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A Mobile Food Irradiation Facility

Margaret Elaine Cunningham
University of Tennessee - Knoxville

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A Mobile Food Irradiation Facility

David Lincolnogger (Coordinator)
Margaret Cunningham
Joshua Marshall
Martin Washington
Ashleigh Seay

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Faculty Advisor
Dr. M.L. Grossbeck

Nuclear Engineering Department
The University of Tennessee

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ABSTRACT

Each year, food spoilage and pests devastate the world's food crop. However, irradiation shows promise as a reliable mode of food pasteurization. The safety and practicality of irradiated foods has been well-documented, and the rising public concern over food safety has demonstrated the need for a mobile food irradiation facility. With this design, it is hoped that one day more produce will be irradiated, thus preserving more lives.

The facility will consist of a tractor trailer, one portable linear accelerator, and a diesel generator. The linear accelerator will be bolted to the floor of the trailer, pointing upward. Food passes over the 4 mA beam in order to be irradiated. Shielding will be comprised of lead, 20 cm thick on each side and 30 cm on top, positioned so as to maximally decrease dose outside the trailer. The unit will also have a network of sensors and monitors to observe motion and radiation levels.

The projected dose to the food is about 3 kGy. The processing rate is about 62 seconds per cubic meter, where the thickness is 10.2 cm (4 inches) which corresponds to a single layer of fruits, vegetables or nuts. Hand calculations predict an equivalent dose rate of about 3.9 μSv/h outside the shielding, which MCNP5 confirms (3.0 μSv/h), and does not require special training. The total cost of our mobile food irradiation facility is under $1.2 million, which is competitive with other food processing plants and makes it practical as an emergency service.

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BACKGROUND AND PURPOSE

In the United States alone, large amounts of food go to waste due to spoilage or pests. Additionally, it is estimated that nearly 5,000 people die from a food-borne illness each year.[15] In a developing country, this loss of food and life can be even more devastating. The purpose of this project is to address the issues of food safety and subsequent prolonging of products' shelf life via pasteurization by irradiation and the design of such a facility.

Food irradiation is a relatively new technology for controlling spoilage and eliminating food-borne pathogens, such as salmonella in meats. Food safety has always been a concern, but recently has become the subject of growing importance to consumers. For example, *E. coli* found on spinach (2006) and salmonella-tainted peanuts (2007) have shaken the nation's trust in food safety. The scope of this project is to provide an emergency irradiator that could be quickly deployed to a contamination site. The facility is small enough to be in storage until it is needed.

A food irradiation facility would act as a preventative measure from food-borne pathogens. The emergency irradiator could possibly save a company from going under due to lawsuits and other costs. Once an outbreak occurs, an irradiation truck can be mobilized and taken to an outbreak site. The irradiation facility then could potentially save the company from losing valuable products and furthering the spread of food-borne pathogens.

These recent outbreaks have caused a shift in public awareness. New studies show that consumers are becoming more interested in irradiated foods. Consumer research conducted by a variety of groups, including the American Meat Institute, the International Food Information Council, the Food Marketing Institute, the Grocery Manufacturers of America, and the

National Food Processors Association has found that a large majority of consumers polled would buy irradiated foods.[6]

The Food and Drug Administration (FDA) has approved irradiation of meat, poultry, and a variety of other foods including fresh fruits, vegetables, and spices. The FDA determined that the process is safe and effective in decreasing or eliminating harmful bacteria. Irradiation also reduces spoilage, bacteria, insects and parasites, and in certain fruits and vegetables it inhibits sprouting and delays ripening. For example, irradiated strawberries stay unspoiled up to three weeks, versus three to five days for untreated berries.

Many health experts agree that using pasteurization by irradiation can be an effective way to help reduce food-borne hazards and ensure that harmful organisms are not in the foods we buy. Irradiation is not a substitute for proper food manufacturing and handling procedures. But the process, especially when used to treat meat and poultry products, can kill harmful bacteria, greatly reducing potential hazards.

COMPARISON OF TECHNOLOGIES

There are several methods of food sterilization used today. Many take advantage of the destructive properties of heat addition. All of these methods attempt to reduce (partially or completely) the pathogens most likely to cause human illness.

Sterilization refers to any process that attempts to completely destroy any pathological agent from a surface, piece of equipment, or type of food. Sterilization was historically accomplished through cooking, which applies lethal heat. Cultures that practice forms of sterilization have a longer life expectancy and lower risk of childhood disease. Many canned foods are sterilized and do not require refrigeration.

Pasteurization is considered a less-harsh form of sterilization. It is not intended to kill all pathogenic micro-organisms but rather to reduce their number so that they are far less likely to cause illness. However, pasteurized foods require refrigeration and have a relatively shorter shelf-life.

Irradiation is similar to conventional pasteurization and is often called "cold pasteurization" or "irradiation pasteurization." Like pasteurization, irradiation kills bacteria and other pathogens that could otherwise result in spoilage or food poisoning. The fundamental difference between the two methods is the source of the energy they rely on to destroy the microbes. While conventional pasteurization relies on heat, irradiation relies on the energy of ionizing radiation. Irradiation does not make foods radioactive nor does it cause harmful chemical changes. The process may cause a small loss of nutrients but no more so than with other processing methods such as cooking, canning, or heat pasteurization.

FOOD IRRADIATION FACILITIES

Most of the food irradiation facilities in use today are stationary, and process tons of food daily. Additionally, they supplement their beam time by processing medical apparatus and other equipment, making them more economical. However, they are fixed in their location and require food to be brought to them and mainly cater to large farms. The goal of this project is to provide a way to take the facility to the product and allow smaller farms to participate, making irradiated food cheaper overall.

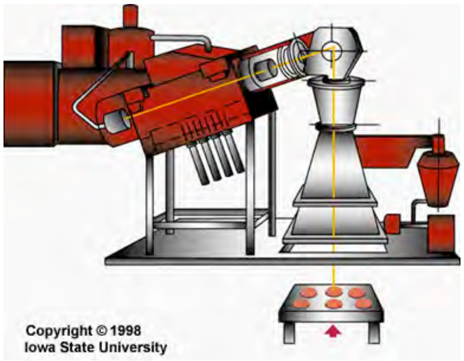


Figure 1 - Typical food irradiator

Food is irradiated in crates or boxes placed on conveyor belts (Figure 1) and moved from a “neutral zone” into the heart of the irradiation facility, where it is exposed to the radioactive source. The source is separated from the rest of the facility by a biological shield, usually lead and concrete, to protect the workers (Figure 2).

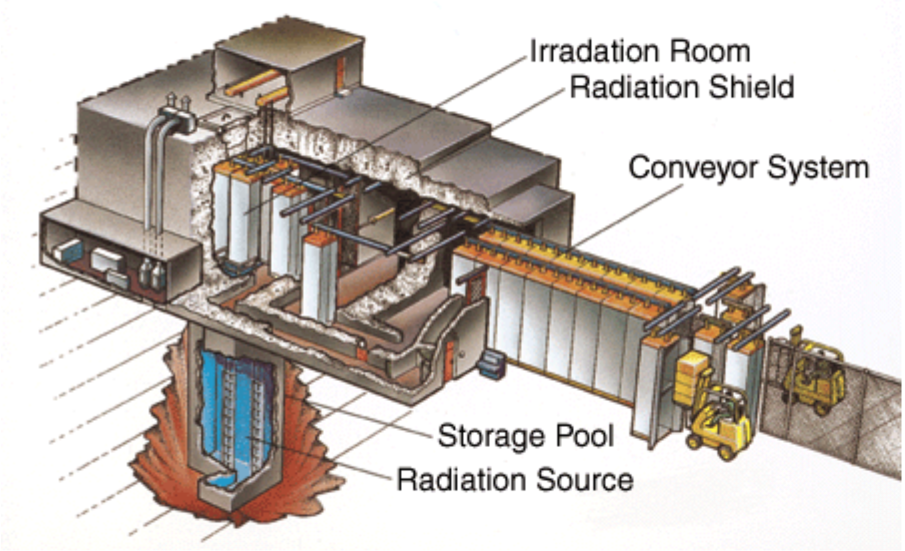


Figure 2 - A stationary irradiation facility

About 30 countries (about 1/7 of existing countries in the world) have irradiation facilities, and 50 countries have legalized irradiation for some foods (Figure 3). There are also approximately 50 irradiation facilities in the United States, many of which irradiate food, including spices, beef, chicken, fruit and vegetables. Many of them also irradiate medical supplies.

Figure 3 - Countries that irradiate food worldwide

The cost to build a commercial cobalt-60 food irradiation plant is in the range of US $3 million to $5 million (based on research by the University of Wisconsin), depending on its size, processing capacity, and other factors. This is within the range of plant costs for other technologies. For example, a moderately-sized, ultra-high temperature plant for sterilizing milk, fruit juices, and other liquids costs about US $2 million. A small, vapor-heat treatment plant for disinfestations of fruits costs about US $1 million.[19]

TYPES OF IRRADIATORS

There are three main types of radiation sources to consider when designing a food irradiation facility: gamma sources, x-ray beams, and linear accelerators. Most facilities utilize a cobalt-60 source, which emits gamma rays (Figure 4). Gamma rays with specific energies are emitted by the spontaneous disintegration of radionuclides. Co-60 is man-made by being bombarded in a nuclear reactor, making it unstable with the tendency to decay

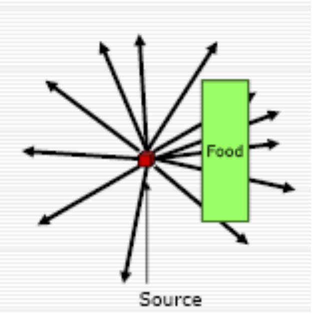


Figure 4 - Gamma sources emit in all directions

to a more stable state. Co-60 has proven its usefulness in the food industry, as well as for sterilizing medical equipment and providing therapeutic cancer treatments. In the case for a stationary food irradiation plant or medical facility, the cobalt is always emitting gamma rays; it cannot be "turned off." After its use, the source is removed from the treatment room and stored in a pool of water. Water is used to attenuate the gamma rays and protect workers from being overexposed.

Cobalt-60 has a half life of 5.3 years. This means within 5.3 years the source strength will be reduced by half. The amount of gammas given off is constantly degrading over time. The time it takes food to irradiate when the source is 5 years old will take twice as long as the food with a fresh source. After time, the Cobalt-60 source will be too weak in source strength to make it profitable to use and it will have to be replaced.

Cobalt-60 was not considered to be a reasonable source of radiation for a portable irradiation facility. Due to its constant emission, it would need to be shielded at all times. The extra weight associated with a lead shield sufficient enough to attenuate the gamma rays was deemed too large by the state weight restrictions on highways. Additionally, the safety of a continuous source if involved in an accident during transport was called into question. The possibility of accidental exposure and unnecessary risk was deemed too great.

X-rays are caused by atomic transitions induced by electron transitioning from higher energy orbital to lower energy orbital, and are usually less energetic than gamma rays. Figure 5 illustrates production of X-rays onto a target. This process is highly inefficient, with less than 0.1% of the energy being converted to x-rays; the rest is released as heat, so the x-ray generator needs a cooling system.

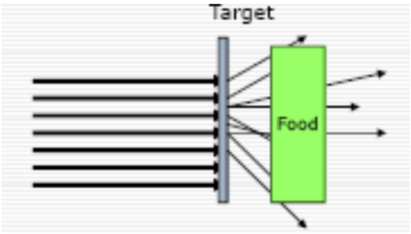


Figure 5 - X-rays scatter

However, unlike cobalt-60 machines, X-ray generators can be turned on or off and thus would not unnecessarily endanger workers, the public, or the environment in the case of an accident. It could be considered a good source for a portable food irradiation facility, but still requires substantial shielding and is very inefficient.

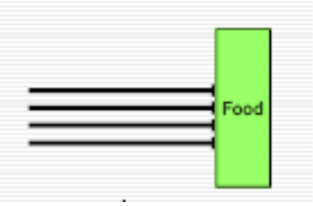


Figure 6 - E-beams move in relatively straight lines

Linear accelerators, particularly electron beams, were considered ideal for this project; see Figure 6. They do not require a radioactive source at any time, meaning that they are safe to handle when they are not actively irradiating. Electrons require less shielding than x-rays of the same energy because their charge slows them down. As a result, electrons have a shorter penetration depth. Therefore, irradiation of thick slabs of meats is probably not feasible. Table 1 lists the advantages and disadvantages of each beam type.

Table 1 - Comparing E-beams to other types of irradiators

	Advantages	**Disadvantages**
Electron Beam	Machine can be turned on/off Cost-efficient In-line capability Compact Produces higher, uniform doses	Poor penetration depth Limited energy range
Gamma	Broad energy range Able to penetrate dense material	Source cannot be turned off Requires excess shielding Requires frequent source disposal/replacement Consumer perception Expensive
X-rays	Can be turned off Higher penetration Broad energy range	Inefficient (< 0.1%) Requires cooling system

A linear accelerator is the type of irradiator used in this facility. It was chosen because of the ability to turn the system off as compared to gamma source. Also, an electron beam was chosen because of the better capability to shield an electron as opposed to an X-ray or gamma ray. X-rays are less efficient than electron beams. Of the electron beam types, the linear accelerator was the best choice for portability.

DESIGN

The facility is housed on a typical tractor-trailer. The Department of Highway weight limit for interstate travel is approximately 36.4 metric tons (40 tons). The weight of the trailer is composed of the linear accelerator, control units, conveyor system, lead shielding, and structural support. The diesel generator power supply will be housed on another trailer.

The conveyor belt system runs the length of the trailer in two sections. At the irradiation point, an electron permeable window will be used to allow penetration to the product. Once the food has been processed, it exits the trailer via the second section of conveyor belt where it can be removed and further processed.

A single L&W Portac linear accelerator is used in the design. The accelerator consists of four items; the beam head, the modulator/power supply, the Thermal Cooling Unit (TCU), and the controls. The beam head is 60" x 36" x 36". The electrons would exit one of the 36" square ends through the scan horn which would project another 24". For an 18" scan width the horn is 24" long by 4" wide. So the overall height from the bottom of the accelerator to the bottom of the irradiation point is 7 feet. The head weighs 700 lb, without shielding.[9] If maintenance needs to be done to the linear accelerator, a window is installed in the lower compartment of the support structure for the linear accelerator. This would help to prevent personnel from entering the truck and collecting any unforeseen radiation incase of a malfunction.

The shielding material is lead. The lead is 20 cm thick around the perimeter of the accelerator which corresponds to laterally around the beam. Above the point of irradiation the lead is 30 cm thick. The lead is a consistent block. Lead bricks will not be used to prevent theft of bricks. A large block of material is easier to keep inventory on over smaller lighter bricks. The lead block will be centered in the middle of the truck to evenly distribute the weight on the truck.

Our design utilizes many safety features, including motion sensors and radiation monitors. During normal operation there is not motion inside the truck. The food is not being shifted back and forth during the irradiation process. Motion sensors are placed at either entrance to the irradiator, as well as above and below the unit. The system is designed so that the irradiator can only be on when the motion sensors give an “all-clear” signal. The conveyor is halted during irradiation, and then restarts after the allotted time; the sensors will detect this change and turn the linear accelerator off. If in any situation someone is locked inside the facility, or is on top of or below the truck, the linear accelerator will not start.

Another safety feature is the doors leading into where the food will be irradiated. The doors are positioned at the entrance and exit of the irradiation zone. They are hydraulically lifted doors that have a fail close mechanism. This prevents anyone from being able to enter the irradiation zone during an abnormal situation. If for some reason the power is inadvertently shut off to the trailer, the doors will closed because the hydraulic pump will not be operational. In the advent of a power failure and personnel try to enter the irradiation zone the doors will have to be manually overridden. If the power is turned back on to the trailer, the irradiator will not come back on because the door open command will not allow the irradiator to come on. Also, if personnel are working on the irradiator the motion sensors would be detecting motion and will not allow the irradiator to turn on as well. Figures 7-9 provide graphical renderings of the design.

In the case of an earthquake or unfavorable weather and the truck is stationed outside, a string with a weight will be positioned over a motion sensor. The rocking back and forth of the trailer will cause the weighted string to swing back and forth and the motion sensor will trip causing the irradiation process to stop. To prevent accidental bumping into the truck from an outside source, a buffer zone around the trailer will be placed. This buffer zone will prevent someone from bumping into the truck with something hard enough that will cause the weighted string to swing tripping the motion sensor.

The linear accelerator is positioned so that it is pointing upwards. A horizontal beam proved too difficult to shield given weight restrictions, and a downward-facing linear accelerator might activate materials beneath the trailer. An upward beam would create sky-shine, so the shielding will be thicker above the beam. The rest of the shielding surrounds the linear accelerator. There is no lead underneath the linear accelerator because the electrons and their generated photons are mainly forward scattering. Minimal amount of radiation backscatters down below the truck. Any radiation that backscatters will be shielded against by the ground below the truck.

Additionally, radiation monitors would be installed in strategic locations around the linear accelerator in order to monitor the dose output. If the system detects either an increase or a drop in normal radiation levels, it too will turn the accelerator off. To prevent downtime, the system will be redundant, with backups in case a monitor fails.

The shielding calculations were performed assuming no food in the irradiator. This results in the lead at the top of the truck acting as a beam stop. Lead, being a high Z material, will create more Bremsstrahlung radiation than that of the air or water. These photons will have much higher penetrating capacity. So as a built in safety feature the amount of lead that is located in the truck is enough to minimize the amount of radiation that escapes the truck when there is no food in the beam’s path to absorb the energy.

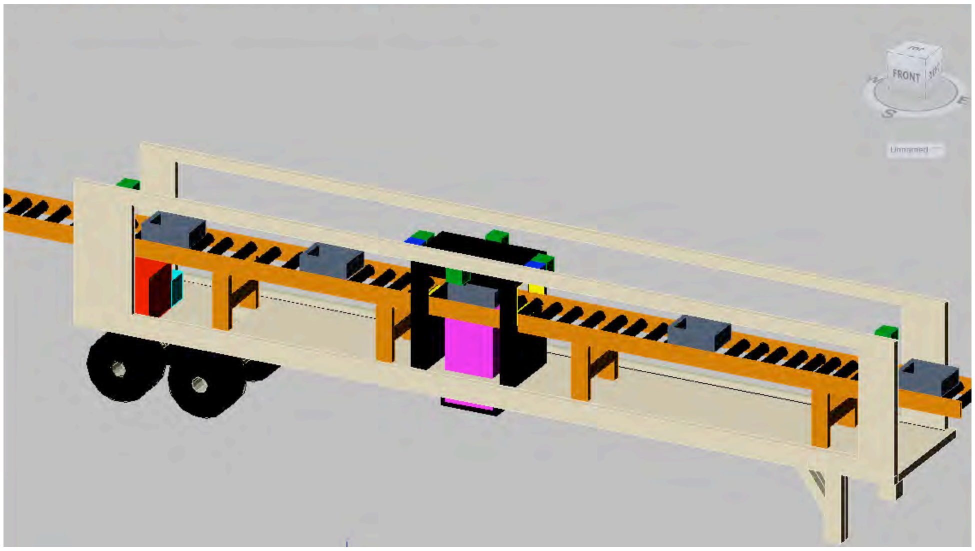


Figure 7 - Southern view

🟨 Motion Sensor
🟩 Radiation Sensor
🟪 Linear Accelerator
🟦 Control Box
🟥 TCU
⬛ Food Storage Containers
🟧 Conveyor Belt
⬛ Lead Shielding
🟩 Trailor

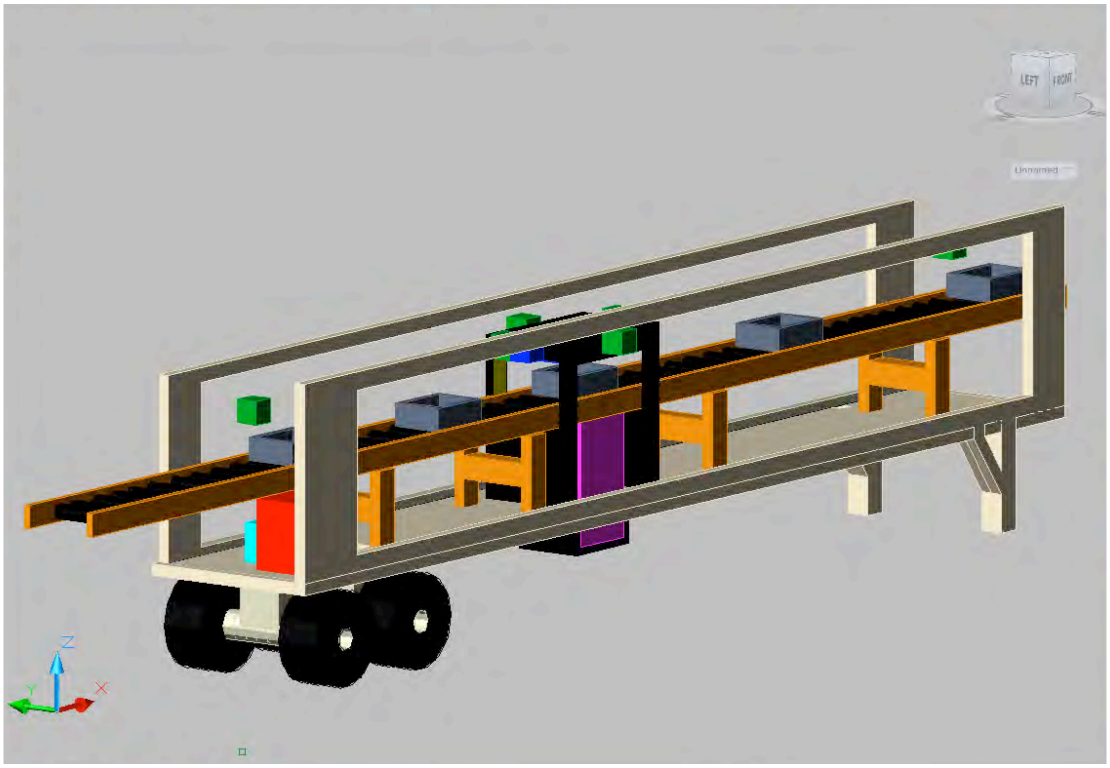


Figure 8 - Northern-view of the mobile facility

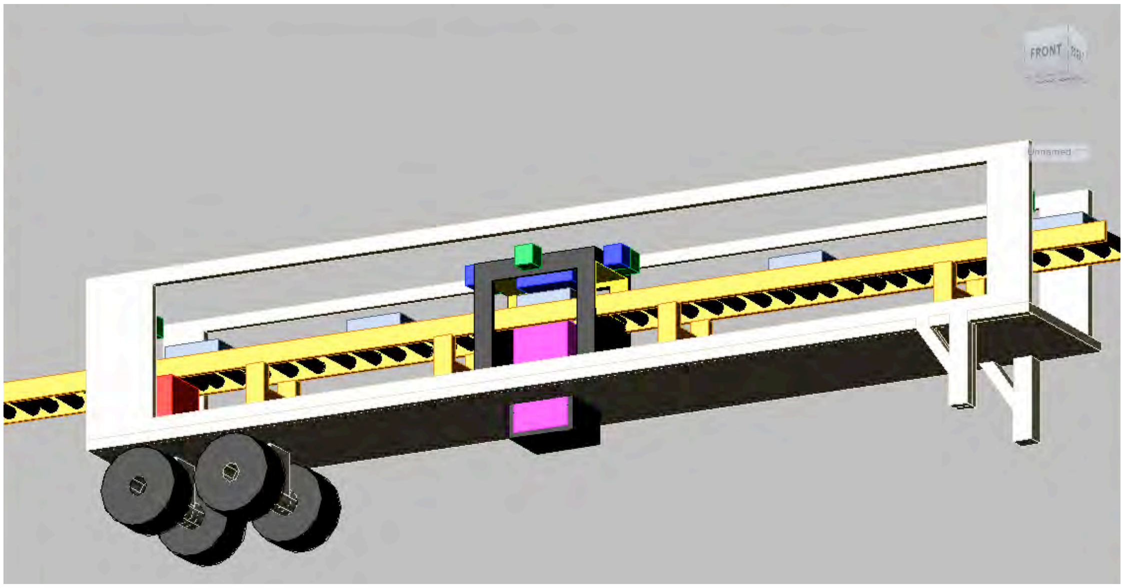


Figure 9 - Bottom-view of the mobile facility

COST ESTIMATION

A 1999 53-foot Great Dane dry van can be found for around $40,000.[24] This type of trailer will suffice due to it being enclosed and the ability to add structural support where needed. The total weight of the mobile facility will be close to road limits. A powerful truck will be needed to supply the power necessary for transport. The 2009 Freightliner CC13264-Coronado is listed at $135,900.[12]

The linear accelerator used is the L&W Portac. The Portac is a compact design and supplies the necessary dose. The cost of this system is $900,000.[9] The linear accelerator requires 15 kW of power. A 300-kW generator can supply all power necessary for the controls of the accelerator and the conveyor belt. This size of generator can be found for $27,000.

This lead used for shielding can be found from MarShield. The weight limit for shielding is approximately 20 tons. The price can be estimated at $1.28 per pound.[14] This equals $51,200 in lead shielding alone.

For safety of the general public and workers at the food irradiation facility, multiple radiation monitors will be placed around the facility to maintain a safe radiation level. A Vista environmental monitoring system with ten probes will be used. The approximate cost of the system is $10,000.[11]

The conveyor system used will actually be placed in two sections with an 18 inch gap between the two sections. The gap will have rails parallel to the direction of travel to support an electron permeable window. The window will support the products being irradiated during irradiation. Following irradiation, the food will be dumped down a descending conveyor section to allow for the unloading of the irradiated product. The conveyor system implemented is approximately $12,000.[21]

The total cost for the mobile food irradiation facility is estimated conservatively at $1,176,100 (Table 2).

Table 2 - Cost estimate

Equipment	Cost
Trailer	$40,000
Semi-Truck	$135,900
L&W Portac	$900,000
Generator	$27,000
Shielding	$51,200
Radiation Monitoring system	$10,000
Conveyor System	$12,000
Total	$1,176,100

FEDERAL REGULATIONS REGARDING IRRADIATION

Due to the nature of the irradiation process, regulations and control limits must be implemented to ensure safety. The safety of the operator and exposure to the general public are both of great concern. The public will also be affected when they consume the irradiated product. Therefore, the design of our portable irradiator must be built with the limiting parameters in mind. The regulations and limits provided in this section are provided by the Department of Transportation (D.O.T), IAEA, and the Food and Drug Administration. Compliance with the rules outlined is mandatory for any operating irradiation facility in America. The laws do not vary and must be followed accordingly.

The mobile irradiation facility will be carried to farms and stores in an 18-wheeler. Due to the weight of the components of the facility, the road restrictions for this transport process must be considered. The Department of Transportation (DOT), the governing body which establishes vehicle limits, allows for each truck to weigh a maximum of 40 tons (80,000lbs). The DOT limits the size of the truck to 259.08 cm (102 inches) wide and 411 cm (13.5 feet) high.

In addition to the size and weight dimensions, the regulations governing the transport of radioactive materials are also referenced. Provided by the International Atomic Energy Association (IAEA), these dose values apply to radioactive materials being packaged and carried over the interstate. Although our source is an electron beam that can be turned off while in transport, the worst case scenario the beam being accidentally left on after normal operation.

The operating voltage and energy of the electron beam must not be in excess of the desired limit to irradiate the food. Therefore careful calculations must be carried out to ensure that the food is irradiated enough to eradicate the harmful pathogens while at the same time not exceeding the limits provided by the governing body. The Food and Drug Administration allows for maximum beam energy of 10 million electron volts (10 MeV).

The food to be treated must receive only the amount of radiation needed to eliminate harmful bacteria. Different foods will require different dosages to irradiate them completely. For this purpose an article of the Food and Safety Act of 1990 has been included in Appendix A to reference dose limits for the foods being processed.

The design of an irradiation facility takes on many responsibilities in the safety of its integral parts. The many parts – ranging from health safety, to road restrictions for transport, and limited environment and community exposure – were all considered in our design. The regulations and operating limits outlined by the D.O.T., the IAEA, and the Food and Drug

Administration have been taken into account, and the design of our facility has been in accordance with their limits.

EXPOSURE AND DOSE

Irradiation units are typically quantified in terms of “exposure.” Exposure is defined for gamma and x-rays in terms of the amount of ionization they produce in air. The unit of exposure is called the Roentgen (R). It was originally defined as that amount of gamma or x-radiation that produces in air one charge of either sign per 0.001293 g of air (the mass of air occupying 1 cm^3 at standard temperature and pressure). The unit Roentgen is now defined as:

$$1R = 2.58 \times 10^{-4} \text{ C/kg} \qquad \textbf{(1)}$$

Absorbed dose is the measure of energy deposited by ionizing radiation in a medium. It is defined as the energy absorbed per unit mass from any kind of ionizing radiation in any target. The SI unit of absorbed dose, J/kg, is called the gray (Gy). The older unit of absorbed dose, the rad, is defined as 100 erg/g. One gray (1 Gy) is equivalent to 100 rad. The absorbed dose is treated as a point function, having a value at every position in an irradiated object.

Radiation with a higher linear energy transfer (LET) is generally more damaging to a biological system per unit dose than radiation with a low LET. Linear energy transfer is synonymous with stopping power. LET is defined as the quotient $-\mathrm{d}E_L/\mathrm{d}x$, where $\mathrm{d}E_L$ is the average energy locally imparted to a medium by a charged particle in traversing a distance $\mathrm{d}x$.[26]

Therefore, the LET of different types of particles (i.e. photons, electrons, neutrons) have different effects on the absorbed dose. Therefore, the equivalent dose (H_T) is a measure of the radiation dose to tissue with the relative biological effects of different types of ionizing radiation. Equivalent dose is therefore more biologically significant than absorbed dose. Equivalent dose has units of Sieverts (Sv). The equivalent dose is calculated by multiplying the absorbed dose to the organ or tissue (D_T) with the radiation weighting or quality factor, w_R: $H_T = w_R \times D_T$. Table 3 below contains the quality factor w_R value dependent upon the LET.[26]

Table 3 - Dependence of Quality Factor, w, on LET of Radiation[26]

LET keV/µm in Water	Q
≥3.5	1.0
3.5 - 7.0	1.0 - 2.0
7.0 - 23	2.0 - 5.0
23 - 53	5.0 - 10.0
53 - 175	10.0 - 20.0
Gamma rays, X rays, electrons, positrons of any LET	1.0

SHIELDING

Shielding the radiation that is generated from the electron beam and the associated radiation that is generated as by products from the electron beam such as x-rays and gammas is of significant importance. The purpose of the electron beam is to irradiate the food inside the beam’s path but dose to the surrounding area needs to be as low as reasonably achievable (ALARA). There are two concerns for this irradiation facility: 1) the amount of radiation produced when the electron beam is running at maximum capacity with no food present in the machine being irradiated and 2) when the machine is turned on and running at maximum capacity when food is present. Both present different scenarios of radiation production. When food is present, most of the energy will be absorbed by the food. The slowing down of the electrons will produce Bremsstrahlung radiation mainly at the food itself and secondary gammas and x-rays. Any electrons that escape from the food will have lower energies than they initially had. If no food is present, the electrons will have sufficient energy to travel to the top of the truck where shielding will be placed and the same radiation that would have been produced at the food is now being produced at the top of the truck. This presents a challenge because the electrons will have higher energies producing stronger radiation at the top of the truck because the electrons have not deposited some of their energy anywhere else other than the little that is lost in the air.

To begin trying to determine the shielding requirements the range of an unshielded 10 MeV electron needs to be figured out. The range R of the electron in low-Z materials is given by equations 2-5 with kinetic energy T in MeV (also see Figure 10):

For $0.1 \leq T \leq 2.5$ MeV

$$R = 0.412T^{1.27-0.0954*\ln T} \tag{2}$$

$$\ln T = 6.63 - 3.24(3.29 - \ln R)^{1/2} \tag{3}$$

For $T > 2.5$ MeV

$$R = 0.530T - 0.106 \tag{4}$$

$$T = 1.89R + 0.200 \tag{5}$$

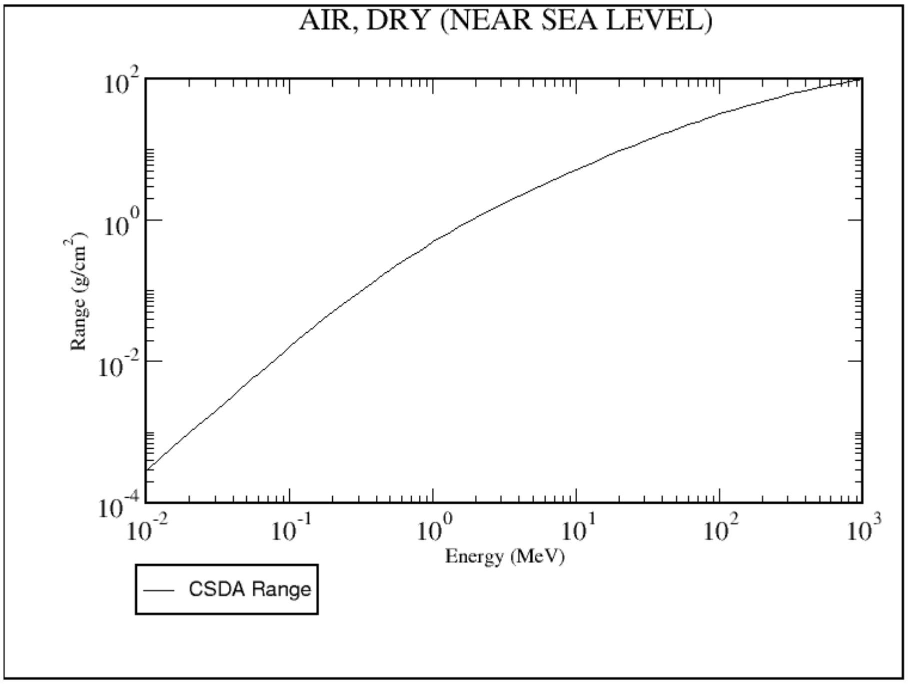


Figure 10 - CSDA Range for Air

In air, a 10 MeV electron will travel approximately 43.3 meters before losing enough energy to stop. This is greater than the height of our truck. Table 4 and Figure 11 below show that after 36 inches (91.44 cm) the electron does not lose much energy while traveling through the air (or 0.046MeV).

Table 4 - Data for the Range of Electrons in Air

Initial Electron Energy			10	MeV
Density of Air			0.0012	g/cc
Range of 10 MeV Electron			5.194	g cm^-2
Distance of 10 MeV Electron			4328.333	cm
			43.28333333	meters
inches	cm	Distance Difference	Range (g/cm^2)	Final Electron Energy
0.1	0.254	4328.079	5.194	9.999
0.2	0.508	4327.825	5.193	9.999
0.3	0.762	4327.571	5.193	9.998
0.4	1.016	4327.317	5.193	9.998
0.5	1.27	4327.063	5.192	9.997
1	1.524	4326.809	5.192	9.997
2	1.778	4326.555	5.192	9.996
3	2.032	4326.301	5.192	9.995
4	2.286	4326.047	5.191	9.995
5	2.54	4325.793	5.191	9.994
10	5.08	4323.253	5.188	9.988
15	7.62	4320.713	5.185	9.983
20	10.16	4318.173	5.182	9.977
25	12.7	4315.633	5.179	9.971
30	15.24	4313.093	5.176	9.965
35	17.78	4310.553	5.173	9.960
36	20.32	4308.013	5.170	9.954

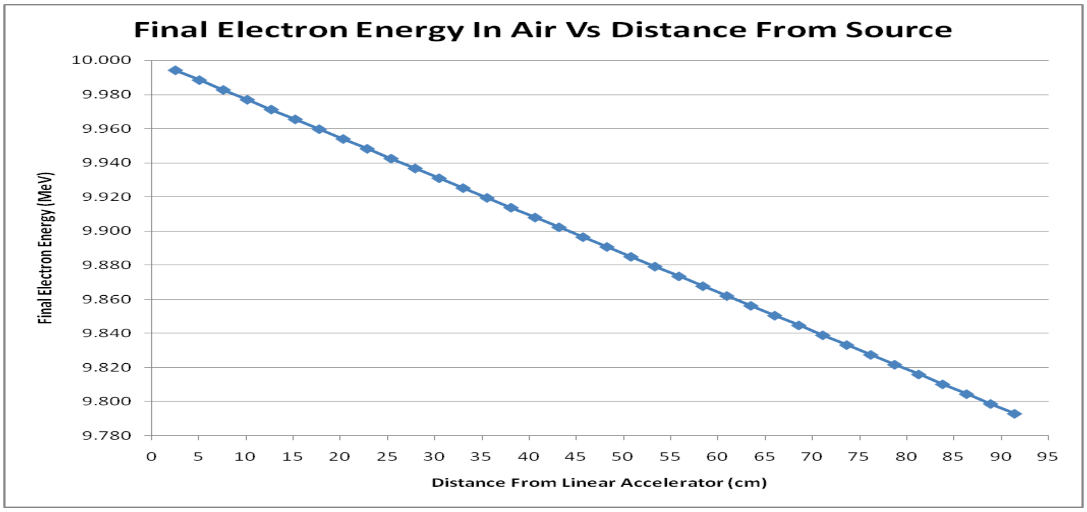


Figure 11 - Electron energy as a function of distance (10 MeV electrons)

The same principles that applied to determining the range in air can be applied to find the ranges for the electrons in water and lead. The following figures express the range in both water and in lead. As with air, water is a low-Z material and can follow equations 2-5. Lead is a high Z material so it follows a little bit different set of equations. But the same principle for calculating the range in lead is the same as for low-Z material, as illustrated in Figures 12-13.

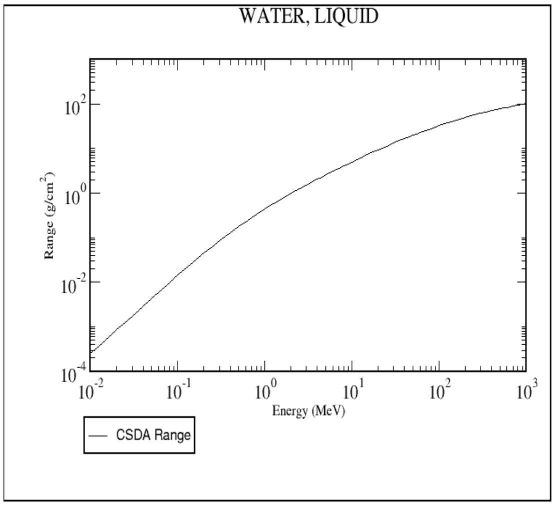


Figure 12 - CSDA Range for electrons in Water

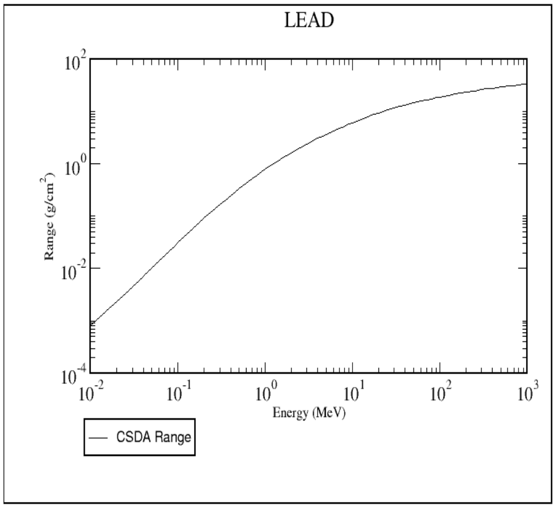


Figure 13 - CSDA Range for electrons in Lead

In a vacuum the electron would travel forever in theory, since there would be nothing to impede its travel. Outside a vacuum setting, though, the electron will encounter obstacles that will cause the electron to lose some of its energy and slow down. The electron can both collide with another particle and impart part of its energy to that particle or it can give off energy in the form of photons. Part of the radiative stopping power is when energy is released in the form of Bremsstrahlung radiation. Figure 14 shows the different ways that an electron can lose its energy when it transverses through lead.

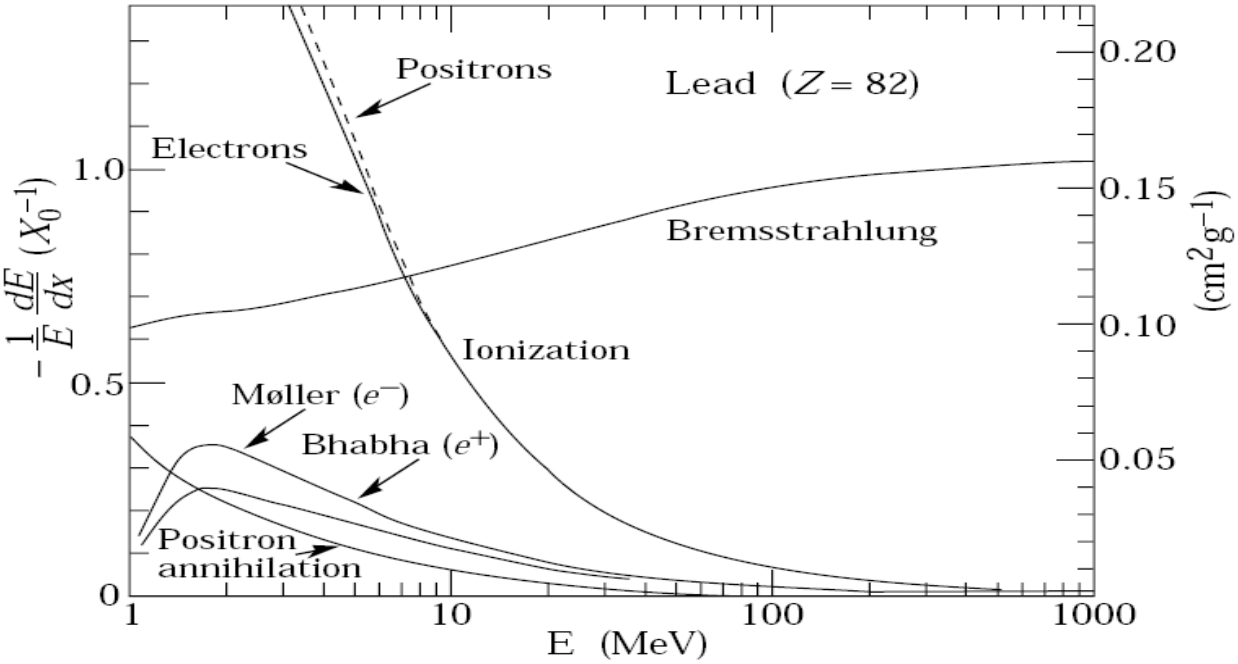


Figure 14 - Fractional Energy Loss for electrons and positrons in lead

Depending on how energetic the electron is and what material it is traveling in is how much energy the electron will lose and in what method it is more likely to that energy. The electron will lose more energy in a collision if the particle that it collides with is of the same relative size as the electron. At higher energies, the electrons will hit a target and scatter in the forward direction not losing much energy (Figure 15). But as the electron moves into the lower energy ranges it begins to impart more and more percentage of its energy into the particles it collides with. But if an electron hits a large target the energy transfer is small. So for materials that are high in hydrogen content, the electron can lose more energy in those mediums than for materials of high Z. So for collisional stopping power a low Z material is the best choice.

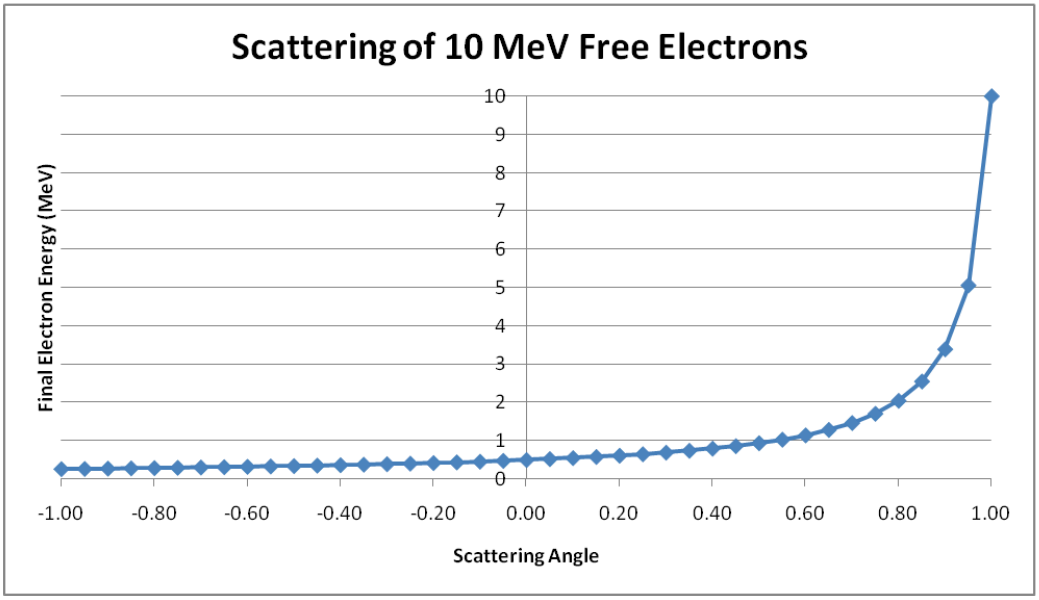


Figure 15 - Scattering of 10 MeV electrons as a function of scattering angle

Electrons, though, can lose energy without colliding with another particle. Electrons can give off energy in the form of photons. The photons are typically given off in the form of Bremsstrahlung radiation. Bremsstrahlung photons can have a maximum energy equal to the energy of the initial electron. Bremsstrahlung radiation, or braking radiation as it sometimes refer to, is produced when the electrons slow down in a given direction. When an electron changes directions due to scattering, it slows down in the direction in which it was initially traveling and it starts to travel in a different path. That change of direction releases photons. The directional change can be from a result of colliding with another particle or it could be due to charge repulsion or attraction. Electrons are negatively charged particles. When this negative charge comes in contact with another negative charged particle field it is repelled. This repulsion changes the direction of the electron releasing energy. Likewise, if the electron's negative charged field came into range of a positively charged field it would be attracted to the oppositely charged field and would bend its trajectory and energy would be released from the resultant direction change (Figure 16).

However, the photons that can be generated from the electrons can have a maximum energy equal to that of the electron. Photons travel greater distances before slowing down than that of electrons. Photons have to collide with more particles to lose the same amount of energy that an electron would lose in a single collision. For this reason, higher density materials like lead are better at stopping photons because there are more particles per unit volume. The photon will travel through more particles, thus imparting more energy to that particular material (Figures 17-18). Figures 19-22 demonstrate stopping power for common materials.

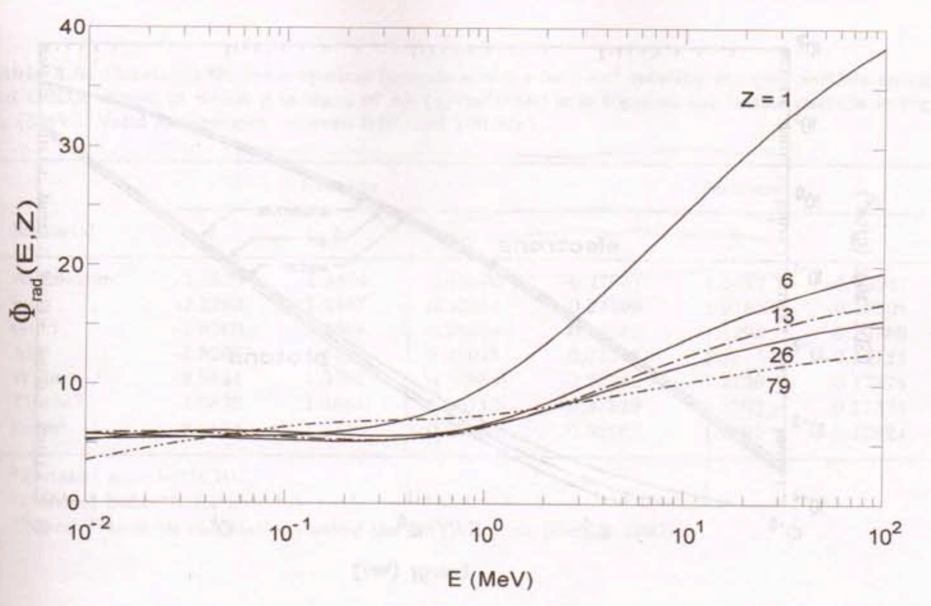


Figure 16 - Scaled dimensionless radiative energy loss cross-sections for electrons in various media

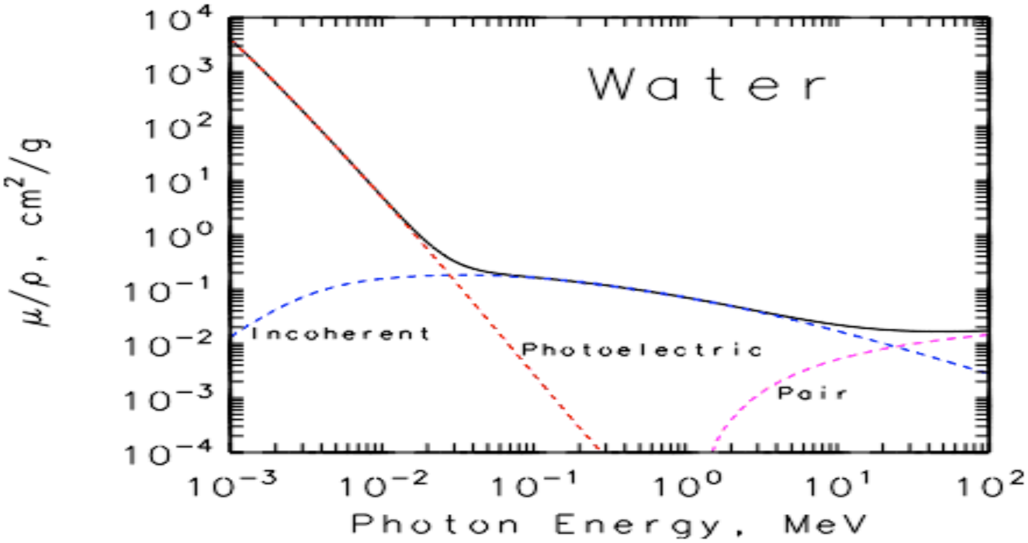
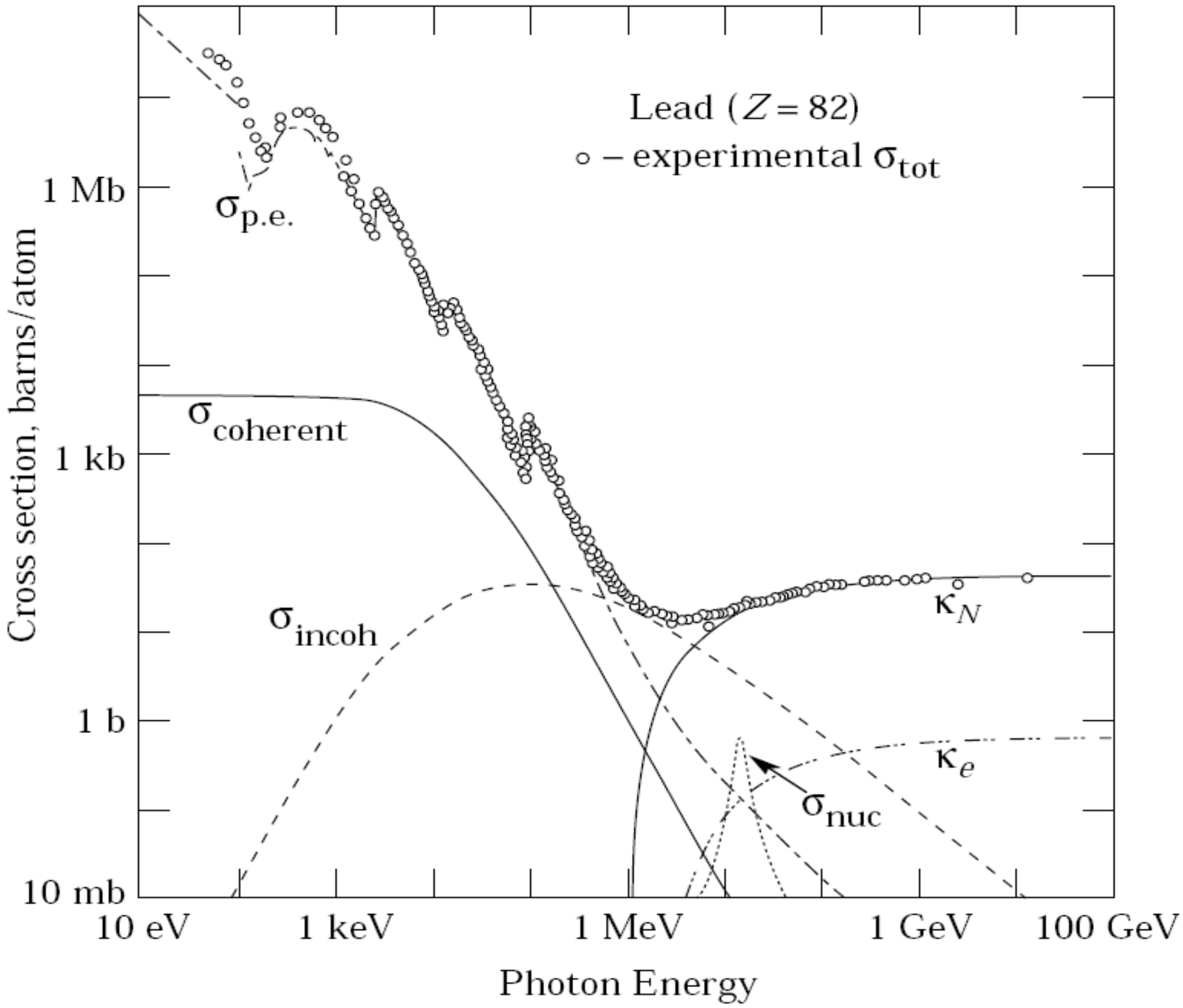


Figure 17 - Photon cross-sections for water



$\sigma_{p.e.}$ = Atomic photo-effect (electron ejection, photon absorption)
$\sigma_{coherent}$ = Coherent scattering (Rayleigh scattering—atom neither ionized nor excited)
$\sigma_{incoherent}$ = Incoherent scattering (Compton scattering off an electron)
κ_n = Pair production, nuclear field
κ_e = Pair production, electron field
σ_{nuc} = Photonuclear absorption (nuclear absorption, usually followed by emission of a neutron or other particle)

Figure 18 - Photon cross-sections for lead

An estimate of radiation yield can give an indication of the potential Bremsstrahlung hazard of a beta-particle source. The initial kinetic energy T of the electrons in MeV that are stopped in an absorber of Z atomic number is given by equation 6 and sample values listed in Table 5.

$$Y \cong \frac{6X10^{-4}ZT}{1+6X10^{-4}ZT} \tag{6}$$

Table 5 - Electron Radiation Yield, Y(T)

T (MeV)	Water	Air	Pb	Al	Mo	Fe	C
0.1	0.0006	0.0007	0.0116	0.0014	0.0054	0.0031	0.0050
0.2	0.0010	0.0011	0.0212	0.0022	0.0093	0.0052	0.0009
0.5	0.0020	0.0022	0.0424	0.0043	0.0179	0.0100	0.0018
1.0	0.0036	0.0040	0.6840	0.0764	0.0297	0.0170	0.0034
1.5	0.0053	0.0058	0.0901	0.0110	0.0410	0.0239	0.0050
2.0	0.0071	0.0077	0.1096	0.0145	0.0519	0.0310	0.0067
4.0	0.0149	0.0158	0.1761	0.0292	0.1136	0.0595	0.0142
6.0	0.0233	0.0242	0.2304	0.0444	0.1325	0.0874	0.0222
8.0	0.0319	0.0327	0.2765	0.0596	0.1677	0.1139	0.0304
10.0	0.0406	0.0411	0.3162	0.0745	0.1999	0.1389	0.0387
15.0	0.0622	0.0618	0.3955	0.1105	0.2689	0.1951	0.0595
20.0	0.0833	0.0817	0.4555	0.1438	0.3252	0.2435	0.0798
50.0	0.1920	0.1825	0.6439	0.2959	0.5249	0.4328	0.1856
100.0	0.3190	0.3022	0.7617	0.4448	0.6673	0.5848	0.3181

Y(T) is the fraction of the initial kinetic energy T lost as Bremsstrahlung. The Yields do not account for the minor effects of radiation losses from energetic secondary electrons (Delta Rays) produced during the deceleration of the primary electron.

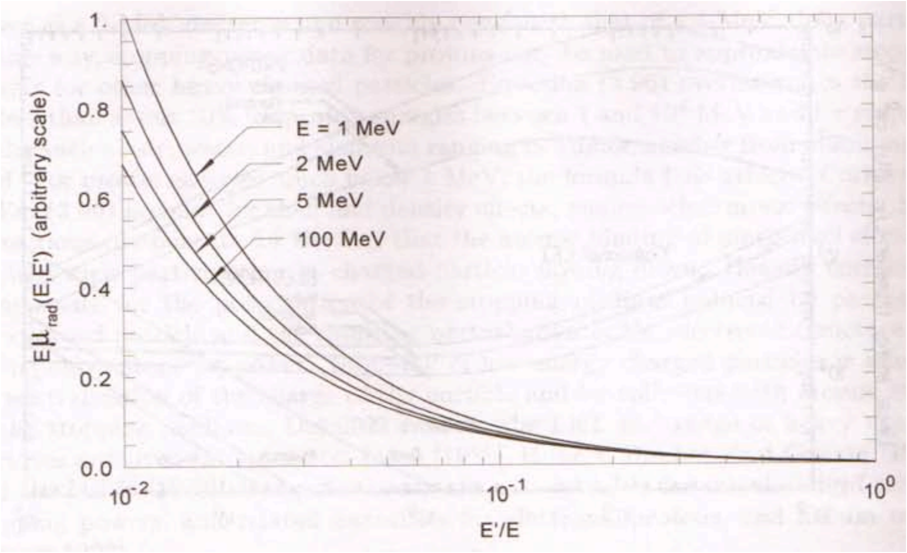


Figure 19 - Energy spectrum of Bremsstrahlung photons released in lead by radiative energy losses of electrons with initial energy E^{2}

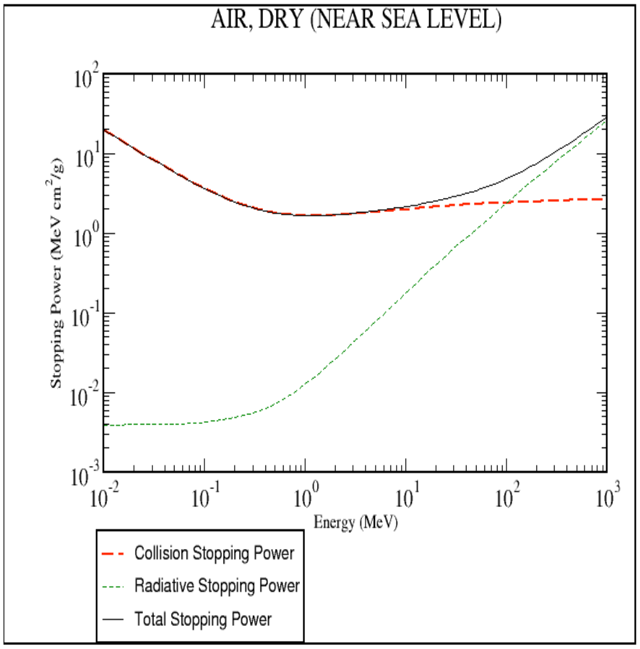


Figure 20 - Stopping power for photons in Air

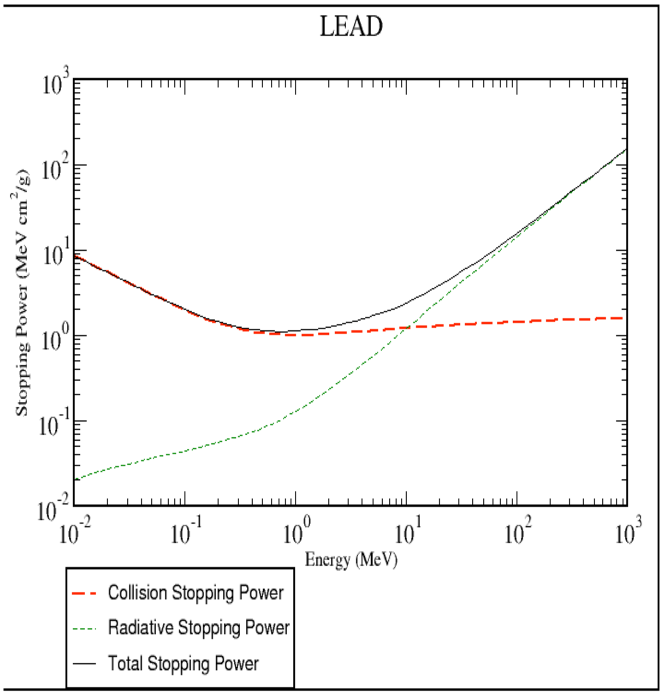


Figure 21 - Stopping power for photons in Lead

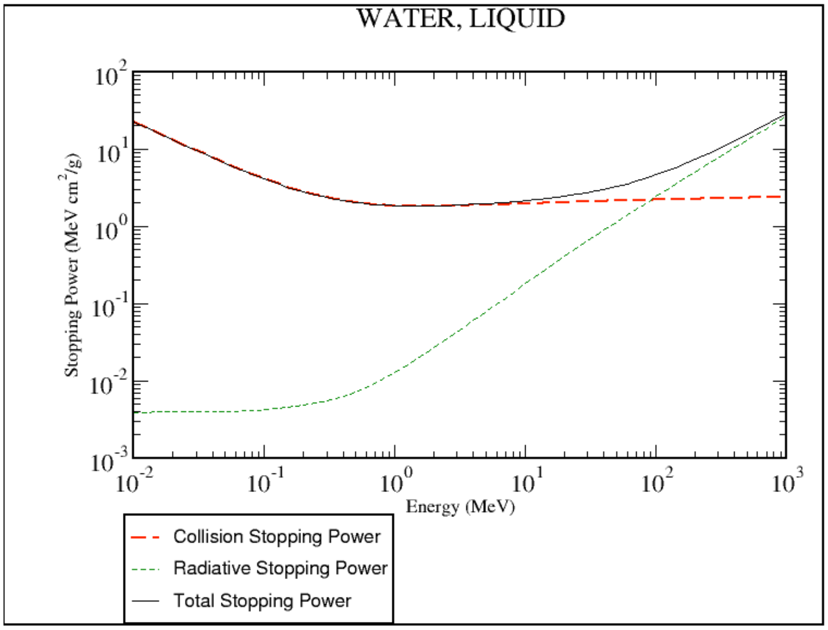


Figure 22 - Stopping power for photons in Water

However, the photons that can be generated from the electrons will have a maximum energy equal to that of the electron. Photons travel greater distances before slowing down than electrons. Higher density materials like lead are better at stopping photons because there are more particles per unit volume. The photon will travel through more particles imparting more energy to that particular material.

SHIELDING CALCULATIONS

The shielding around the area where the food is being irradiated needs to be considered. Lead will be the primary material to be used to shield the radiation that is being generated inside the food irradiator trailer. Structural members used to hold the linear accelerators and lead in place, as well as structural materials that make up the trailer, are not being considered at this moment in the shielding calculation. These members will only aid in reducing the amount of radiation that is received to the outside of the trailer.

For a 10 MeV electron source only one type of radiation field needs to be considered: electromagnetic component (gammas, electrons, and positrons)[1]. The beam power is 4 mA, which corresponds to $N_e = 2.5 \cdot 10^{16}$ e^-/s.

Lead will be placed on five surfaces surrounding the food – top and sides. Underneath the linear accelerator is the single area that will not have lead placed around it due to the fact that if any electromagnetic components scatter back through that area it will be directed to the ground. The ground will be whatever the trailer is sitting on when it is being used. The lead will be 20 cm thick on all sides and 30 cm on top perpendicular to the beam.

PERPENDICULAR SHIELDING

Equivalent Dose from the Electromagnetic Component[1]

At 20 cm distance, for $5 \cdot 10^9$ electrons of energy 6.3 GeV, the dose will be 150 mSv. The electromagnetic component of the dose rate immediately outside the shield of the 20 cm lead will then be given by ($\lambda_{lead} = 0.7$ cm^{-1})[1].

A significant part of the normal beam losses is inelastic scattering against nuclei in gas molecules. Bremsstrahlung radiation will be produced, and the main point where it needs to be stopped is downstream from the straight sections. Since the mean current will be around 4 mA, the production rate for this current is $2.5 \cdot 10^{16}$ e^-/s. It will also be assumed that this machine will operate around 970 Torr. The constituent molecules will then be, for our case, comparable with air molecules. One radiation length in air is 308 m at atmospheric pressure. The straight sections will be around 0.305m. Equations 7-8 calculate the dose as:

$$n = \frac{0.305x970}{308x760} 2.5x10^{16} \qquad \textbf{(7)}$$

n = 3.16·10^{13} e^{-}/s

$$H_\gamma = \frac{3.16 \cdot 10^{13}}{5 \cdot 10^{9}} \frac{0.0095}{6.3} 150 e^{-30 \cdot 0.7} 3600 \text{mSv/h} \qquad \textbf{(8)}$$

H_γ = 0.0039 mSv/hr

LATERAL SHIELDING

Equivalent Dose from the Electromagnetic Component[1]

$$H_\gamma(x,\theta,d) = D_T(\theta) A_T e^{-\lambda x} / d^2 \qquad \textbf{(9)}$$

$D_T(90^\circ) = \frac{0.0095\text{GeV}}{5\text{GeV}} 5\text{mSv} = 0.0095 \text{ mSv}$, for 10^{11} e^{-} and at 1m distance;

A_T = 0.3 λ_{lead} = 0.7 cm^{-1} d=150 cm x= 20 cm

$$H_\gamma(x,\theta,d) = \frac{3.16x10^{13}x0.30x0.0095x\ e^{-0.7x20}}{1x10^{11}} \frac{3600\text{mSv/hr}}{150^2}$$

$H_\gamma(x,\theta,d)$ = 1.2E-4 µSv/hr

SKY-SHINE RADIATION SHIELDING

Radiation scattered through air or "sky-shine" (for example, due to a weaker shield on the accelerator roof) may cause radiation at remote occupied areas which are not in direct sight of the accelerator. Sky-shine may contribute to the dose to the public beyond the boundary of the accelerator site.

The long distance sky-shine propagation of neutrons (only neutrons are considered) that escape the shielded accelerator roof can be found from the expression[22],

$$D(Sv/year) = 6.67 \times 10^{-17} N' \frac{E}{r^{1.5}} e^{-\lambda x} \tag{10}$$

Where *D(Sv/year)* is the equivalent dose per year, *N'* is the number of electrons lost per year at specific point along the beam and *r* is the distance, in meter, from the source.

An assumption of 10% loss of electrons per year, 9.97E19, has been taken to evaluate the sky-shine after 0.3 meter of lead as a roof; the annual doses are presented below for different distances from the source point with λ=0.7 cm-1 and x =30 cm. Table 6 below lists the predicted dose rate from sky-shine

Table 6 - Dosage from Sky-shine

r (Meters)	Equivalent Dose (Sv/yr)	Equivalent Dose (mSv/yr)
1	5.042E-05	5.042E-03
3	9.704E-06	9.704E-04
5	4.510E-06	4.510E-04
10	1.595E-06	1.595E-04
15	8.680E-07	8.680E-05
20	5.638E-07	5.638E-05
25	4.034E-07	4.034E-05
50	1.426E-07	1.426E-05

LINEAR ENERGY TRANSFER IN FOOD

The ultimate purpose of the food irradiator is to use the transfer of energy from the electrons and its associated photons it produces to the food that is being irradiated. To figure out the amount of dose that is supplied to the food, the Linear Energy Transfer (LET for water, shown in Figure 23) needs to be calculated. The food will be modeled as a block of water.

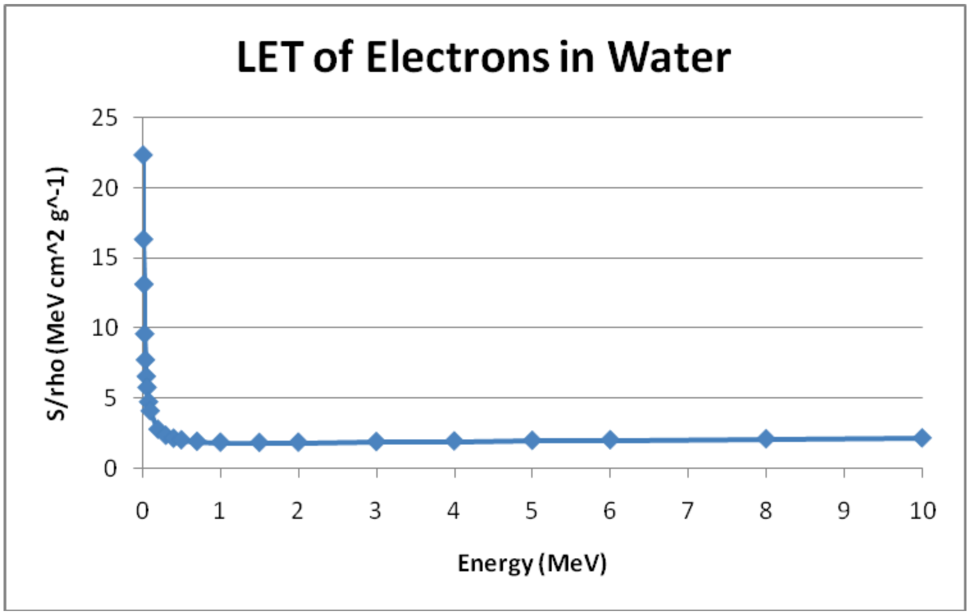


Figure 23 - Linear Energy Transfer for electrons in water

Table 7 is an extension of Table 5 previously mentioned above. The electron does not hit the food with the intial 10 MeV. Table 7 takes into account that the electron has lost some of its energy while traveling through the air. The lost of energy effects how far the electrons can travel through the food. Water is considerably denser than air is; this increase in density will slow the electron even further down. Table 7 shows that the electron will travel approximately 5.0 to 5.20 cm in water before losing all of its energy, as demonstrated in Figure 24.

Table 7 - Electron distance in water

Density of Water 1 g/cc

Initial Electron Energy (MeV)	Range (g cm^{-2})	Distance in water (cm)
9.999	5.194	5.194
9.999	5.193	5.193
9.998	5.193	5.193
9.998	5.193	5.193
9.997	5.192	5.192
9.994	5.191	5.191
9.988	5.188	5.188
9.983	5.185	5.185
9.977	5.182	5.182
9.971	5.179	5.179
9.942	5.164	5.164
9.914	5.148	5.148
9.885	5.133	5.133
9.856	5.118	5.118
9.827	5.103	5.103
9.799	5.087	5.087
9.793	5.084	5.084

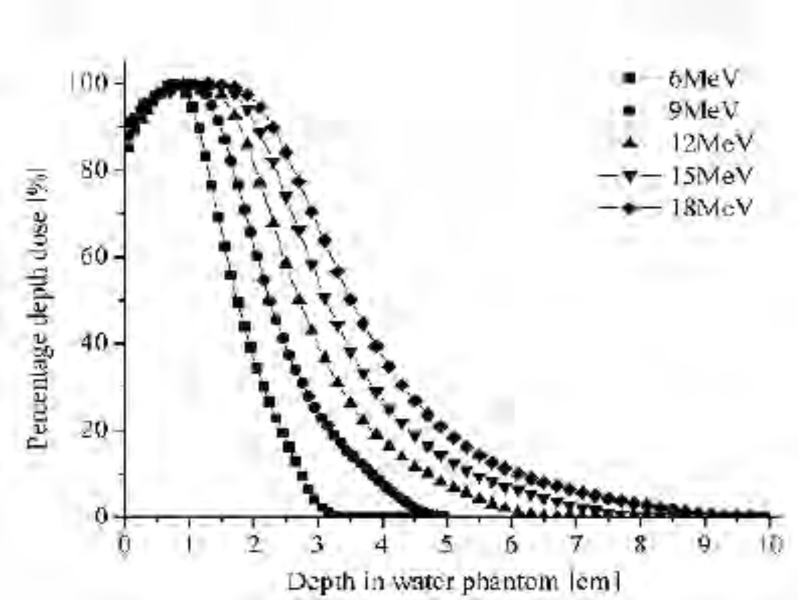
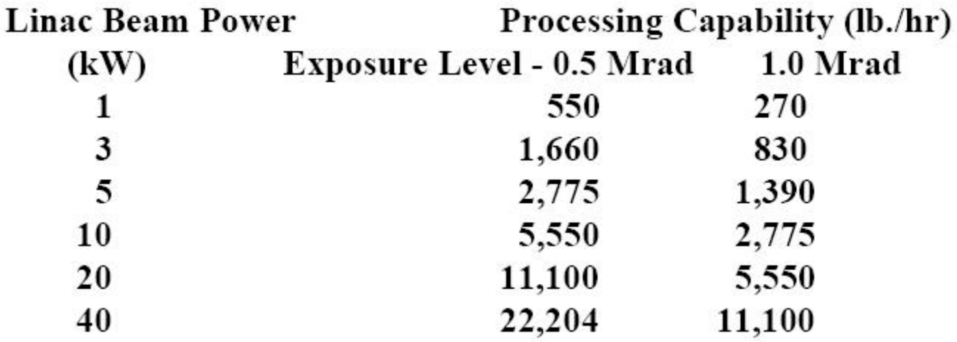


Figure 24 - Electron depth percentage in water for varying energies

The electron is depositing all of its energy within that range of distances. But, as previously stated, the electron is not depositing all of its energy directly into the water.

Some of the converted energy has went into the creation of photons and x-rays. Table 7 shows that about 4% of the energy transferred from the electron goes into the creation of Bremsstrahlung radiation which eqates to appoximately 400 keV worth of energy in the from of Bremsstrahlung photons. Photons have a much higher penetrating abilities and not all the energy of the created photons released from the electrons will deposit their energy before escaping the food. So a rough ball park estimate of the amount of energy being deposited per electron is about 9.5 MeV. Table 8 provides a rough estimate of the power required for certain electron beam energies.

Table 8 - Product power requirements



Linac Beam Power (kW)	Processing Capability (lb./hr) Exposure Level - 0.5 Mrad	1.0 Mrad
1	550	270
3	1,660	830
5	2,775	1,390
10	5,550	2,775
20	11,100	5,550
40	22,204	11,100

$$D \cong \frac{9.5MeV * 1.602 * 10^{-13}J/MeV * 3.16 * 10^{13}e/s}{1.0kg/m\text{^}3} \tag{13}$$

$$D \cong 48.09\ Gy\ m^3/s$$

The maximum dose that the food that will be ran through this food irradiator is on the order of approximately 3 kGy. At the rate at which energy is being deposited into the food this will take about 62 seconds to irradiate a 1 cubic meter of water. The food will be sent through the irradiation zone in a single layer. The food being irradiated is only one layer thick. Pending on the type of food being irradiated at that particular time will determine the thickness of water being modeled.

ADDITIONAL INFORMATION

The actual set up of the truck has support member made of steel located throughout the irradiated site. For example, the lead at the top of the truck used to shield against radiation from escaping is supported by a steel basket. On the other side of the lead is another layer of air and finally before the radiation exits the truck it goes through a layer of aluminum that comprises part of the truck itself. These additional layers that the radiation will have to attenuate through will reduce the amount of dosage on the outside of the truck even further.

The outside of the top layer of lead shielding has 0.0039 mSv/hr. This is the worse case scenario when there is no food in the path of the beam to absorb energy. The beam is pointed on purpose up at the sky. This is for the fact that the air at the top of the truck is being irradiated. Air is vast, dynamic, and constantly moving. Any activiation of particles in the air will be quickly diluted and transported away in the atmosphere which was the raise of concern for sky-shine.

Another source of error is the air in which the beam is traveling through. The air was modeled as dry air. Pending on the humidity of the air at the time of use will change the amount of dosage received. The higher the humidity the more water content is in the air which increases the density of the air.

FUTURE WORK

Currently, the dose calculations were performed with hand calculations. To be more precise a computer generated code, like MCNP, needs to be run to get a more detail approximation of what the dose to the public and to the food actually is when in operation. Also, to further reduce time a second linear accelerator should be tested to see where the optimal location would be for it. The second linear accelerator would cut the time down for how long the food would need to be in the irradiator. However, this second linear accelerator would add to the dose and require a substantial addition of shielding.

A conveyor belt system will experience radiation damage during operation of the linear accelerator. The electron permeable window used in the area of irradiation decreases the amount of conveyor belt that will experience radiation damage. The electron permeable window may also experience radiation damage however it will be easy to replace since the entire belt does not need to be removed for replacement of the window. Since the electron permeable window is over the area of irradiation, the conveyor belt will receive minimal radiation dose. However, normal wear on the belt will require replacement of the belt. The conveyor system allows for a simple procedural replacement of the conveyor belt on either side of the electron permeable window.

CONCLUSIONS

The facility described successfully accomplishes all of the group’s goals. It is economical and competitive with other methods. Our predicted dose to the environment is within reason, and procedures have been outlined to protect personnel and keep them within the safe operating limit. We believe this design will be helpful in emergency situations, where it can be deployed quickly, as well as enable small farmers to easily and cheaply pasteurize their product.

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Appendix A – Federal Regulations

During transport:

Packages, *overpacks* and *freight containers* containing *radioactive material* and unpackaged *radioactive material* shall be segregated during transport and during storage in transit:

(a) from workers in regularly occupied working areas by distances calculated using a dose criterion of 5 mSv in a year and conservative model parameters;
(b) from members of the critical group of the public, in areas where the public has regular access, by distances calculated using a dose criterion of 1 mSv in a year and conservative model parameters;
(c) from undeveloped photographic film by distances calculated using a radiation exposure criterion for undeveloped photographic film due to the transport of *radioactive material* of 0.1 mSv per *consignment* of such film; and
(d) The *radiation level* under routine conditions of transport shall not exceed 2 mSv/h at any point on, and 0.1 mSv/h at 2 m from, the external surface of the *conveyance*, except for *consignments* transported under *exclusive use* by road or rail, for which the radiation limits around the *vehicle* are set forth in paras 573(b) and (c).

On Irradiating Food:

(1) In these Regulations, except where the context requires otherwise
"the Act" means the Food Safety Act 1990;
"food" has the meaning which it has in section 16(5)(a) of the Act;

(2) For the purposes of these Regulations—
(a) "properly irradiated food" means food—
(b) food falls within one of the seven permitted descriptions of food when (excluding the weight of any added water) no less than 98 per cent of it by weight falls within that description,
(c) the seven permitted descriptions of food are—
(i) fruit,
(ii) vegetables,
(iii) cereals,
(iv) bulbs and tubers,
(v) spices and condiments,
(vi) fish and shellfish, and
(vii) poultry;
(d) in those seven permitted descriptions of food—
(i) "fruit" includes fungi, tomatoes and rhubarb,
(ii) "vegetables" excludes fruit, cereals, bulbs and tubers and spices and condiments but includes pulses,

(iii) "cereals" has the meaning which it has in the Intervention Functions (Delegation) Regulations 1972;
(iv) "bulbs and tubers" means potatoes, yams, onions, shallots and garlic,
(v) "spices and condiments" means dried substances normally used for seasoning,
(vi) "fish and shellfish" includes eels, crustaceans and molluscs, and
(vii) "poultry" means domestic fowls, geese, ducks, guinea fowls, pigeons, quails and turkeys;
(e) food has been over-irradiated when the overall average dose of ionising radiation absorbed by it, measured by the approved method of measurement, exceeds, in the case of food falling within the permitted description of—
(i) fruit, 2 kGy,
(ii) vegetables, 1 kGy,
(iii) cereals, 1 kGy,
(iv) bulbs and tubers, 0.2 kGy,
(v) spices and condiments, 10 kGy,
(vi) fish and shellfish, 3 kGy, or
(vii) poultry, 7 kGy.

Source: Food and Safety Act of 1990

a) Food treated with ionizing radiation shall receive the minimum radiation dose reasonably required to accomplish its intended technical effect and not more than the maximum dose specified by the applicable regulation for that use.

b) Radiation treatment of food shall conform to a scheduled process. A scheduled process for food irradiation is a written procedure that ensures that the radiation dose range selected by the food irradiation processor is adequate under commercial processing conditions (including atmosphere and temperature) for the radiation to achieve its intended effect on a specific product and in a specific facility.

(c) A food irradiation processor shall maintain records as specified in this section for a period of time that exceeds the shelf life of the irradiated food product by 1 year, up to a maximum of 3 years.

Source: Food and Safety Act Section 179.25

APPENDIX B

The construction of the mobile irradiation facility must be built on a solid design basis. The design of the facility is dependent on radiation exposure to the food, operators, and the environment. In order to protect operators and their respective environments, careful consideration must be taken in the analysis of radiation exposure. While our intent is to expose all food inside the eighteen wheeler to the irradiation process, it is crucial that none of the ionizing radiation escape from the shielded containment. For these reason's, models have to be made to examine the impact of the electron and photon presence in the material being irradiated. The shielding calculations presented show the importance of limiting the range of the electron beam to just its food target. This slowing down and attenuation of the electron due to its contact in lead reduces the amount of radiation exposure. With lead being the shielding material, it is hopeful that the computer model will give results that reflect doses being delivered to the food, while at the same time being shielded from the environment.

The computer code chosen to model the effect of this high energy electron beam on the food was the Monte Carlo N Particle (MCNP). While tutorials area available for the correct operation of this computer program, the student has received minimal explanation on how MCNP is run. Much of the design reflects that of the design presented in class. Had more time been allotted to work with the program the results may have been more favorable to the specifics of our design features. But following 2 runs and a 36 hour run time, analysis of the output deck was of utmost importance. Finding the answer proved harder than the creation of the input deck, but careful evaluation of the tallies and locations of photon/electron interactions painted the clearest picture.

The design of the input deck included an electron beam operating at 10 MeV, and it called for 390,000 particle tracks. The total amount of particles is directly proportional to the run time. So 390,000 particles were chosen and if any more tracks were needed it would merely reflect the same trend as can be seen in data. Also included in the input deck was the lead shield surrounding the beam and target at a thickness of 4 inches, as well as the air filling the rest of the void in the truck. The volume of the void is 8ft^3. The food to be irradiated was treated as water because of water's high density and its common use as a target substitute in the MCNP reference libraries. A design factor unique to the computer model was the division of the water block into layers. 6 even layers made up the whole 6 inch thick water block being irradiated. This unique feature would allow one to see how the dose was being distributed throughout the entire block. An ideal outcome would be for the dose at the front of the food to be the same as the dose in the back of the food. But as nuclear engineer's who understand real world physics it is understood that the penetration of X-rays is minimal (normally 1 - 3cm), and most electrons get attenuated before they can make it all the way through the food. For these reasons, the former theory shall fail.

In the output deck there were many relationships between surfaces and electron/photon interactions. The categories that model the effects of electron interactions in the materials are: the photon and electron importance, the photon and electron weight balance, and the photo atomic activity.

There are four surfaces on which these interactions occur and are noted by the respective material numbers. Material 1 was defined as the air between the water and the lead shield. Material 2 is the lead shielding. Material 3 represents the food being irradiated and is modeled as water in the calculations. Lastly, material 4 is the air outside the water and lead shield. The photon and electron interactions in these surfaces were compared and contrasted on the pie graphs provided to show where the electrons are interacting.

From the objectives of the experiment, one can hypothesize that the interactions would be greatest in material 3. This is desired because material 3 is the target food being irradiated. With interactions and activity greatest in this material, it shows that this is where the most attenuation is happening. With the attenuating and ionizing activity greatest in Material 3 it then follows that the food is being irradiated.

In the cases of the other materials, the activity and electron presence should be significantly lower than in material 3. These results would reflect the fact that the other areas in the facility are being shielded from the ionizing radiation. Lead is the shielding mechanism used. It is Material 2 and it surrounds the target and electron beam from the rest of the truck. The lead shielding will show some significant interaction with the electron beam because its job is to slowdown and attenuate any electrons that escape. The lead shielding will concentrate the beam energy on the target, thus keeping the operators and the environment safe.

Material 1 and 4 are modeled as the air that surrounds the target and the air outside of the shielding, respectively. The dose rates and electron/photon interaction in these material areas will be least. The goal of the shielding is to keep the radiation out of the air; for this is where operators and the outside world will be. Low electron activity in the air surrounding the system proves that the facility is safe for operators and shielded from the environment.

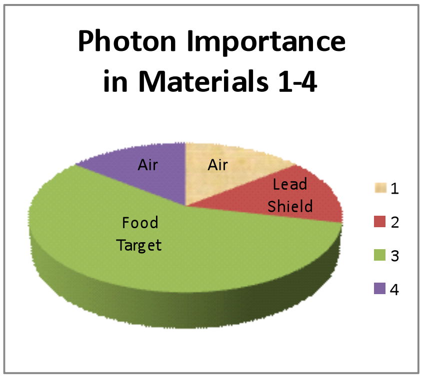

Figure 1 – Photon Importance

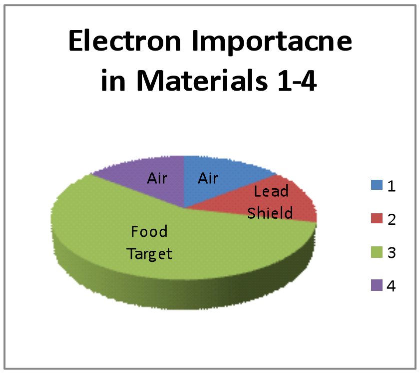

Figure 2 – Electron Importance

This figure is a normalized pie graph showing the electron/photon importance in material's 1-4. Electron importance is the count of electron activity in the material as compared to the other materials analyzed. It can be seen that the electron importance is greatest in Material 3 and least in all other materials. This data agrees with the hypothesis which states that because this is the target material being irradiated, electron importance is greatest here. Also this is the location that the 10 MeV electron beam is directed towards.

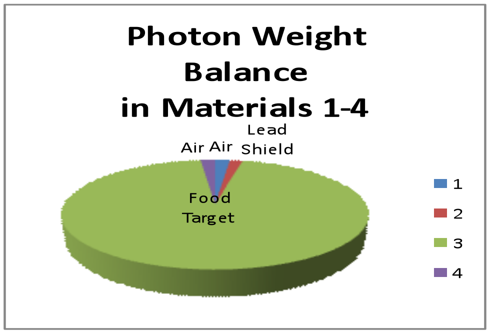

Figure 3 – Photon weight balance

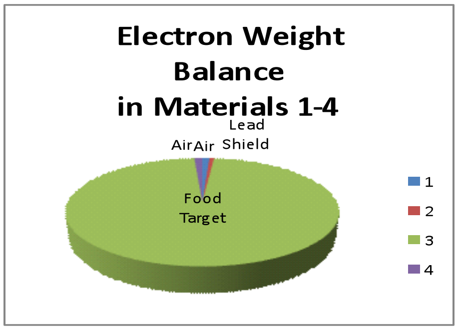

Figure 4 – Electron weight balance

This figure is a normalized pie graph showing the electron/photon weight balance in material's 1-4. The weight balance is a measure of the weight of electron and photon deposits in the material as compared to the other materials analyzed. It can be seen that the electron importance is greatest in Material 3 and least in all other materials. This data agrees with the hypothesis which states that because this is the target material being irradiated, electron/photon weight balance is greatest here.

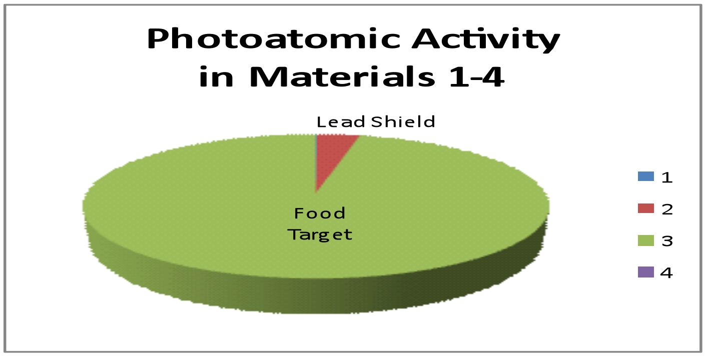

Figure 5 – Photoatomic activity

This figure is a normalized pie graph showing the photo-atomic Activity in material's 1-4. The photo-atomic activity is a measure of the activity of photon and electrons in the material as compared to the other materials analyzed. It can be seen that the photon activity is greatest in Material's 2 and 3, while it's least in all other materials. Material 2, the lead shield, was included here because of its shielding characteristics. In order for lead to work as a shield, the electrons must slow down and be attenuated in the lead. For this reason, Fig 4 shows that both the food and shield have a large number of photoatomic activity within their materials.

The Monte Carlo calculations proved of significant importance in the mobile food irradiator design. This computer program helped to identify where the dose was being delivered. It also showed where the dose wasn't being delivered due to the shielding. From Fig 6, it can be seen that the highest dose is being delivered to the food, marked in red. The lead shield received significant interaction and is marked in orange. Lastly, the air between and surrounding the facility is marked in yellow. This yellow color denotes the area of least activity. These results reflect the desired outcome of treating the food with ionizing radiation while protecting the rest of the world from radiation exposure.