and outside the irradiation room [9]. The licensing of such a facility requires that the radiation levels within the irradiation room be below a maximum dose before personnel are able to enter the room that the door remained locked except for when access is approved and required, and that none of the required safety features prevent someone from exiting the room at any time [29]. The control console shall be located outside of the irradiation room and behind a secondary barrier. The entrance to the radiation area should be visible from the console, and mechanical or electrical means shall be provided to prevent the useful beam from striking the control room barrier [11]. The owner of the facility is further responsible for ensuring that only person competent to use radiation sources are allowed to do so. A radiation protection supervisor, established for each installation, is responsible for the monitoring of personnel in controlled areas who could receive more than one fourth of the maximum permissible dose [11].

### **9.2.4 Maintenance**

Maintenance work on radioactive accelerator components involving machining, soldering, or welding may produce radioactive particles or fumes, which can spread contamination and even result in the inhalation or ingestion of radioactivity. This is especially a concern in the decommissioning of the accelerator. "Experience at accelerators world-wide is that the largest cause of radiation exposure incurred by accelerator workers arises from operations on the maintenance of radioactive components, handling and moving of activated items, radiation surveys, and radioactive waste handling," [9]. It is important, that a proper amount of decay time is allowed between the activation of accelerator components and maintenance or decommissioning work is done.

It should be noted that additional floor space is allotted for overall facility flexibility. The space is programed for a 9 MV Varian Linatron and is large enough to accommodate bigger equipment to allow for future facility upgrades. All calculations are done expecting possible upgrades with a maximum of a 22 MV electron accelerator. The facility is therefore shielded adequately for accelerator energies at least as high as 22 MV. Care should be taken when either upgrades or maintenance tasks are performed.

### 9.3 ADDITIONAL TASKS

This report should serve as the preliminary facility shielding analysis. Although the suggested shielding and subsequent procedure suggestions are correct and valid, the MCNP results justify the continuation of shielding analysis (See Section 7). The results are well below the dose limitations (See Section 3.3), which leaves room for optimization. Further work could be done to complete the optimization in a few ways. First, it is possible that the current shielding could be reduced in thickness while maintaining a dose below dose regulations. The ceiling barrier would be of special interest in this type of optimization. Similarly, the ceiling barrier could be reduced in size and/or cost if research was done to change its material. It is possible that the optimal barrier is a combination of two or more materials.

Further research and calculations should be done to verify activation quantities within and around the facility. It has been shown that comparable facilities experience a level of activation below background. Furthermore, no cases of earth activation have been found in which the activation approaches a level above regulation [9, 11]. However, it is most appropriate to perform these calculations in direct regard to the accelerator facility specifications. Activation of the lift during accelerator operation is of most concern.

The NCRP methods could also be improved, possibly decreasing the thicknesses of the initial shielding suggestions. This could be done when more is known about the facility and its uses. For example, the variable  $W$ , which represents the workload of the accelerator in Gy/wk, is assumed to be 500Gy/wk [11]. If it can be reliably determined that the actual workload of the accelerator will be less than this, the shielding required to contain radiation doses will be smaller. Conservative factors such as the occupancy factor can also be decreased with proper validation.

If none of these methods adequately reduces the required shielding and shielding costs, the first floor of the facility can be readdressed as a controlled space. This will increase the allowable dose from 0.02 mSv/wk to 0.1 mSv/wk and thereby reduce the amount of shielding needed to achieve these goals. All of these options should be reviewed at length as part of a complete shielding analysis. .

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## **APPENDIX A: GANTT CHARTS**

In general, every member was responsible for a portion of the shielding research, design, or calculation. In other words, not everyone needs to know every detail of every decision, but instead, should be well equipped to manage one section of the project in extreme detail. This works out to the following divisions:

Christopher (Tyler) Crutcher:

Tyler was most responsible for the regulatory requirements and dose limitations of the project. He is in charge of determining dose and exposure goals for both controlled and uncontrolled areas in and around the facility. It was also his job to ensure that those requirements are met and maintained throughout iterations of the project. Tyler was responsible for the preliminary MCNP geometries.

Adrian Moore:

Adrian was in charge of floor plan layout as it relates to comparable facilities research and materials cost analysis. It was Adrian's job to research and present accelerator shielding facilities as start point models. Adrian worked to develop a project cost estimate and comparison. Adrian was also responsible for the design and implementation of the lift needed to make the facility operable.

Melissa (Missy) Megonigal:

Missy's work covered the SolidWorks portion of the shielding verification process. The SolidWorks model is critical in conveying the results of the shielding. Missy was also assigned to participate in the regulatory requirements verification and was in communication with a handful of industry contacts throughout the project.

Kaitlyn Darby:

Kaitlyn was to be over the NCPR calculation method as a whole. Kaitlyn also worked to develop the MCNP geometry from the agreed upon floorplan and make adjustments as needed. As each member summarized their work and portion of the project, it was be Kaitlyn's job to compile individual reports into the final accelerator shielding report.

Tucker McClanahan:

Tucker led the accelerator simulations in MCNP. Tucker worked to familiarize himself with accelerator source term creation and developed a MCNP input deck in which to run dose calculations throughout the project. Visualization of shielding effectiveness and setup was a key feature to Tucker's work in Visit. It should be noted that Tucker served as the team leader as well.

## Accelerator Shielding Design

| ACTIVITY                                | 3-Nov | 10-Nov | 17-Nov | 24-Nov | 1-Dec | 8-Dec | 15-Dec | 22-Dec | 29-Dec | 5-Jan | 12-Jan | 19-Jan | 26-Jan | 2-Feb | 9-Feb | 16-Feb | 23-Feb | 2-Mar | 9-Mar | 16-Mar | 23-Mar | 30-Mar | 6-Apr | 13-Apr | 20-Apr | 27-Apr |
|-----------------------------------------|-------|--------|--------|--------|-------|-------|--------|--------|--------|-------|--------|--------|--------|-------|-------|--------|--------|-------|-------|--------|--------|--------|-------|--------|--------|--------|
| Research:                               |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Radiation dose limits (goals)           |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Other Regulation Requirements (?)       |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| NCRP report 151                         |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| McGinley Analytical Solution            |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Software Review:                        |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| MCNP (source terms especially)          |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Attila                                  |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Solid Works                             |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| CAD                                     |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Construction:                           |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Limitations (?)                         |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Floor plan                              |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Comparison of floor plans and revision  |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Material costs                          |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Accelerator Specs                       |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Tungsten Source Term:                   |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Research                                |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Model Set up                            |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Accelerator Source Term                 |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Initial Shielding Estimates:            |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Use factor, Workload, Occupancy         |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Primary and Secondary Wall barriers     |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Ceiling/Floor                           |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| HVAC/door/maze/beamline opening         |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| MCNP model (entire room)                |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| CAD model                               |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Optimize in MCNP                        |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Verify Results:                         |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Compare MCNP to NCRP methods            |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Compare to standard building            |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Final cost estimates (per optimization) |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Room to upgrade?                        |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Check Regulatory Requirements           |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Report/Presentation:                    |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Combine models                          |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Report Introduction and Methods         |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Report Results and Conclusions          |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Presentation Slides                     |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |
| Final Review                            |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |        |       |        |        |        |

\*Tasks should be completed BEFORE the corresponding weekly meeting. The person responsible should be ready to present at meeting. The final color for each task represents the person with whom to check your work before presenting it to the remainder of the group.

## Accelerator Shielding Design

| ACTIVITY                               | 3-Nov | 10-Nov | 17-Nov | 24-Nov | 1-Dec | 8-Dec | 15-Dec | 22-Dec | 29-Dec | 5-Jan | 12-Jan | 19-Jan | 26-Jan | 2-Feb | 9-Feb | 16-Feb | 23-Feb | 2-Mar | 9-Mar | 16-Mar | 23-Mar | 30-Mar  | 6-Apr | 13-Apr | 20-Apr | 27-Apr |
|----------------------------------------|-------|--------|--------|--------|-------|-------|--------|--------|--------|-------|--------|--------|--------|-------|-------|--------|--------|-------|-------|--------|--------|---------|-------|--------|--------|--------|
| Research:                              |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Radiation dose limits (goals)          |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Other Regulation Requirements (?)      |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        | Adrian  |       |        |        |        |
| NCRP report 151                        |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        | Tyler   |       |        |        |        |
| McGinley Analytical Solution           |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        | Missy   |       |        |        |        |
| Software Review:                       |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        | Kaitlyn |       |        |        |        |
| MCNP (source terms especially)         |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        | Tucker  |       |        |        |        |
| Attila                                 |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        | Group   |       |        |        |        |
| Solid Works                            |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| CAD                                    |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Construction:                          |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Limitations (?)                        |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Floor plan                             |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Comparison of floor plans and revision |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Material costs                         |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Accelerator Specs                      |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Tungsten Source Term:                  |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Research                               |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Model Set up                           |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Accelerator Source Term                |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Initial Shielding Estimates:           |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Use factor, Workload, Occupancy        |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Primary and Secondary Wall barriers    |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Ceiling/Floor                          |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| HVAC/door/maze/beamline opening        |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| MCNP model (entire room)               |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| CAD model                              |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Optimize in MCNP                       |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Verify Results:                        |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Compare MCNP to NCRP methods           |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Compare to standard building           |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Final cost estimates                   |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Room to upgrade?                       |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Check Regulatory Requirements          |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Report/Presentation:                   |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Combine models                         |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Report Introduction and Methods        |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Report Results and Conclusions         |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Presentation Slides                    |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |
| Final Review                           |       |        |        |        |       |       |        |        |        |       |        |        |        |       |       |        |        |       |       |        |        |         |       |        |        |        |

\*Tasks should be completed BEFORE the corresponding weekly meeting. The person responsible should be ready to present at meeting. The final color for each task represents the person with whom to check your work before presenting it to the remainder of the group.

## APPENDIX B: FLOOR PLAN

### NOTES:

1. FLOORS ARE 18 FT TALL WITH A 4 FT FLOOR BETWEEN THE TWO LEVELS

2. AREA HATCH/FILL

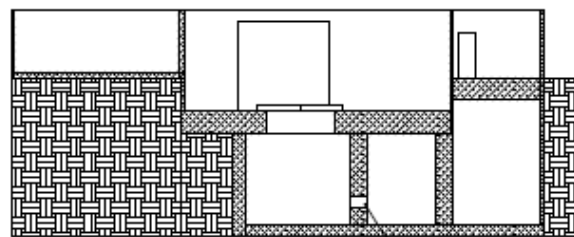
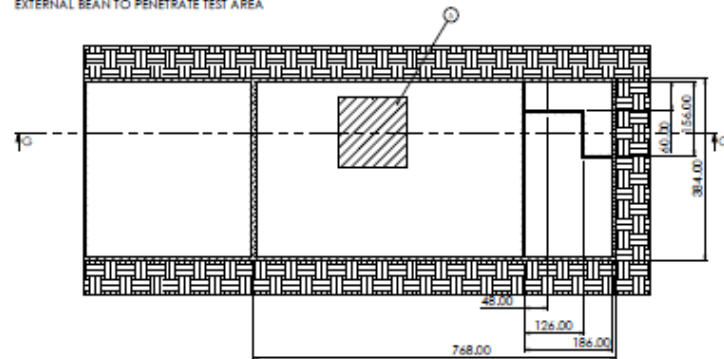
1. CONCRETE
2. DIRT

3. UNLESS OTHERWISE SPECIFIED:

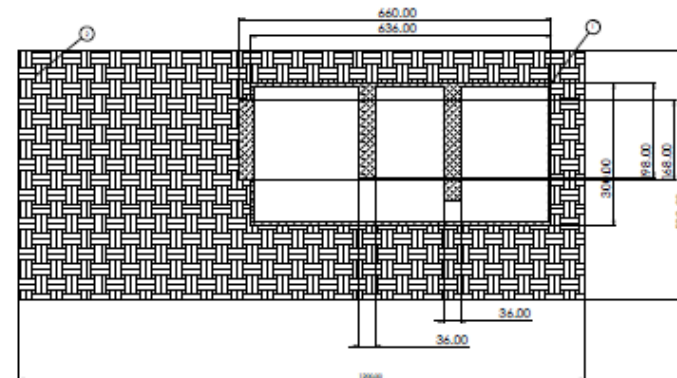
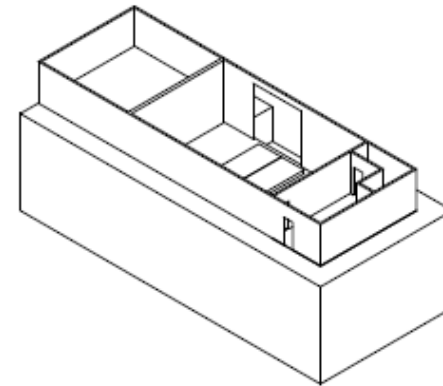
- A. WALLS ARE 6" THICK
- B. FLOOR THICKNESS OF 48"

3. CUTOUT IN FLOOR:  
MATERIALS ARE BROUGHT TO THE LOWER FLOOR BY LIFT

4. 24" x 24" CUTOUT 48" FROM FLOOR  
IN THE WALL TO ALLOW  
EXTERNAL BEAM TO PENETRATE TEST AREA



SECTION 0.0  
SCALE 1:1/8"



| Item | Description        | Quantity | Unit |
|------|--------------------|----------|------|
| 1    | LINEAR ACCELERATOR | 1        | EA   |
| 2    | Floor Plan 1       | 1        | EA   |

NOTES:

1.FLOORS ARE 18 FT TALL WITH A 4 FT FLOOR BETWEEN THE TWO LEVELS

2.AREA HATCH/FILL

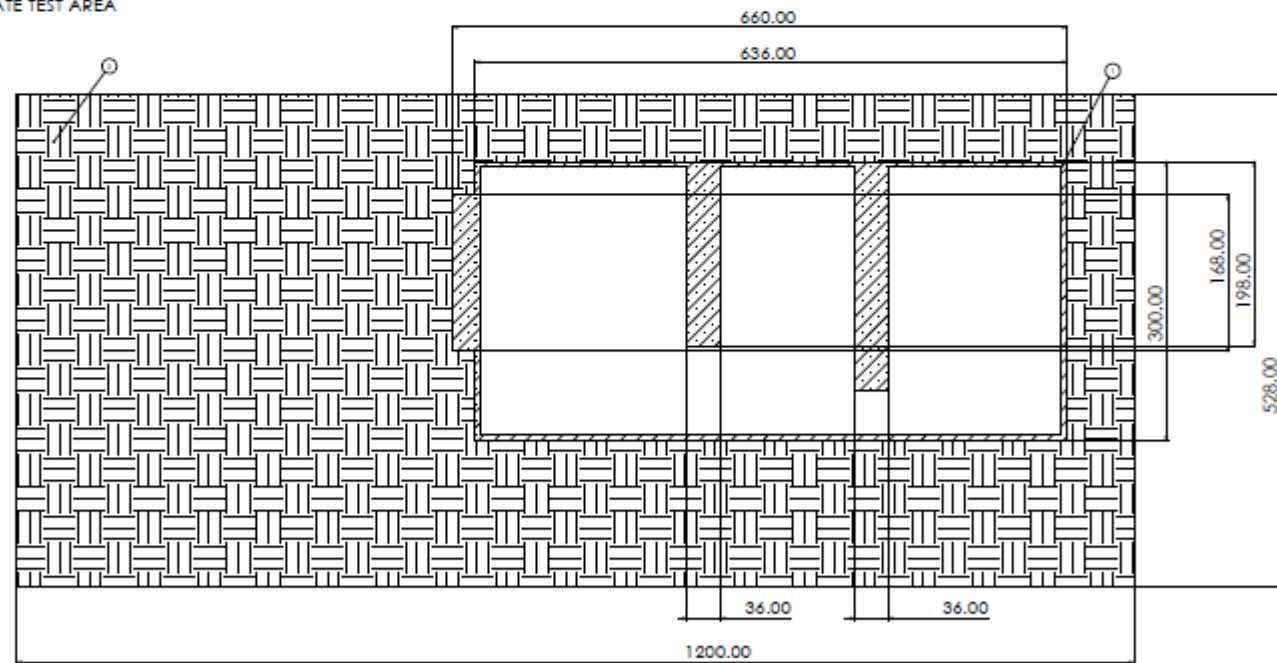
- 1.CONCRETE
- 2.DIRT

3.UNLESS OTHERWISE SPECIFIED:

- A. WALLS ARE 6" THICK
- B. FLOOR THICKNESS OF 48"

3. CUTOUT IN FLOOR:  
MATERIALS ARE BROUGHT TO THE LOWER FLOOR BY LIFT

4. 24" x 24" CUTOUT 48" FROM FLOOR  
IN THE WALL TO ALLOW  
EXTERNAL BEAM TO PENETRATE TEST AREA



|                |                    |
|----------------|--------------------|
| Project Name   | Linear Accelerator |
| Project Number |                    |
| Revision       |                    |
| Drawn By       |                    |
| Checked By     |                    |
| Approved By    |                    |
| Scale          |                    |
| Sheet Number   |                    |
| Sheet Title    | Linear Accelerator |
| Room Plan      |                    |



## **APPENDIX C: AVAILABLE SOFTWARE**

### **ATTILA4MC [30]**

ATTILA4MC is newly developed software by Transpire that offers the feature of converting a CAD model directly into Constructive Solid Geometry (MCNP geometry) by creating an unstructured mesh. ATTILA4MC also uses the deterministic solver within Attila to produce weight windows and provide source-biasing factors to apply to the MCNP simulation for an overall performance boost. Although the team originally planned to use ATTILA4MC, the software package was not released in the time frame the team needed in order to incorporate it into the project.

### **CINDER [31]**

CINDER is an exported controlled transmutation code. CINDER well describes the activation of stable isotopes given a source term generated by MCNP. When coupled with MCNPX, CINDER calculates the inventory of nuclides in an irradiated material. The team planned to utilize CINDER in the shielding analysis, but the activation analysis will have to be a part of the future work of this project.

### **MATLAB [22]**

MATLAB is both a language and an interactive GUI that provides the avenue for data manipulation, visualization and simulation developed by MathWorks. MATLAB combines the whole scripting environment into a single window by combining the command prompt and the scripting window. MATLAB has many built-in functions that allow the programmer to create very power scripts to process and visualize data.

### **MCNP [15]**

Please see Section Overview of the Monte Carlo N-Particle Code7.1

### **SolidWorks [32]**

SolidWorks is a 3D CAD program with design capabilities and utilizes a parametric feature-based approach to create models and assemblies.

### **VisEd [15]**

MCNP comes equipped with in-house software for the visual representation of the coded geometries called VisEd. VisEd has a multitude of features, however, only the geometry viewer features were used in this report.

### **VisIt [23]**

VisIt is an open source, interactive visualization and graphical software package that is used for a wide variety of scientific data applications. VisIt has an extensive support community and is well maintained. The VisIt software package originated at Lawrence Livermore National Laboratory (LLNL). VisIt provides a vast array of visualization techniques and features to the user in both two- and three-dimensional modes.

## APPENDIX D: NCRP CALCULATIONS

### **Primary Barrier:**

The primary barrier is the wall/barrier into which the beam is directly pointed at. All other barriers are considered secondary.

$$B_{pri} = \frac{Pd_{pri}^2}{WUT}$$

P – Shielding design goal expressed as dose equivalent beyond the barrier and given in Sv/wk.

For uncontrolled areas the limit is 0.02 mSv/wk; for controlled: 0.1 mSv/wk

The limit is divided by a factor of 10 to achieve ALARA doses.

The P used for the primary barrier is then  $0.1 * 10^{-4}$  Sv/wk

$d_{pri}$  – The distance between the X-ray target and the point protected in meters.

The distance between the target and the outside of the primary barrier is 27 feet = 8.2296 meters

W – The workload in Gy/wk (for photons, the quality factor is 1 such that this is equivalent to Sv/wk.)

The workload used is the workload assumed for unspecified operation: 500 Gy/wk

U – The use factor or fraction of the workload that the primary beam is directed at the barrier.

The use factor of a LinAcc with a fixed orientation is 1.

T – The occupancy factor for the protected location or fraction of the work week that a person is present beyond the barrier in question.

A list of accepted occupancy factors can be found in NCRP report 151 pg 160 and is based on the function of the adjacent areas.

The occupancy factor of 1/3 is used in this calculation because the room that would be adjacent to the LinAcc room is considered may be occupied about 1/3 of the time. However, we have moved our facility underground. According to a similar evaluation done by McGinley, 1/20 is an acceptable use factor.

$$B_{pri} = \frac{0.1 * 10^{-4} * 8.2296^2}{500 * 1 * \frac{1}{20}} = 0.000027$$

$$n = -\log(B_{pri})$$

$$t_{barrier} = TVL_1 + (n - 1)TVL_e$$

n – The number of TVL's needed in between the source and the point to be protected.

$t_{barrier}$  – Thickness needed to limit the dose to the dose goal (P).

TVL – The Tenth Value Layer is the thickness of a given material required to reduce the radiation field quality by a tenth of its original value. (Specific to particle energy and type)  $TVL_1$  – The first TVL value.

$TVL_e$  – All subsequent TVL equivalent layers.

The  $TVL_1$  of lead, earth, and concrete are: 5.7, 76.8, and 49.0. The  $TVL_e$ 's are: 5.7, 72.1, 46.0 cm.

The TVL of earth is not given but can be found by multiplying a known TVL by the inverse ratio of densities. As density increases, the thickness of material needed decreases.

A second series of TVLs has been reported by Varian and will also be used to find barrier thickness.

The TVLs given by Varian are 5.2, 61.8, and 39.4 cm for lead, earth, and concrete respectively.

The NCRP reported TVLs are used in the following calculations as an example. The result of the Varian TVLs is also calculated and the final answers shown following the NCRP values.

$$n = -\log(0.000027) = 4.56718$$

$$t_{barrier-earth} = 76.8 + (4.56718 - 1)72.1 = 333.994 \text{ cm} = 10.96 \text{ ft}$$

$$t_{varian \text{ TVLs}} = 282.252 = 9.26 \text{ ft}$$

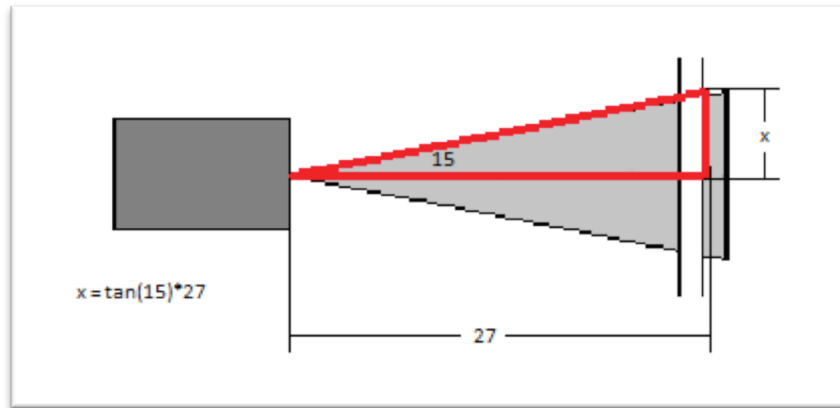
Because n gives the number of TVLs needed, some part of those may be substituted with a material of a thinner TVL (For example 2.0 feet of concrete before the earth barrier)

$$TVL_{concrete} = \frac{2.0ft * 2.54 * 12}{49} = 1.244$$

$$t_{barrier-earth} = (4.56718 - 1.244)72.1 = 239.601 \text{ cm} = 7.86 \text{ ft}$$

$$t_{varian TVL's} = 186.647 = 6.12 \text{ ft}$$

The width of the primary barrier is defined as the area perpendicular to the beam line direction which creates a 15° angle between the center line of the beam and a line running from the accelerator head to any point along the primary barrier border plus 30 centimeters on all sides.



Note that this calculation is done from the far side of the barrier such that the barrier thickness must be known. A primary barrier thickness of concrete was calculated and used to determine the final distance of about 27 feet. The result is a primary barrier of thickness  $t_{barrier}$  and at least 7 feet in all directions from the center. A box of 15 feet in width and spanning the entire height of the facility was decided upon to improve ALARA standards.

### **Secondary Barriers:**

Secondary barriers are the non-primary walls/barriers which, instead of receiving radiation doses from the beam directly, are irradiated by scattering, accelerator leakage, or secondary particles.

### **Scatter:**

Some of the radiation that reaches the secondary barrier is first scattered and redirected by the target of the beam itself.

$$B_s = \frac{P}{\alpha_{AWT}} d_{sca}^2 d_{sec}^2$$

P = Shielding design goal expressed as dose equivalent beyond the barrier and given in Sv/wk.

For uncontrolled areas the limit is 0.02 mSv/wk; for controlled: 0.1 mSv/wk

The limit is divided by a factor of 10 to achieve ALARA doses.

The inside wall, back wall, and ceiling are considered controlled, whereas the outside wall would typically open up to an uncontrolled area. Once again, this is different for the underground calculation. We will assume that all areas underground are controlled.

The P is then either  $0.1 * 10^{-4}$  Sv/wk or  $0.02 * 10^{-4}$  mSv/wk.

$\alpha$  – The differential dose albedo is a dimensionless reflection coefficient and is a function of incident photon energy, incident material, and incident angle.

The  $\alpha$  chosen here is  $5 * 10^{-3}$ .

A – The area of the beam at the scattering surface in meters squared.

The area is calculated as a disk perpendicular to the beam line and at a distance equal to the distance between the accelerator and the target. The radius is such that there is a 15° angle between the center line of the beam and a line connecting the accelerator to any point on the outside of the disk.

$$A = \pi r^2 \quad r = \tan(15) * d_{sca}$$

W – The workload in Gy/wk (for photons, the quality factor is 1 such that this is equivalent to Sv/wk).

The workload used is the workload assumed for unspecified operation: 500 Gy/wk.

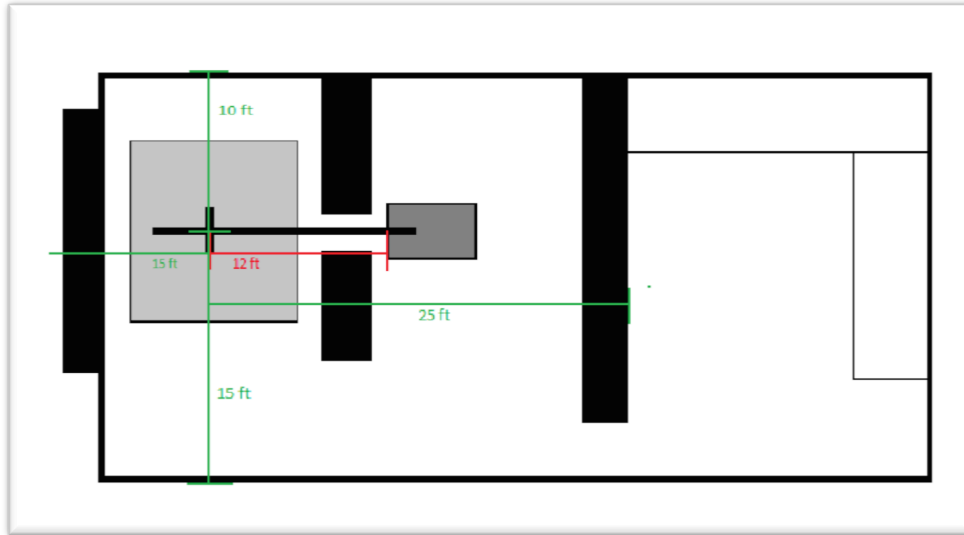
T – The occupancy factor for the protected location or fraction of the work week that a person is present beyond the barrier in question.

A list of accepted occupancy factors can be found in NCRP report 151 pg 160 and is based on the function of the adjacent areas.

The occupancy factors that would be used for the outer wall, inner wall, back wall, and ceiling are 1/20, 1/20, 1/40, and 1/2 respectively. The underground calculations again use an occupancy factor of 1/20.

$d_{sca}$  – The distance between the accelerator and the target/scattering surface in meters.

$d_{sec}$  – The distance between the target/scattering surface and the point to be protected in meters. (pg 32)



$D_{sca}$  distances are marked in red, while the relevant  $d_{sec}$  distances are shown in green. The  $d_{sec}$  between the target and the ceiling is 15 feet. Note that all of these distances should be converted to meters.

$$A = \pi \left[ \tan(15) \left( 12 \text{ ft} * 12 \frac{\text{in}}{\text{ft}} * 0.0254 \frac{\text{m}}{\text{in}} \right) \right]^2 = 3.0175 \text{ m}^2$$

Note that calculations are done such that the inner and outer walls are surrounded by earth, while the back wall is made of concrete and separates the stairwell from the treatment room. Similarly, the ceiling is made of concrete and separates the first level from the basement.

Inner wall:

$$B_{s-inside} = \frac{0.1 * 10^{-4}}{(5 * 10^{-3})(3.0175)(500) \left( \frac{1}{20} \right)} (3.6576^2)(4.5720^2) = 0.007414$$

$$n = -\log(0.007414) = 2.12995$$

$$t_{\text{barrier-earth}} = 76.8 + (2.12995 - 1)72.1 = 158.270 \text{ cm} = 5.19 \text{ ft}$$

$$t_{\text{varian TVLs}} = 131.631 = 4.32 \text{ ft}$$

Outer wall:

$$B_{s-outside} = \frac{0.1 * 10^{-4}}{(5 * 10^{-3})(3.0175)(500) \left(\frac{1}{20}\right)} (3.6576^2)(3.0480^2) = 0.003295$$

$$n = -\log(0.003295) = 2.4813$$

$$t_{barrier-earth} = 76.8 + (2.4813 - 1)72.1 = 183.662 \text{ cm} = 6.02 \text{ ft}$$

$$t_{varian TVLs} = 153.396 = 5.03 \text{ ft}$$

For the back wall between the accelerator and the stairwell and for the ceiling, there are steps to accounting for the location of a person behind that barrier. An additional 30 cm away from the wall and 50 cm above the ceiling have been added to the calculated distances according to the NCRP report 144. This measure does not need to be taken for barriers that will “protect” the earth.

Back wall:

$$B_{s-stairwell} = \frac{0.1 * 10^{-4}}{(5 * 10^{-3})(3.0175)(500) \left(\frac{1}{40}\right)} (3.6576^2)(7.9200^2) = 0.044495$$

$$n = -\log(0.044495) = 1.35168$$

$$t_{barrier-earth} = 49.0 + (1.35168 - 1)46.0 = 65.1773 \text{ cm} = 2.13 \text{ ft}$$

$$t_{varian TVLs} = 53.2562 = 1.74 \text{ ft}$$

Ceiling:

$$B_{s-ceiling} = \frac{0.1 * 10^{-4}}{(5 * 10^{-3})(3.0175)(500) \left(\frac{1}{2}\right)} (3.6576^2)(5.0720^2) = 0.000912$$

$$n = -\log(0.000912) = 3.03981$$

$$t_{barrier-concrete} = 49.0 + (3.03981 - 1)46.0 = 142.831 \text{ cm} = 4.69 \text{ ft}$$

$$t_{varian TVLs} = 119.768 = 3.93 \text{ ft}$$

### Leakage:

Although the linear accelerator is shielded to prevent radiation dose outside of the beam path, there is some amount of radiation that will escape as leakage radiation. If this value is not prescribed by LinAcc manufacturer, it can be calculated.

$$B_l = \frac{Pd^2}{10^{-3}WT}$$

P = Shielding design goal expressed as dose equivalent beyond the barrier and given in Sv/wk.

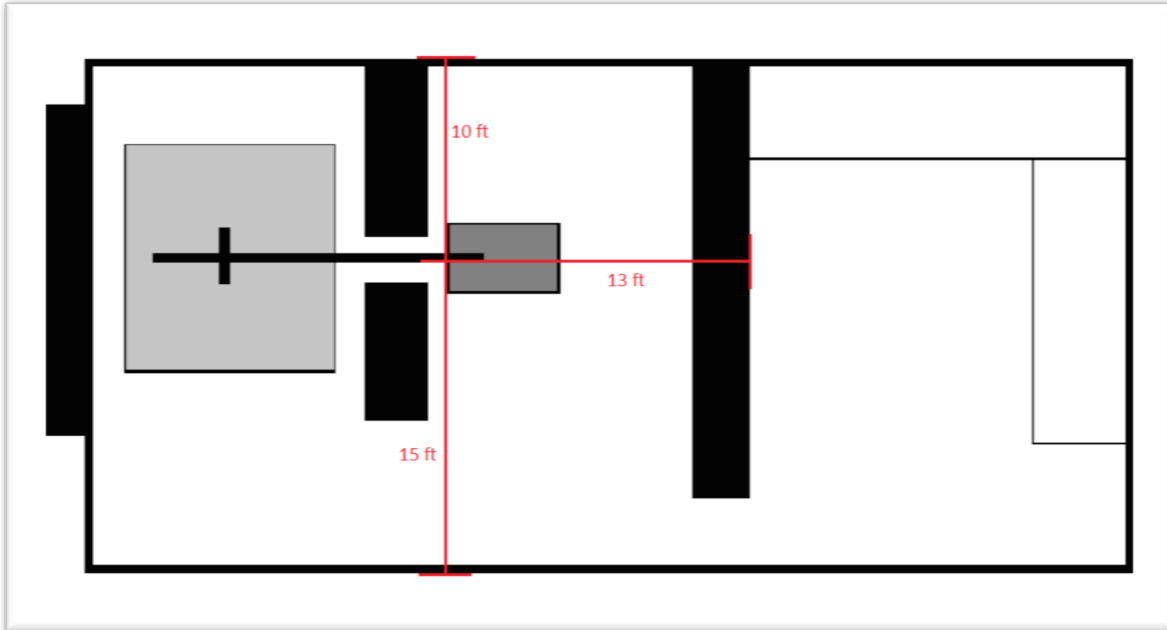
For uncontrolled areas the limit is 0.02 mSv/wk; for controlled: 0.1 mSv/wk

The limit is divided by a factor of 10 to achieve ALARA doses.

The inside wall, back wall, and ceiling are considered controlled, whereas the outside wall would typically open up to an uncontrolled area. Once again, this is different for the underground calculation. We will assume that all areas underground are controlled.

The P is then either  $0.1 * 10^{-4}$  Sv/wk of  $0.02 * 10^{-4}$  Sv/wk.

d – The distance between the accelerator and the point of protection in meters. As shown below (in feet).



W – The workload in Gy/wk (for photons, the quality factor is 1 such that this is equivalent to Sv/wk.)

The workload used is the workload assumed for unspecified operation: 500 Gy/wk.

T – The occupancy factor for the protected location or fraction of the work week that a person is present beyond the barrier in question.

A list of accepted occupancy factors can be found in NCRP report 151 pg 160 and is based on the function of the adjacent areas.

The occupancy factors used for the outer wall, inner wall, back wall, and ceiling are 1/20, 1/20, 1/40, and 1/2 respectively. The underground calculations use an occupancy factor of 1.

Note that calculations are done such that the inner and outer walls are surrounded by earth, while the back wall is made of concrete and separates the stairwell from the treatment room. Similarly, the ceiling is made of concrete and separates the first level from the basement.

Inner wall:

$$B_{l-inside} = \frac{(0.1 * 10^{-4})(4.572)^2}{10^{-3}(500)(1/20)} = 0.008361$$

$$n = -\log(0.008361) = 2.07773$$

$$t_{barrier-earth} = 76.8 + (2.07773 - 1)72.1 = 154.504 \text{ cm} = 5.07 \text{ ft}$$

$$t_{varian TVLs} = 128.404 = 4.21 \text{ ft}$$

Outer wall:

$$B_{l-outside} = \frac{(0.02 * 10^{-4})(3.048)^2}{10^{-3}(500)(1/20)} = 0.003716$$

$$n = -\log(0.003716) = 2.42991$$

$$t_{barrier-earth} = 76.8 + (2.42991 - 1)72.1 = 179.897 \text{ cm} = 5.90 \text{ ft}$$

$$t_{varian TVLs} = 150.168 = 4.93 \text{ ft}$$

Back wall:

$$B_{l-stairwell} = \frac{(0.1 * 10^{-4})(4.2624)^2}{10^{-3}(500)\left(\frac{1}{40}\right)} = 0.014534$$

$$n = -\log(0.014534) = 1.8376$$

$$t_{barrier-concrete} = 49.0 + (1.8376 - 1)46.0 = 87.5297 \text{ cm} = 2.87 \text{ ft}$$

$$t_{varian TVL's} = 72.4015 = 2.38 \text{ ft}$$

Ceiling:

$$B_{l-ceiling} = \frac{(0.1 * 10^{-4})(5.072)^2}{10^{-3}(500)\left(\frac{1}{2}\right)} = 0.001029$$

$$n = -\log(0.001029) = 2.98758$$

$$t_{barrier-concrete} = 49.0 + (2.98758 - 1)46.0 = 140.429 \text{ cm} = 4.61 \text{ ft}$$

$$t_{varian TVL's} = 117.711 = 3.86 \text{ ft}$$

The required barrier thickness is then decided by choosing the greater thickness needed for either scatter or leakage radiation and adding a HVL.

HVL – The Half Value Layer is the required thickness of a given material need to reduce the beam quality of a certain particle and energy by half.

The HVL of earth is found (again) by multiplying a known HVL by the inverse of their densities. The HVL for earth is 22 cm. The HVL for concrete is 15 cm.

**The final barrier thickness for the underground facility are then:**

Inside wall:  $158.270 + 22 = 180.27 \text{ cm} = 5.91 \text{ ft}$  earth

Varian:  $131.631 + 22 = 153.631 \text{ cm} = 5.04 \text{ ft}$  earth

Outside wall:  $183.662 + 22 = 205.662 \text{ cm} = 6.75 \text{ ft}$  earth

Varian:  $153.396 + 22 = 175.396 \text{ cm} = 5.75 \text{ ft}$  earth

Back wall (stairwell):  $87.5297 + 15 = 102.53 \text{ cm} = 3.36 \text{ ft}$  concrete

Varian:  $72.4015 + 15 = 87.4015 \text{ cm} = 2.87 \text{ ft}$  concrete

Ceiling:  $142.831 + 15 = 157.831 \text{ cm} = 5.18 \text{ ft}$  concrete or concrete equivalent

Varian:  $119.768 + 15 = 134.768 \text{ cm} = 4.42 \text{ ft}$  concrete

Primary barrier:  $(4.56718 - 1.244)72.1 = 239.601 \text{ cm} = 7.86 \text{ ft after } 2.0 \text{ ft of concrete}$

Varian:  $186.647 = 6.12 \text{ ft after } 2.0 \text{ ft of concrete}$

**Secondary Particles:**

Although LinAcc energies greater than 10MV produce secondary electrons, it has been shown that facilities that operate below 30MV and are shielded adequately for photons are also shielded sufficiently for neutrons.

## APPENDIX E: ADDITIONAL DOCUMENTATION

### Dynaco Armor Door Quote



INDEPENDENT MATERIAL  
HANDLING.docx

### American Custom Lifts



American\_Custom\_Lifts.docx

### Baker Concrete Quote



Concrete\_Quote.docx

### MCNP Input for Neutrons



Floor\_Plan\_Model\_  
Neutrons\_Latest.dat

### MCNP Input for Photons



Floor\_Plan\_Model\_  
Photons\_Latest.dat

### MATLAB Shielding Calcs.



SeniorDesignCalc.m

### Source Generation



accel\_source\_gener  
ator.pl

### Plots Creation



Read\_and\_Plot\_Md  
ata.m

### VTK Write File



vtkwrite.m