

A Mobile Facility for Food Irradiation

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Abstract

This analysis details the design of a mobile food irradiator which can be transported to the desired location for irradiation of various food products. The design includes two electron accelerators, one above and one below the product, to allow for products up to 10cm in thickness to be irradiated. The accelerators have a variable power and can produce electrons from 5-10MeV which along with a variable speed steel mesh conveyor allows for control of dose received by the product. High density polyethylene blocks are utilized for shielding to stop electrons while minimizing Bremsstrahlung radiation and lead shields of 2-3cm in thickness are also used to reduced exposure and attenuate photons produced. The entire design fits into a standard semi tractor trailer container including cooling and vacuum systems. Preliminary calculations indicate that, with the proposed design, irradiation of more than 22 metric tons of product per hour can be achieved with little exposure to workers.

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1.0 Background and Purpose

Irradiation of food involves exposing food to ionizing radiation to destroy microorganisms, bacteria, viruses, or insects that could contaminate the food. Irradiation of food products can also delay ripening of fruit, cause sprout inhibition, increase juice yield and improve rehydration. This technology is also used for the sterilization of medical instruments, the manufacturing of plastics, and the processing of items ranging from tires to gemstones.

This analysis develops a mobile food irradiation device. It can be easily transported to wherever it is needed and is designed to provide a dose up to 1 kGy for food thicknesses less than 10cm, although higher doses are possible with special consideration. This design was targeted primarily for the delay of fruit ripening/spoilage and the inhibition of sprouting in some vegetables. This report details the use of an electron beam produced from a linear electron accelerator. There are other options for sources which will be detailed in this report. The design involves two linear accelerators, one above and one below the product, allowing the product to move on a conveyor between the beams and receive a more even dose of radiation throughout the entire volume of food.

For this design, a large diesel generator can be used to provide power for the entire facility, including the vacuum pump and cooling pump for the linear accelerator. The transport for the system will be a large fully enclosed truck for the protection of the linear accelerator. The shielding is detailed as high density polyethylene containing primarily hydrogen and carbon atoms (low Z materials) to minimize Bremsstrahlung

radiation production while stopping electrons. Behind the polymer is a lead shield to attenuate any Bremsstrahlung radiation that is produced as the electrons slow down.

Safeguards are also addressed to ensure the proper safety of all personnel in the area during operation. Regulations involved with the transport and use of a linear accelerator for food irradiation are also addressed in this report.

The process of mobile radiation technology would offer a promising means to control microorganisms such as bacteria and other pathogens, which cause millions of food borne illnesses and death each year. Food irradiation could help prevent many of the deaths and illnesses associated with certain types of coliforms such as *E. coli*, since these bacteria are easily killed when irradiated at small to medium doses.

2.0 Food Irradiation

Food irradiation is a safe process and has been approved by some 50 countries worldwide and applied commercially in the USA, Japan, and several European countries for many years (15). Approved irradiated foods include fruits, vegetables, meat, poultry, fish and seafood, roots and tubers, cereals, legumes, spices and dried vegetable seasonings (15).

The effect of radiation on food relates to damage to the cell caused by the ionization products produced from the radiation. The water molecules contained in the cell are ionized by the radiation and the reaction products remove chemically active species from the cell (3). This creates cell damage which ultimately leads to cell death. Another form of cell damage is by the interactions of the radiation with cellular DNA. DNA is the basic

genetic information that promotes life. When the DNA structure of microorganisms is irradiated, it can no longer proliferate or continue its pathogenic activity. This can be caused by direct or indirect effects of the radiation (3). Direct effects would be produced by the initial radiation with the molecule itself. One example is if the radiation acts on the DNA molecule and the ionization causes the molecule to break. Indirect effects are caused when the radiation interacts with a different molecule and the ionization of that molecule creates free radicals which in turn affect another molecule. These secondary molecules can be DNA or any other molecules in the cell which will eventually lead to cell death (3).

The treatment of foods by ionizing radiation can produce some of the same effects as heat pasteurization; however irradiation is able to cleave molecules and induce ionization that can not be achieved by heating (15). This allows the food to be processed without the need for heat.

When food is irradiated, it passes through an enclosed irradiation chamber where it is exposed to ionizing energy. This can be in the form of gamma rays from specific radioisotope sources, x-rays or electron beams from machine-made sources. All three types of ionizing radiation have the same ability to inactivate spoilage and disease-causing microorganisms without causing harmful changes to the food.

Regardless of the source of ionizing energy, the food is treated by exposing it to the radiation source for a precise time period. In the case of e-beam, food is irradiated in just a few seconds and the food is never in contact with the radiation source. The ionizing radiation penetrates into the food and deposits energy. Irradiation does not make food radioactive nor does it leave any residues (15). The levels of ionizing energy

used to treat foods for pathogen reduction or disinfestations are often measured in kilo Grays (kGy) which is defined as one joule per kilogram of absorbing material. This unit is a measure of dose. In food irradiation, the dose that the product receives is not something added to the food. The dose is the amount of energy absorbed by the food during the exposure time (15). The dose is controlled by the intensity of the radiation and the length of time the food is exposed to the source (3).

3.0 FDA Regulations on Food Irradiation

Food irradiation needs to be controlled in order to ensure safety. Many countries irradiate food and while no international standards exist, each country varies on rules and regulations for food irradiation. In the U.S. the FDA regulates the use of food irradiation and follows Title 21 of the code of Federal Regulations, Chapter 179 (1) “Irradiation in the Production, Processing, and Handling of Food”.

General guidelines for irradiation are found under 21CFR179.25. These guidelines include:

- The food type must receive the minimum dose (if the food has a required minimum dose), and no more than the maximum dose.
- Must follow correct packaging requirements
- Facility and process must conform to a scheduled process with written procedures and qualified personnel
- Must maintain records for a specific period of time. Records include type of food, scheduled process, evidence of compliance with schedule,

radiation source used, calibration, dosimetry, dose distribution and date of process.

All these are general guidelines and must be followed.

Section 179.26, Ionizing Radiation for the Treatment of Food, has limits on dose for multiple food groups as well as limits on radiation source strength. The maximum energy for an electron beam, the beam is limited to electrons no higher than 10 MeV. X-rays have a maximum energy of 5 MeV (1). As mentioned earlier there is no international standard set for food irradiation, however general agreement between several countries involved in the process have agreed on a maximum of a 10 kGy dose as safe for consumption in most food groups.

All foods that have been irradiated must be labeled, mainly to inform the customer that food has undergone the process. The standard radura symbol must be placed on the package and the words “Treated with Radiation” or “Treated by Radiation” must appear on the package as well. If the food is unpackaged it must bear the same sign and wording, however since it is unpackaged the labeling must be placed on the bulk package, container or some other appropriate device (1).

All facilities involved in food irradiation must follow these guidelines in order to operate.

4.0 Current Food Irradiation Facilities

Food irradiation is a relatively new and under used option when it comes to extending the life of food. As such there are not very many places which have expanded and used this ability to great effect. In many countries there are only one or two food

irradiators; however there are 6 in France and as many as 5 irradiators in Brazil (13). There are six main contractors who build the irradiation facilities in North America. Several of these companies sell to other countries and corporations, where their irradiators are used for the sterilization of surgical equipment to destroying parasites in foods.

A few different problems have slowed down the growth of irradiating foods. One problem which has stunted the growth of irradiation is the stigma that comes with the word radiation. Another problem is the cost to build the facility, especially if Cobalt 60 is used. The facility will cost anywhere between \$3 to \$5 million depending on the size and the source strength. Finally, another detractor from food irradiation is the fact that in order to be competitive the facility has to get the food processed without being cost prohibitive. For example, the irradiation of meat is economically viable only if the irradiation cost is around 7 to 10 cents per pound (14). These factors combine to make food irradiation look less attractive to the consumer.

There are also safety concerns with irradiation facilities which include health of workers, general public exposure and ecological effects. Previous use of Cs-137 has been eliminated since the salt mixture containing the source can dissolve, causing a containment hazard (18). There have also been minor accidents involving workers in electron beam facilities mostly due to workers going into unauthorized areas while the electron beam was in operation. Despite some public concern over irradiation facilities, many countries that have an agricultural export of fruits or vegetables have gone to using food irradiators of some kind whether they are electron beams, x-rays or gamma source.

5.0 Economics of Food Irradiation

According to USDA tests, irradiation doses of 3.0 kGy eliminate over 99 percent of the Salmonella organisms contained in poultry. For ground beef, irradiation doses up to 0.8 kGy eliminated greater than 90 percent of five common pathogens (*E. coli*, *Campylobacter jejuni*, *Listeria monocytogenes*, *Salmonella*, and *Staphylococcus aureus*) in 1993 tests by the Center for Food Safety and Quality Enhancement at the University of Georgia (17).

By killing pests on domestic and imported produce, irradiation eliminates the need for post-harvest fumigants that can leave undesirable residues. It also reduces the need for pesticides when crops are cultivated. Pesticides have been proven to cause health effects if digested or inhaled.

Irradiation decreases post-harvest food losses, according to the International Atomic Energy Agency (IAEA) (18). The process can extend the shelf life of food by inactivating spoilage organisms and, in some produce, by delaying ripening and sprouting. The results could be beneficial to human and environmental effects by reduced or elimination of chemical treatments (16).

In the US alone for example in 2009, Salmonella in peanut butter from Peanut Corporation of America in Georgia has become one of the nation's worst known outbreaks of food-borne disease in recent years. Nine people have died and an estimated 22,500 were sickened due to tainted peanut butter. The peanut processing company is going out of business after losing over \$1 billion (20). This would have been prevented

if mobile food irradiation technology had been available at the factor or distribution center.

6.0 Radiation Sources

In investigating possible radiation sources, several criteria were carefully considered. The source of the radiation must be constant and consistently produce radiation at the specified energy to provide the best results for the product. The source needs to be transportable and safely shielded at all times. The dose also needs to be sufficient to achieve the desired results for the customer, which could range from extending shelf life to sterilization. The radiation source needs to be cost effective. If it costs more to operate or requires more power than can be provided on a mobile basis, then it is not a viable option. Also, the throughput of product based on the energy of the source and the needs of the customer must be high enough to justify its price and difficulty of use. Given these requirements, three options for the source of radiation of the food irradiation system were considered: cobalt 60, x-ray beam and electron beam.

6.1 Cobalt-60

First, a Cobalt 60 source was considered. Other isotopes were not considered since Cobalt 60 is the primary source used in current stationary food irradiators. This source would require no power since it produces radiation by spontaneous decay. Also, it would require only safety systems but no other support systems such as pumps or cooling. Co-60 emits gamma rays which provide adequate penetration of the product being irradiated (4). Good penetration is important in food irradiation so that the full volume of the food product receives the same dose (4). However this source posed the

major problem for transportation. The regulations restricting the use of Cobalt 60 are very detailed and strict. Transporting the radioactive isotope is possible; however, the amount of paperwork, just to move the source across a state line, would be prohibitive (5).

Besides the transportation issue, another problem with Cobalt 60 is shielding. Since Cobalt 60 is always emitting gamma radiation through spontaneous radioactive decay, the issue of continually shielding the source poses a serious problem. In order to provide the required dose to the product at an economically efficient speed, a high activity source would be needed, which would consequently require a large amount of the radioactive material. The Cobalt 60 source is isotropic; meaning that it would emit radiation in all directions, not just the direction of the product to be irradiated. This would require shielding all around the source. Thus the shielding would have to be the same around the entire source with a small opening or aperture for the food product to receive radiation. The half value layer for Cobalt 60 is 1.25 cm for lead. Thus, the lead shield would have to be around a half a meter to attenuate the radiation flux to a safe level for a 1 kCi source. The extra weight added to the system would prevent it from being considered mobile. The amount of Cobalt 60 needed for the radiation would also have to be loaded into the irradiator by some means while still maintaining shielding and mobility (4). Between the transportation, shielding and loading downfalls, Co-60 was eliminated as an economically or logistically viable source.

6.2 X-ray Machines

Next, an x-ray beam was analyzed for a source for mobile food irradiation. The x-ray beam provided the option of powering down the source for transportation. This would

eliminate a majority of the regulations involved with transportation (6). X-rays also have a good depth of penetration and would deliver a constant dose throughout the product (6). Although the transportation issue is solved there are other issues that need to be considered. X-ray systems are very inefficient at energy conversion from power to the x-ray system to beam power. The x-rays are produced by accelerating electrons into a Tungsten target. This then produces x-rays which are directed toward the target food to be irradiated through an aperture. This conversion process is very inefficient, on the order of 4 to 6% energy conversion (7). Thus to provide the product with the needed amount of energy for the proper dose a massive amount of electricity would be needed to power the x-ray beam source.

Another problem with the x-ray source is the fact that a massive amount of shielding would also be needed. An x-ray of only 5 MeV would require around 1.6 cm of lead shielding to reduce the radiation to one-half the incident number. Assuming that the x-ray flux is 3% of the electron flux, the amount of lead required to reduce the x-ray flux to an acceptable level would be on the order of meters. This would dramatically increase the weight of the system. The x-rays would have to be very energetic to provide the required dose, so the shielding would have to be thick enough to stop these highly energetic x-rays. The weight of the lead prevents the system from being considered mobile. In addition to stopping the x-rays, the shielding would have to stop any by-products produced from the x-rays interaction with matter in the irradiator. The x-rays could produce other forms of radiation through interactions with the product, the shielding, the conveyor, or any of the equipment contained in the irradiation system (7). These products can range from heavy charged particles to even the possibility of

photonuclear processes, which would also have to be considered for shielding. Finally the x-ray source is not very robust. X-ray sources can be difficult to transport due to the electronics and elements used in the production of the x-rays. After this analysis the x-ray source was eliminated primarily due to its massive shielding requirements. The next source examined was the electron beam.

6.3 Electron Beam

The type of electron beam production considered for this food irradiation system was a linear accelerator. This source uses multiple electric fields to accelerate electrons down a tube to produce a beam of electrons that can be used for irradiation. This allows for a uniform irradiation rate and a constant dose. The penetration of the electrons is not as deep as for the Cobalt 60 or the x-rays. This is due to the fact that electrons are charged and the x-rays or gammas produced by Cobalt 60 are not (8). However, this problem can be dealt with fairly easily. Two beam sources can be used, one on the top of the product and one below the product. With this setup the only stipulation is that the product is no thicker than about 3 to 4 inches based on the range of electrons in water (3). This does limit the possibilities of uses for this irradiation system but it still allows for uniform dose throughout the entire volume of the product. Another consideration for the electron beam is shielding. Like the x-rays, the electron beam can be turned off for transport thus eliminating the difficulties with NRC and state regulations. However, the shielding while the electron beam is in use would still need to be fairly thick and dense. But, unlike the x-rays or the gammas from Cobalt 60 the shielding would not need to be

as thick or as heavy (9). This lowers the weight of the transport as well as decreases the cost.

The problem with electronics still exists just as it does for x-rays. Even though this is a concern, some electron beams have very robust systems that would be able to tolerate the transport of the system. The support systems for the electron beam would have to be very robust as well. The electron beam has to have a constant power supply. The electron beam would need a cooling system as well as a vacuum system to ensure that ozone gas is not produced in the radiation process (9). Vacuum systems prevent the production of ozone by removing the atmosphere from the linear accelerator and more importantly reduce the attenuation of electrons in air (3). These systems can be difficult to deal with, however there are some rugged systems available that would provide the cooling and vacuum necessary for the safe operation of the electron beam. Since the electron beam requires the least amount of shielding and has the least number of problems, it was selected as the source for this mobile food irradiation system.

7.0 Facility Design

7.1 Layout

The general layout of the device can be found below in Figure 1. It is designed to easily fit inside a standard semi tractor trailer truck's container and is fully equipped with the two linear accelerators (one to irradiate food from the top and the other to irradiate food from the bottom), necessary cooling and vacuum equipment, conveyor system and shielding. . The operator will place food on the conveyor; the conveyor will then move

the food through the two beams of electrons and out through the exit where the food will be off loaded.

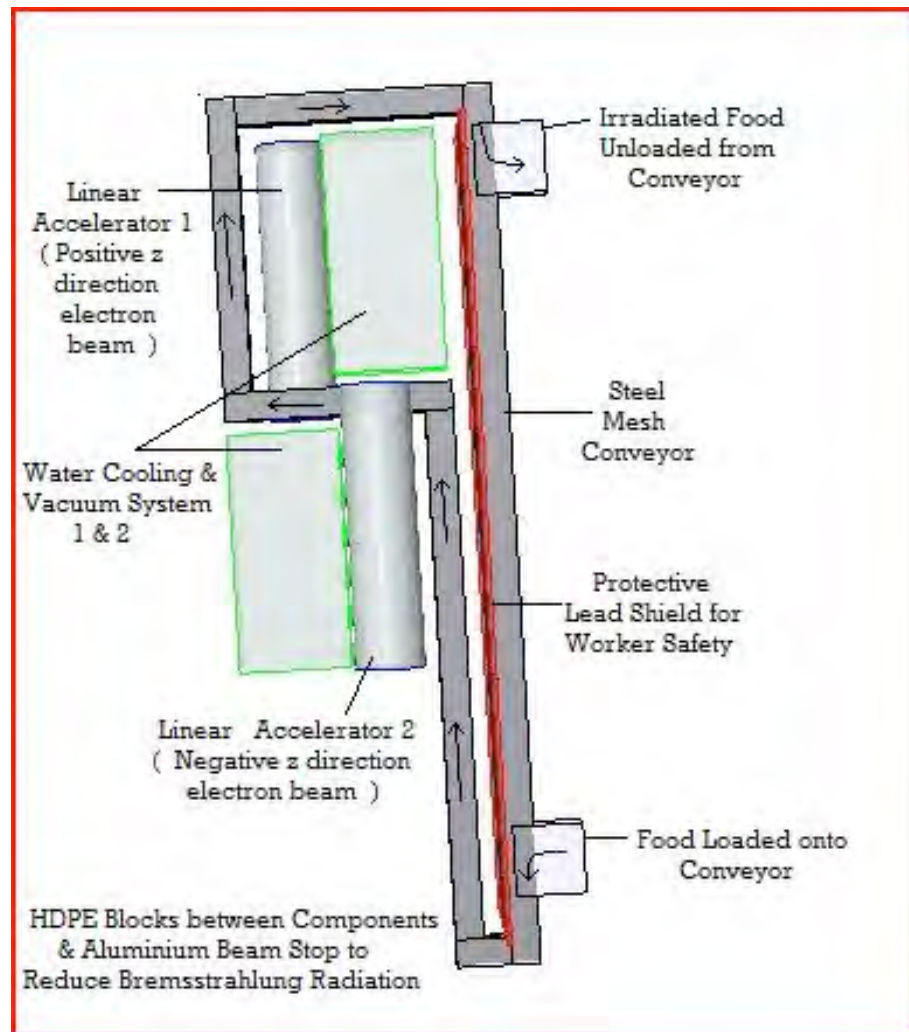


Figure 1: Top View of Mobile Food Irradiation Device

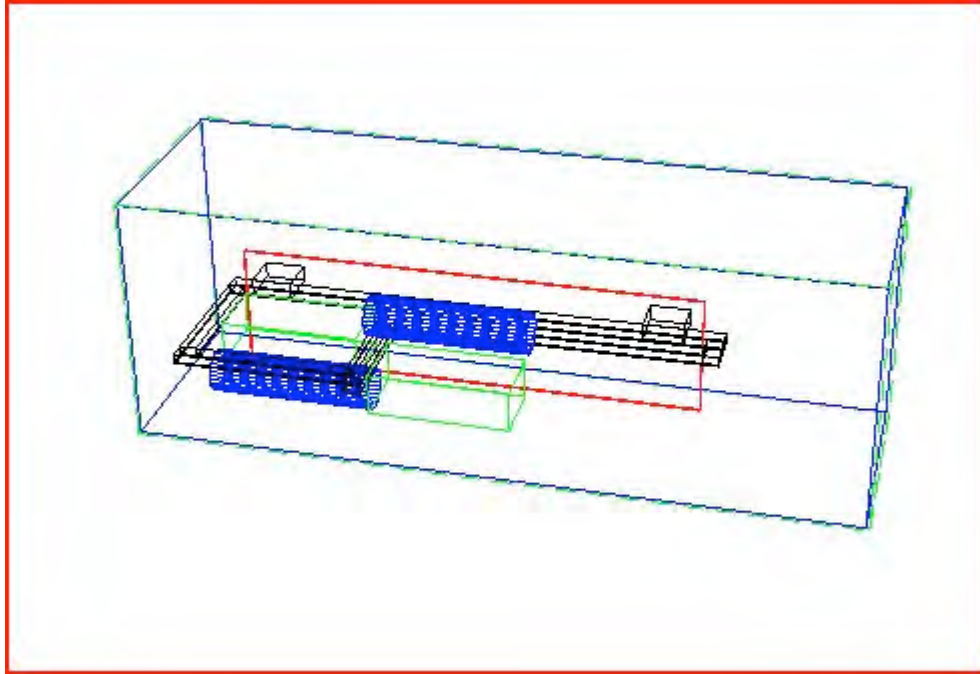


Figure 2: Side View of Mobile Food Irradiation Device inside Container

7.2 Source

The selected electron beam source is produced by Linac Technologies. This company is located in France and is a major manufacturer of linear accelerators (11). Linac Technologies has over 25 years in the irradiation industry and conducted research in many areas including food irradiation, medical accelerator applications and research applications. They produce a variety of accelerators from 10 keV to 10 MeV. Linac Technologies provides all the support systems necessary to operate their accelerators as well as detailed specifications for application and use (11). In this section of the report the specifications and design of the accelerator will be detailed.

The accelerator produced by Linac Technologies selected in this mobile food irradiation facility is the MeVAC. The MeVAC is a pulsed linear accelerator operating at 2998 MHz and producing electrons with energies below 10 MeV. The maximum power

achievable from this kind of accelerator is 3 kilowatts at a beam current of 0.3 mA (11). The MeVAC comes standard with a 20 cm wide scan horn and a programmable controller. The programmable controller can control the machine parameters as well as communicate with the conveyor system, production line and ancillary equipment such as the power supply, cooling system and the vacuum system. This allows for simple control of all the systems involved with the irradiation facility in one single controller. The MeVAC complies with FDA, AAMI and European standards so it could be operated essentially anywhere in the world. The water cooling requirements include 2500 liters per hour at a regulated temperature of about 25 degrees Celsius (11). This cooling system is required to remove around 20 kilowatts of power in the form of heat from the accelerator. The MeVAC requires 400 Volts 3-phase 50/60 Hz of electricity at 15 kilovolt amperes current (11). The physical dimensions for this accelerator are 2 meters long and 0.5 meters in diameter with a weight of 200 kg. The high performance of this accelerator is shown by the example of the ability to sterilize more than 1 cubic meter per hour for products with a 0.15 density at 25 kGy (11). This is a very high rate considering the food irradiation facility will only be irradiating food products to a maximum dose of about 5 kGy. The final specification for this accelerator is the price. The MeVAC linear accelerator is around 3.25 million dollars. A computer generated image of the accelerator is shown in Figure 3 below. With these specifications, the design of the accelerator for the irradiator can be determined and outlined.



Figure 3: Computer model of MeVAC Accelerator

The design of the accelerator involves how it will be located and positioned in the mobile irradiation system. The considerations involved in the design include how to achieve maximum penetration, how to make it mobile and how to shield the sources. To achieve maximum penetration, this irradiation facility will utilize two MeVAC accelerators. One accelerator will be positioned above the product and one accelerator will be positioned below the product. Both accelerators will direct the flow of electrons toward the product being conveyed on a conveyor belt between the accelerators in the irradiation facility. These accelerators will be offset so that they do not direct electrons directly at each other. To meet transportation requirements, the beams will be turned 90

degrees so that the accelerators will fit above and below the conveyor and still be below the required height for the department of transportation regulations (12). These 90 degree bends will each have an extra 2 cm of lead around them to shield for the photons that are produced while turning the beam. Each electron beam will have its own target once it passes through the product being irradiated or the conveyor system when there is no food on the belt. These targets are constructed of aluminum and cooled with the same system used to cool the accelerator. This would help attenuate the electrons and reduce the amount of shielding needed for safety for the operators and personnel around the irradiator. The basic design seen from the side is shown below in Figure 4.

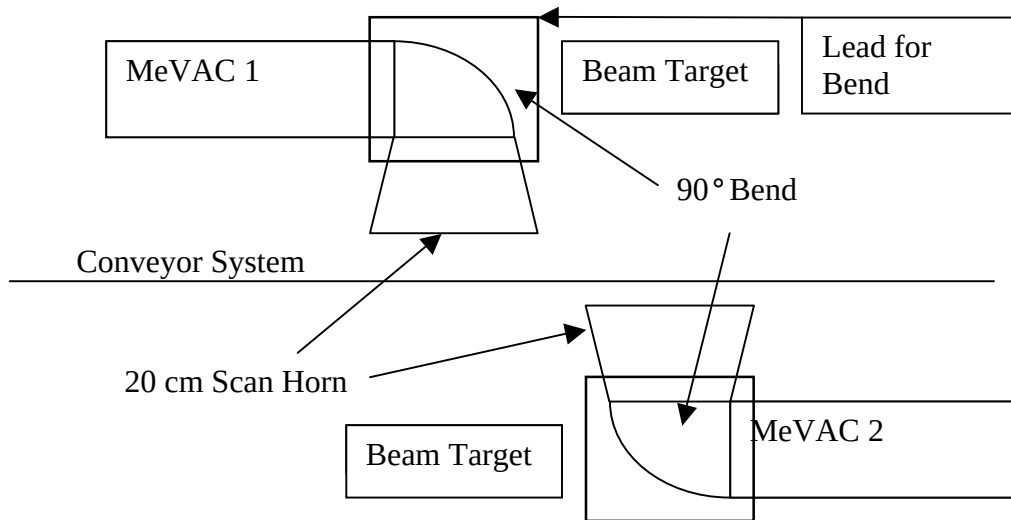


Figure 4: Irradiator Layout

The MeVAC linear electron accelerator specifications and layout described above will allow for maximum penetration over a wide range of products. The ability for the accelerator to produce a beam between 5 and 10 MeV allows for different dose rates and amount of energy deposited in the product. This will allow for a wide range of applications and this range can be extended by adjusting the speed of the conveyor belt.

The slower the belt moves and the higher the energy of the beam, the higher the dose rate to the product. The 20 cm scan horn width allows the conveyor system to be 20 cm in width which keeps the facility compact but still efficient. This scan horn essentially means that the product is passing through a 20 cm wide plane of electrons as it moves past each accelerator scan horn (11). Irradiating from both sides of the product allows for a guaranteed consistent dose throughout the product (9). The mobile irradiation facility with a MeVAC linear accelerator from Linac Technologies laid out in the design shown above will allow a safe, cost effective and efficient operation.

7.3 Materials

The food will need to be moved through the radiation beam to receive dose since the beam is stationary. A conveyor belt will be used to accomplish this task. Several materials were considered for the conveyor, mainly steel, rubber, and plastic. Nylon and cloth type materials were not considered due to the possibility of heavy products and a need for durability as well as difficulty in cleaning.

Plastic and rubber materials (polymers) have similar characteristics in radiation fields. Since polymers are made of organic compounds with weak bonds between the atoms in the structures, radiation can irreversibly break these bonds. When these bonds are broken many changes can occur in polymers such as changes in chemical or physical properties, appearance, and finally mechanical properties. To add to these effects, gas is often created in the materials as well. Polymers can undergo two different types of changes, either crosslinking or degradation can occur depending on the type of material. Crosslinking is the formation of new bonds in the polymer structure. This does not allow

the material to hold the necessary three dimensional networks for the material to remain as it is. Degradation refers to the permanent breaking of bonds in the material and can lead to weakening of the material. Both of these processes will lead to the polymer becoming brittle.

Rubber provides for a more flexible belt material than plastic. However, radiation fields such as the electron field used for the irradiation of food will cause crosslinking in most types of rubber and will undergo changes similar to those in the vulcanization (or curing) process. This increases the hardness while decreases the flexibility of the rubber and will eventually become brittle over prolonged periods of time. Figure 5 below shows several different types of rubber and the dose that causes the rubber to be of limited use or no use.

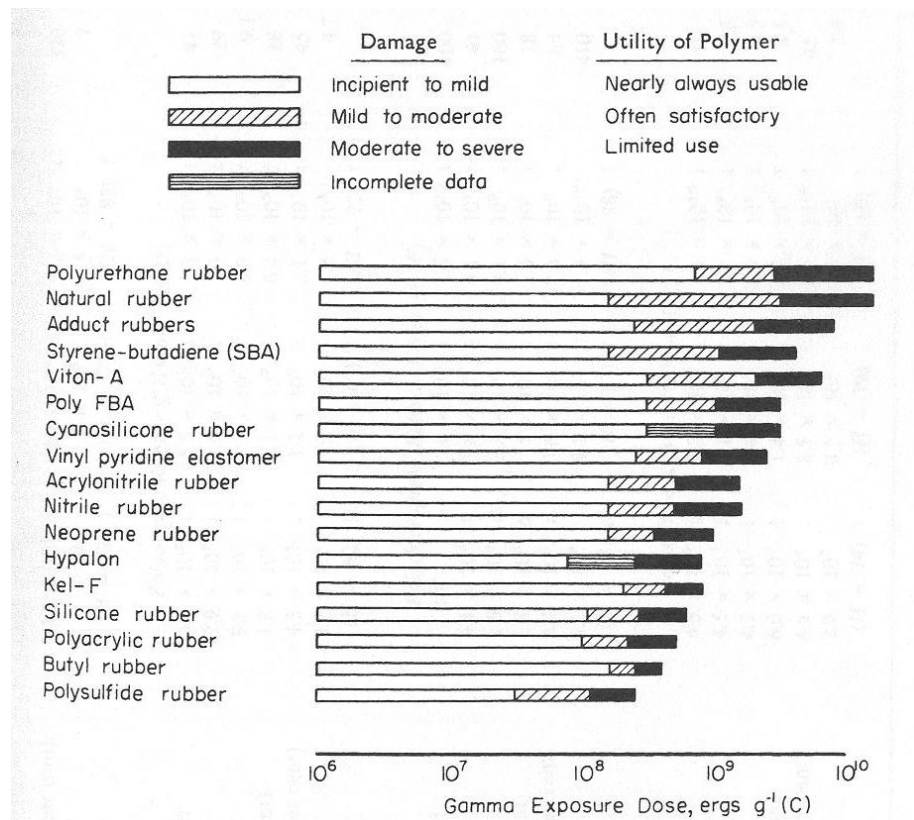


Figure 5: Radiation doses for multiple types of rubber.

From Figure 5 most types of rubbers are not useful over large doses and have significant damage after 10^8 to 10^9 ergs/g. This is equal to about 1 to 10 Mrad, or 10 - 100 kGy.

Plastic is more resistant to radiation compared to rubber. However, plastic will still undergo degradation. Most plastics become useless at ranges of 10 – 100 Mrads, 100 – 1000 kGy, while some hard plastics are more radiation resistant. This is shown in figure 6 below.

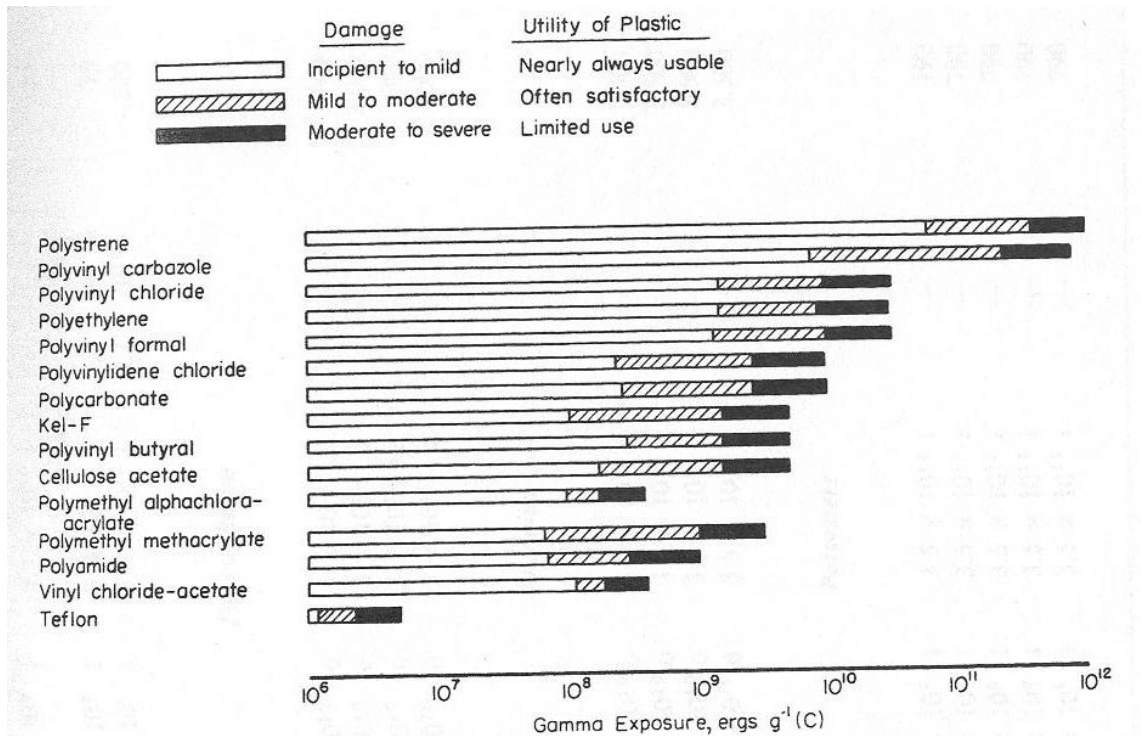


Figure 6: Radiation doses for plastics.

These are high radiation doses for polymers, however in high radiation fields it will accumulate quickly. The electron beam used in this design will give a dose of 1 kGy/sec for an area of 600cm^2 . At this rate, an area of 600cm^2 , comparable to 1ft^2 , will receive a maximum dose of 1 kGy in 1 second.

To overcome the radiation damage, steel mesh conveyor belts will be used. Steel is much more resistant to radiation and electrons will cause little damage to steel.

However, electrons will cause atom displacements (dpa) in metals. As calculated in section 8.5, the beam current used is 1.87×10^{16} electrons/sec. As a conservative approach, if each electron displaces one atom and Avogadro's number counts for the number of iron atoms in one mole of steel. There will be approximately 1×10^{-4} dpa/hr, this leads to 2.6×10^5 hr for 30 dpa. 30 dpa is low enough to not cause serious damage to steel which will allow the conveyor to provide flexibility and durability beyond any polymer conveyor in a radiation field.

The problem with a steel conveyor is the creation of Bremsstrahlung radiation from the interaction of electrons with the heavier elements in steel. These will not be much of a problem since shielding will be initially modeled for Bremsstrahlung.

7.4 Shielding

Providing a food irradiation device which ensured the safety of workers and the public was a major criterion in this design. To meet this objective while the device was operational meant designing an effective shield which protected people around the truck but which still allowed the intended purpose of fast, reliable food irradiation to take place. First, an aluminum beam stop was employed due to being a lightweight, low Z metal which decreased Bremsstrahlung radiation while stopping electrons. High density polyethylene (HDPE) blocks were also utilized around the conveyor, linear accelerator and vacuum/cooling systems for the same reasoning. In addition, lead shields of 2-3cm were placed at the perimeter to attenuate any Bremsstrahlung radiation produced. In order to accurately estimate the effectiveness of the design's shielding given above design

components employed, MCNP simulations were utilized in our final calculations (Appendix 11.2).

The premise of our shielding design was to stop the maximum 10MeV electrons while producing as little Bremsstrahlung radiation as possible. This meant using lots of low Z materials in the truck, which also helped in reducing the overall truck weight, but still having enough lead to stop the photons which were produced during operation. The design includes a 20x20x20cm cube of Aluminum (Z=13) as a beam stop located directly across the conveyor from both linear accelerators and high density polyethylene blocks machined to fit between and around components.

Polymers however are not entirely radiation resistant and will receive some damage in radiation fields. Since having effective shielding is of concern, it was necessary to determine what damage would occur to the HDPE and when.

There is often a threshold damage limit calculated for materials. This is where radiation damage becomes noticeable, but doesn't compromise important properties of the material [2]. Damage can consist of broken bonds that can cause the material to become brittle and decrease tensile strength.

The major polymer for shielding, polyethylene, has tensile strength reaching threshold damage levels at 17 Mrad (100 kGy) and 25% damage at 7300 Mrad (73 MGy). With an absorbed dose rate of 1 kGy hr^{-1} , threshold damage occurs at 170 hours, and 25% damage occurs at 73,000 hours. Shear strength reaches 50 percent damage at 2900 kGy (2,900 hours). Elongation, this refers to a decrease in elongation, of polyethylene, which can reach up to 250 percent the original length, starts occurring at a threshold of 210 kGy (210 hours). Elongation reaches 50 percent damage at 1600 kGy (1,600 hours) [2].

Given the material properties detailed above, polyethylene shielding will need to be monitored to ensure safety is not compromised. The electron beam used has a dose rate of 1000 Gy /sec, this is higher than the dose rate stated above for the damage levels. The higher dose rate used in this design will cause threshold damage levels to be reached at a quicker pace than stated. However, since polyethylene is not used as a beam stop there will be a lower dose to the surrounding polyethylene shield and it is expected to last longer than times given.

Lead shielding was designed to line the entire truck to stop any photons that were produced due to Bremsstrahlung radiation from the electron beams. At the sides of the truck the lead lining is 4cm thick while only 2cm thick on the top and bottom. In addition, a wall of 3cm thick lead is also used to shield workers at their most probable location where food is loaded and unloaded.

The MCNP5 simulation for shielding utilized the layout seen in Figures 1-2 and can be found in Appendix 11.2. The results of the simulations show that no photons pass through the area where the food would be loaded and unloaded and where any workers present during operation would most likely be located. A photon flux of approximately $3.4\text{E}+7\text{s}^{-1}$ however is present at the opposite side of the truck directly in line with the two accelerators where attenuation is at its lowest. Additional shielding as well as prohibiting workers in this area during operation would be needed to ensure the lowest possible exposure to those present.

7.5 Dose Calculations

Determining the dose that the product will receive by the irradiator is of extreme importance. FDA regulations set the minimum and maximum dose that a particular food can receive for a given purpose. This means that the center of the food must reach the minimum dose requirement before the surface reaches the maximum allowable dose. In order to obtain a reasonable estimate of the dose a product might receive with the given design both analytical and computational methods were employed.

First, several assumptions had to be made before starting the calculations. It was assumed that while the proposed linear accelerator can produce electrons in a variable energy range, it would most likely be used at the maximum energy of 10MeV to maximize the throughput of product thus increasing the affordability of use. Also, the assumption was made that the majority of food products to be irradiated would consist mostly of water, thus allowing the use of water as a reasonable substitute for dose calculations.

An analytical method was first utilized to give a rough estimate of how much surface dose could be obtained with the design's purposed linear accelerators. Equation 1 (below) is the approximate dose rate from monoenergetic electrons on a uniform medium (3). Here $(dE/\rho dx)$ is the collisional stopping power at depth x , which is equal to 2 MeV·cm²/g for 10MeV electrons (3). This equation only holds when the radiative stopping power is not a large percentage of the total stopping power. Since the radiative stopping power for 10MeV electrons is 8.4% of the total stopping power, this method is only used as a rough estimate for the surface dose.

Next, the fluence rate ($\dot{\phi}$) for the linear accelerator was calculated using Equations 2-3 (below). As was stated in the previous section, the maximum power output of the MeVAC is 3kW. Using this, it was determined that the maximum flux rate from the accelerator when it is producing 10MeV electrons is 1.87E+15 e⁻/s (Equation 3). In order to determine dose however, the area which would be absorbing the energy had to be calculated. To do this a hypothetical dose of 1kGy (the maximum allowed dose for delayed ripening of fruits) was used to work backwards to determine the minimum velocity of the 20cm wide conveyor (Equations 4-6). Thus it was determined that at the maximum allowed energy of 10MeV and the maximum power output of 3kW, the conveyor would need to move at a rate of 30cm/s.

$$\dot{D} = \dot{\phi} \left(-\frac{\delta E}{\rho \delta x} \right)_{col} \quad (1)$$

$$1 \text{ eV} = 1 \text{ V} \times 1.602 \times 10^{-19} \text{ C} = 1.602 \times 10^{-19} \text{ J} \quad (2)$$

$$3 \text{ kW} = 3000 \frac{\text{J}}{\text{s}} = 1.87 \times 10^{15} \frac{\text{e}^-}{\text{s}} \text{ (for } 10 \text{ MeV e}^- \text{)} \quad (3)$$

$$D = \left(3.74 \cdot 10^{15} \frac{\text{MeV} \cdot \text{cm}^2}{\text{g} \cdot \text{s}} \right) \div \text{Area/s} = 1 \text{ kGy} = 1 \frac{\text{kJ}}{\text{kg}} \quad (4)$$

$$\text{Area/s} = \text{Velocity} \cdot \text{width} = \left[\left(3.74 \cdot 10^{15} \frac{\text{MeV} \cdot \text{cm}^2}{\text{g} \cdot \text{s}} \right) \left(1.602 \cdot 10^{-13} \frac{\text{kJ/kg}}{\text{MeV/g}} \right) \right] / 1 \frac{\text{kJ}}{\text{kg}} = 600 \frac{\text{cm}^2}{\text{s}} \quad (5)$$

$$\therefore V_{\min} = 30 \text{ cm/s} \quad (6)$$

This calculation can then be used to give a rough idea of throughput of the product. For example, suppose a crop of strawberries was to be irradiated which had an average diameter of 3cm. By applying an approximated spherical model, roughly 60 strawberries per second could be irradiated at the maximum energy and minimum speed. Assuming the strawberries have a density of 1g/cc, this means that over 6kg/s or 21,600kg/hr of strawberries could be irradiated at the minimum speed.

More precise MCNP calculations were also completed. The simulation model (found in Appendix 11.1) consisted of a 10MeV electron beam incident on a 12"x12"x6" (30.48 x 30.48 x 15.24cm) slab of water surrounded by air. A mesh tally was used to determine the dose in different thicknesses of water. The results of the simulation show that $3.457\text{E-}13$ Gy/electron was deposited in the first 2.54cm of water with a cross-sectional area of 929cm^2 . Thus, for this same volume to receive a dose of 1kGy, it would need to be irradiated by the linear accelerator (providing $1.87\text{E+}15$ e⁻/s at maximum power) for a period of 1.54 seconds. This corresponds to an area of 600cm^2 receiving a dose of 1kGy/s. Therefore, the conveyor would need to be traveling at a minimum velocity of 30.03cm/s to stay below the maximum allowable dose of 1kGy – a figure surprisingly close to the analytical calculation.

The MCNP simulation also provided dose estimates at greater depths into the water/tissue simulate (see Figure 7 below). At 2.54 to 5.08cm, the dose is calculated at $2.661\text{E-}13$ Gy/e⁻. If the minimum required dose were 0.3 kGy, as is the case for controlling *Trichinella spiralis* in pork, then the conveyor would need to move at a maximum speed of 77cm/s. Therefore, in such a case where the pork were no thicker than 10cm, the conveyor could move the food through at a speed anywhere between 30 and

77cm/s with the minimum dose reached at the center of the meat before the maximum dose was received at the surface.

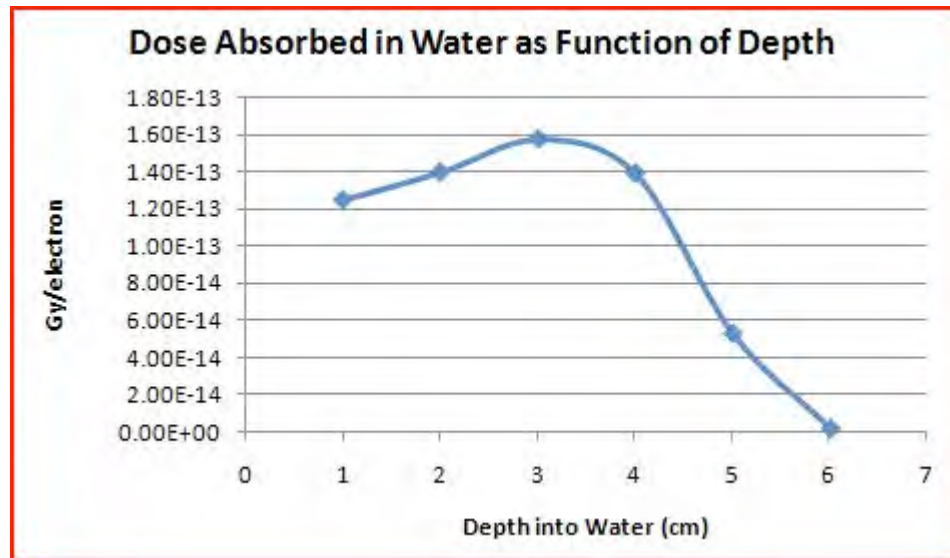


Figure 7: Dose as a function of depth

The dose was also simulated at greater thicknesses of water but starting at 5.08 to 7.62cm the dose dropped off significantly to $2.7\text{E-}15\text{Gy/e}^-$. This result however was expected as the range of 10MeV electrons in water is only 4.88cm (3). Given the previous scenario where a min dose of 0.3kGy and max dose of 1kGy were required, it would be impossible for food of thicknesses above 10 cm to receive the minimum dose at the center before the surface reached a maximum allowed dose. Given these calculations and the known range of 10MeV electrons in water, this proposed food irradiation device is only intended for a maximum food thickness of 8-9cm and through design will not permit food thicknesses above 10cm since the open space for loading is only 10cm high.

7.6 Power Supply

The power supply for the food irradiation facility must provide enough electricity for the linear accelerator and the support systems necessary for its operation. This requires that the generator be able to produce a high voltage as required by the linear accelerator but also a high current. The support systems will not require anywhere near as much electricity as the linear accelerator (11). The support systems include the vacuum system for the removal of air from the accelerator, the pump system for cooling the accelerator and the electron targets, the conveyor belt for moving the product under the beams and the detectors and safety systems in operation at all times to ensure the facility meets all regulations. The current for the electricity also needs to be constant and continuous (11). Not only does the power supplied have to be constant but the cost of operation has to be low enough so that the food irradiation facility is cost effective. The cost for operation for a generator is the gasoline or diesel fuel used to generate the electricity, so the fuel consumption rate must be analyzed. Finally, the power supply must be mobile. The electric generator must be able to travel with the food irradiation facility and be plugged in to the facility and power the entire operation.

The generator found to fill this need is the Triton MMG230 – 204kW John Deere sound attenuated generator set with trailer (19). The linear accelerator needs around 80 kW of continuous electricity for constant operation (11). Since there are two linear accelerators in the mobile food irradiation facility this requirement becomes 160 kW of electric power. With a 204kW generator this leaves 44kW for the support electronics. This is more than enough power needed for the full facility to operate. The Triton MMG230 is only 210 inches by 86 inches by 93 inches with the double axel trailer so it is

certainly mobile and could easily be pulled alongside the facility by a support truck which would be needed to transport the workers (19). This generator produces 480 volts at 303 amps (19). The generator has a 286 horsepower six cylinder diesel engine that includes a 360 gallon fuel tank (19). This generator consumes fuel at 13.3 gallons an hour at 1800 revolutions per minute which is the typical operating speed. This means that the generator can be operated for around 27 hours on one tank of diesel fuel (19). This consumption rate is cost effective and will allow for long operational periods. Finally the price of the Triton MMG230 is \$64,000. This is a small price to pay in comparison with the massive costs of the linear accelerators. A picture of the MMG230 is shown below in Figure 8.



Figure 8: Triton MMG230 204kW Diesel Generator

7.7 Safeguards

There are three categories that these fall in under; passive, administrative, and active. The passive safeguards are as simple as the electron beam will not be able to be turned on until all of the shielding is in place. The administrative safeguards are the written rules of the site; such as warning signs that are placed in the areas of radiation, and a red light on the outside of the trailer that turns on if the beam is turned on. The active safety measures are the emergency shut off switches that are around the trailer. According to IAEA document Safety Series No. 107,

“Means shall be provided such that the personnel access door to the radiation room is closed and secured before the irradiation process can begin. The door interlocks shall be integrated with the master control system such that violation of the interlock system or use of the door will cause the radiation to be automatically terminated. Any failure of the control system shall generate visible and audible alarm signals. Opening the access door shall also disable the source hoist control circuit and cut off the motive power to the source hoist operating mechanism in the case of gamma facilities, or switch off the high voltage supply for electron beam facilities. The disabling of the source hoist control circuit and the cut-off of the motive power to the source hoist operating mechanism must be accomplished by independent actions.” (21)

For the design, the shielding is permanent; however, there are small sections of shielding which is removable. The facility has a system which interlocks access panels and a personal access door to repair the electron beams and the conveyor belt as well as clean the interior of the trailer. There will be emergency shutoff switches inside the

trailer placed in areas of maintenance and loading to ensure that no personnel will be inside the facility during times of operation. Another emergency shut off switch is on the outside of the trailer next to the personnel access door and on the exterior of the diesel generator. All of the emergency shut offs will be on the same circuit. Also, there is a circuit along the shell of the trailer that goes through the parts of the trailer which provide access to the interior of the facility. This is similar in principle to the door and window alarms that are used for home security. Both of these circuits automatically shut off the electron beam if the circuit is broken. On another circuit will be a system which detects if the conveyor belt is stopped for any reason. This is in the event that the conveyor malfunctions or stalls preventing the product and conveyor from moving from radiation field. When any one of the systems is compromised, they will automatically disrupt current flow and shut off the electron beam. The systems cannot be turned back on until all of the separate systems are reset and confirmed as being safe and ready for use.

The workers will have training courses on the safe uses, as well as informed of the consequences for the unsafe usage of the machinery. Also, due to radiation from Bremsstrahlung no one will be allowed in a 10 foot radius of the facility during operation. The area will be cordoned off with removable barriers and security personnel will be employed to ensure trespassing does not occur. The only exemption for this rule will be those who are loading and unloading the foods on and off the conveyor belt. The loading and unloading access is not big enough for access to the interior of the facility so radiation is not a concern.

Inside the trailer, there are also a couple of built in safety systems. These systems will monitor the electron beams to make sure everything is operating within the

parameters. This will also be a way to log any failures and plan future repair schedules. The other system will have test points for machine diagnostics without resorting to disabling the electron beam or bypassing the interlocks (21). There will be a closed circuit television to monitor this.

8.0 Future Work

The design and layout for this facility needs more work from different engineering specialties. Mechanical, civil, industrial, electrical and systems engineers are needed to enhance the design and functionality of the facility. There are several areas that require the contribution of other engineering disciplines for the facility to be ready for production.

One area that needs more work is the design of the facility. How the food is loaded and unloaded as well as how the food moves through the beam. The basic layout was examined and a reasonable system was determined. However an engineer with experience in conveyor systems and loading and unloading systems could make the system more efficient and more reliable. Higher efficiency means lower cost and more throughput of the product. The more reliable the facility is the more food can be processed and the less down time the facility has. This will allow for more profit from the facility since less money will need to be spent to fix the system.

Another area that needs more development is the maintenance of the facility. Currently the maintenance is not addressed in depth. Additional work needs to be done to make the conveyor, electron beams, and support systems more easily serviceable. The more easily serviceable the facility is the quicker it can be brought back to working

condition if something does break. This allows less down time and more time to be running product through the facility for irradiation. Some designs have been discussed that should be looked into further with more time. One idea suggested was to make the whole system able to be raised with hydraulic rams from the base. This would allow a worker to crawl under the facility and service the components from below and inside the system. Another option was to make the shielding removable, thus allowing access to the components from the sides and top of the facility. Both of these are viable options and need more research and future work.

Future work is also needed on how all of the systems in the facility are integrated together. Essentially this means how the electron beam is coupled to the conveyor belt and all the other support systems contained in the irradiation facility. There are many variables that can be adjusted to provide the product with the appropriate amount of irradiation. The conveyor speed can be adjusted, the distance to the product can be adjusted, the energy and intensity of the beam can be adjusted, the thickness of the product may vary and all need of the various factors need to be considering for maintaining minimum and maximum dose rates to the product. All of these factors can be integrated into one primary control system that is used to maintain the correct amount of radiation for the desired output product. This would allow an operator to input the variables and receive required system settings without calculations. This would eliminate the element of human error and possibly make the facility safer. This is an area that an electrical engineer would be needed as well as a systems engineer or someone with system knowledge.

There are many areas where future work needs to be performed before the irradiation facility goes to production. Some of these areas are listed in this report; others are not included but would be discovered upon more in depth research into this challenge. All of these areas need to be developed fully before a prototype is produced. The work for these sections could not be included in this report due to time constraints and lack of information and knowledge. However, given more time and a more diverse group of engineers these areas of future work could be developed and moved to production.

9.0 Conclusion

This paper details the design of a mobile irradiation facility. The facility will use electron beams produced by two linear accelerators to irradiate products passing between them. The linear accelerators will produce electrons from 5 to 10 MeV with a maximum power of 3 kW. The electron beam produced by the linear accelerator was selected mainly due to the fact that less shielding was required than for the Cobalt 60 source or for the x-ray source. The food products will pass between the linear accelerators via a conveyor belt made of steel mesh. Steel mesh was selected for the conveyor belt since it is highly radiation resistant. The operators and personnel around the irradiator will be protected from the radiation by high density polyethylene and lead shielding. High density polyethylene was used for the primary shielding because it will effectively stop electrons while producing a small amount of Bremsstrahlung radiation. Lead shielding was also used to stop the Bremsstrahlung produced in the polyethylene and other materials contained in the facility. The facility will be powered by a generator contained on a trailer. The generator was selected for its uniform power production and ease of use.

Safety systems were designed to ensure the safe operation and maintenance of the system. The total cost of the system is estimated to be between 7 and 8 million dollars. This cost is reasonable due to the need for a mobile facility. A mobile irradiation facility could travel to a manufacturer where an outbreak of infected or diseased product has been detected and ensure that the future products produced do not endanger the health of the consumers. The ability to rapidly respond to special situations makes this mobile irradiation facility a necessity.

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11.0 Appendix

11.1 MCNP5 Model for Dose Calculations

food irradiator: 10 MeV e- on target, lead shielded, water target

c Cell Descriptions

c W converter

c 1 1 -19.3 2 -3 -1 imp:p,e=1

c air between W and Pb

2 4 -1.20479e-3 4 -5 6 -7 8 -9 imp:p,e=1

c (-2:3:1) imp:p,e=1

c Pb shielding

3 2 -11.344 10 -11 12 -13 14 -9

(-4:5:-6:7:-8:9) imp:p,e=1

c water being irradiated

4 3 -0.9982 15 -16 17 -18 19 -191 imp:p,e=1

41 3 -0.9982 15 -16 17 -18 191 -192 imp:p,e=1

42 3 -0.9982 15 -16 17 -18 192 -193 imp:p,e=1

43 3 -0.9982 15 -16 17 -18 193 -194 imp:p,e=1

44 3 -0.9982 15 -16 17 -18 194 -195 imp:p,e=1

45 3 -0.9982 15 -16 17 -18 195 -20 imp:p,e=1

c air outside pb and water

5 4 -1.20479e-3 10 -11 12 -21 22 -20

(-10:11:-12:13:-14:9)

(-15:16:-17:18:-19:20) imp:p,e=1

6 0 (-10:11:-12:21:-22:20) imp:p,e=0

c Surface Descriptions

c converter surfaces

1 cz 10

2 pz 0

3 pz .2

c inside air surfaces

4 px -30.48

5 px 30.48

6 py -30.48

7 py 30.48

8 pz -30.48

9 pz 30.48

c lead shield surfaces

10 px -40.64

11 px 40.64

12 py -40.64

13 py 40.64

14 pz -40.64

c block of water surfaces

15 px -15.24

16 px 15.24

17 py -15.24

18 py 15.24

19 pz 60.96

191 pz 63.5

192 pz 66.04

193 pz 68.58

194 pz 71.12

195 pz 73.66

20 pz 76.2

c boundary of problem - add 1 cm for mesh tallies

21 py 41.64

22 pz -41.64

mode p e

c

c Variance reduction

c

c bbrem 1 1 46i 100 1

c

c Source

```

c
c 10 MeV electrons into W
sdef pos=0.0 0.0 0.0          $ spatial
    erg=10                     $ energy
    par=e                      $ source type
    vec=0 0 1 dir=d1          $ direction
si1 -1 0 0 0.970142500 1
sp1 0 0      0 1
c
c Tallies
c fc4 Photon dose rate tally behind electron accelerator - cSv/hr (rem/hr)
fmesh4:p geom=xyz origin=-40.64 -40.64 -41.64
    imesh 40.64 iints 30
    jmesh 40.64 jints 30
    kmesh -40.64 kints 1
    out=ij
de4 log 0.01 0.03 0.05 0.07 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6
    0.65 0.7 0.8 1 1.4 1.8 2.2 2.6 2.8 3.25 3.75 4.25 4.75 5 5.25 5.75 6.25
    6.75 7.5 9 11 13 15
df4 log 3.96E-06 5.82E-07 2.90E-07 2.58E-07 2.83E-07 3.79E-07 5.01E-07 6.31E-07
    7.59E-07 8.78E-07 9.85E-07 1.08E-06 1.17E-06 1.27E-06 1.36E-06 1.44E-06
    1.52E-06 1.68E-06 1.98E-06 2.51E-06 2.99E-06 3.42E-06 3.82E-06 4.01E-06
    4.41E-06 4.83E-06 5.23E-06 5.60E-06 5.80E-06 6.01E-06 6.37E-06 6.74E-06
    7.11E-06 7.66E-06 8.77E-06 1.03E-05 1.18E-05 1.33E-05
c fc14 Photon dose rate tally above electron accelerator - cSv/hr (rem/hr)
fmesh14:p geom=xyz origin=-40.64 40.64 -40.64
    imesh 40.64 iints 30
    jmesh 41.64 jints 1
    kmesh 40.64 kints 30
    out=ik
de14 log 0.01 0.03 0.05 0.07 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6
    0.65 0.7 0.8 1 1.4 1.8 2.2 2.6 2.8 3.25 3.75 4.25 4.75 5 5.25 5.75 6.25
    6.75 7.5 9 11 13 15
df14 log 3.96E-06 5.82E-07 2.90E-07 2.58E-07 2.83E-07 3.79E-07 5.01E-07 6.31E-07
    7.59E-07 8.78E-07 9.85E-07 1.08E-06 1.17E-06 1.27E-06 1.36E-06 1.44E-06
    1.52E-06 1.68E-06 1.98E-06 2.51E-06 2.99E-06 3.42E-06 3.82E-06 4.01E-06
    4.41E-06 4.83E-06 5.23E-06 5.60E-06 5.80E-06 6.01E-06 6.37E-06 6.74E-06
    7.11E-06 7.66E-06 8.77E-06 1.03E-05 1.18E-05 1.33E-05
c fc24 Photon flux tally at the exit of the Pb shield
fmesh24:p geom=xyz origin=-30.48 -30.48 30.48
    imesh 30.48 iints 24
    jmesh 30.48 jints 24
    kmesh 31.48 kints 1
    out=ij
c fc34 Photon flux in irradiated water
fmesh34:p geom=xyz origin=-15.24 -15.24 60.96
    imesh 15.24 iints 12
    jmesh 15.24 jints 12
    kmesh 76.2 kints 6
    out=ij
c fc44 Electron flux in irradiated water
fmesh44:e geom=xyz origin=-15.24 -15.24 60.96
    imesh 15.24 iints 12
    jmesh 15.24 jints 12
    kmesh 76.2 kints 6
    out=ij
c fc8 Exact absorbed dose in irradiated water - Gy
*f8:p,e 4 41 42 43 44 45 t
e8 1e30
em8 6.80188641e-14
c
c Materials
c
c tungsten 19.3 g/cc
m1 74182 0.26420
    74183 0.14280
    74184 0.30700
    74186 0.28600
    nlib=70c plib=04p pnlib=70u elib=03e
c

```

```

c lead 11.344 g/cc
m2 82204 0.0140
    82206 0.2410
    82207 0.2210
    82208 0.5240
    nlib=70c plib=04p pnlib=70u elib=03e
c
c water 0.9982 g/cc
m3 1001 1.9997
    1002 0.0003
    8016 0.9976
    8017 0.0024
    nlib=70c plib=04p pnlib=70u elib=03e
c
c dry air at sea level 1.20479e-3 g/cc
m4 6000 -0.000127
    7014 -0.76508
    8016 -0.234793
    nlib=70c plib=04p pnlib=70u elib=03e
c
c Physics options
c
phys:n
phys:p 4j 1
phys:e
c
c Cutoffs
cut:n
cut:p j 0.001 $ default energy cut off, 1 keV
cut:e j 0.001 $ default energy cut off, 1 keV
c elpt $ cell by cell energy cut off, could be useful
nps 3900
c ctme 10
c
c Peripheral
print
rand gen=2 stride=305835
prtmp 3j 2
c

```

11.2 MCNP5 Model for Shielding Calculations

```

c
c Simple Geometry Setup for Mobile Food Irradiator
c Created for NE472 Senior Design Project 3/25/09
c *****
c           Cell Cards
c *****
c
c 6
206 17 -11.34 (-6 5 1 2) IMP:P,E = 1
c
c 5
205 3 -0.95 (-5 1 2 3 4 7 8 9 10 11
    12 13 14 15 16 17 18 19 20 21 22 24 25) IMP:P,E = 1
c
c 3
203 10 -3.054 (-3) IMP:P,E = 1
c
c 4
204 10 -3.054 (-4) IMP:P,E = 1
c
c 8
208 10 -3.054 (-8) IMP:P,E = 1
c
c 9
209 10 -3.054 (-9) IMP:P,E = 1

```

```

c
c 17
217 22 -7.86 (-17) IMP:P,E = 1
c
c 18
218 22 -7.86 (-18) IMP:P,E = 1
c
c 19
219 22 -7.86 (-19) IMP:P,E = 1
c
c 20
220 22 -7.86 (-20) IMP:P,E = 1
c
c 21
221 22 -7.86 (-21) IMP:P,E = 1
c
c 22
222 22 -7.86 (-22) IMP:P,E = 1
c
c 7
207 17 -11.34 (-7) IMP:P,E = 1
c
c 2
202 7 -0.001205 (-2) IMP:P,E = 1
c
c 1
201 7 -0.001205 (-1) IMP:P,E = 1
c
c 10
210 7 -0.001205 (-10) IMP:P,E = 1
c
c 11
211 7 -0.001205 (-11) IMP:P,E = 1
c
c 12
212 7 -0.001205 (-12) IMP:P,E = 1
c
c 13
213 7 -0.001205 (-13) IMP:P,E = 1
c
c 14
214 7 -0.001205 (-14 1 2) IMP:P,E = 1
c
c 15
215 7 -0.001205 (-15) IMP:P,E = 1
c
c 16
216 7 -0.001205 (-16) IMP:P,E = 1
c
c 24
224 4 -2.7 (-24) IMP:P,E = 1
c
c 25
225 4 -2.7 (-25) IMP:P,E = 1
c
c 26
226 7 -0.001205 (-26) IMP:P,E = 1
c
c Explicit Blackhole/Universe
c 00023 0 +1 IMP:N,P,E = 0
c
c 98 7 -0.001205 (-23 6 1 2 26) IMP:P,E = 1
98 0 (-23 6 1 2 26) IMP:P,E = 0
99 0 (23) IMP:P,E = 0

c *****
c SurfaceCards
c *****
c
c 1

```

1 BOX	550.00	200.00	87.00	50.00	0.00	0.00
	0.00	50.00	0.00	0.00	0.00	20.00
c						
c 2						
2 BOX	50.00	200.00	87.00	50.00	0.00	0.00
	0.00	50.00	0.00	0.00	0.00	20.00
c						
c 3						
3 Box	50.00	40.00	25.00	200.00	0.00	0.00
	0.00	0.00	0.00	50.00	0.00	0.00
c						
c 4						
4 Box	230.0	95.00	100.00	200.00	0.00	0.00
	0.00	0.00	0.00	50.00	0.00	0.00
c						
c 5						
5 BOX	-18.00	-18.00	2.00	864.00	0.00	0.00
	0.00	255.00	0.00	0.00	0.00	300.00
c						
c 6						
6 BOX	-22.00	-22.00	0.00	872.00	0.00	0.00
	0.00	261.00	0.00	0.00	0.00	304.00
c						
c 7						
7 BOX	45.00	190.00	2.00	580.00	0.00	0.00
	0.00	3.00	0.00	0.00	0.00	150.00
c						
c 8						
8 BOX	50.00	92.00	50.00	170.00	0.00	0.00
	0.00	80.00	0.00	0.00	0.00	50.00
c						
c 9						
9 BOX	260.00	12.00	50.00	170.00	0.00	0.00
	0.00	80.00	0.00	0.00	0.00	50.00
c						
c 10						
10 BOX	230.00	12.00	86.00	20.00	0.00	0.00
	0.00	163.00	0.00	0.00	0.00	10.00
c						
c 11						
11 BOX	230.00	12.00	75.00	20.00	0.00	0.00
	0.00	163.00	0.00	0.00	0.00	10.50
c						
c 12						
12 BOX	230.00	12.00	87.00	0.00	20.00	0.00
	-210.00	0.00	0.00	0.00	0.00	10.00
c						
c 13						
13 BOX	20.00	32.00	87.00	20.00	0.00	0.00
	0.00	163.00	0.00	0.00	0.00	10.00
c						
c 14						
14 BOX	650.00	195.00	87.00	0.00	20.00	0.00
	-630.00	0.00	0.00	0.00	0.00	10.00
c						
c 15						
15 BOX	630.00	155.00	87.00	20.00	0.00	0.00
	0.00	40.00	0.00	0.00	0.00	10.00
c						
c 16						
16 BOX	630.00	155.00	87.00	0.00	20.00	0.00
	-380.00	0.00	0.00	0.00	0.00	10.00
c						
c 17						
17 BOX	230.00	12.00	85.50	20.00	0.00	0.00
	0.00	163.00	0.00	0.00	0.00	0.50
c						
c 18						
18 BOX	230.00	12.00	85.00	0.00	20.00	0.00
	-210.00	0.00	0.00	0.00	0.00	2.00
c						
c 19						

19 BOX	20.00	32.00	85.00	20.00	0.00	0.00
	0.00	163.00	0.00	0.00	0.00	2.00

c

c 20

20 BOX	650.00	195.00	85.00	0.00	20.00	0.00
	-630.00	0.00	0.00	0.00	0.00	2.00

c

c 21

21 BOX	630.00	155.00	85.00	20.00	0.00	0.00
	0.00	40.00	0.00	0.00	0.00	2.00

c

c 22

22 BOX	630.00	155.00	85.00	0.00	20.00	0.00
	-380.00	0.00	0.00	0.00	0.00	2.00

c

c 23

23 BOX -1000 -1000 -1000 2000 0 0 0 2000 0 0 0 2000

c

c 24

24 Box 230.00 55.00 96.00 20.00 0.00 0.00 0.00 20.00 0.00 0.00 0.00 20.00

c

c 25

25 Box 230.00 110.00 55.00 20.00 0.00 0.00 0.00 20.00 0.00 0.00 0.00 20.00

c

c 26

26 Box 230.00 -40.00 76.00 20.00 0.00 0.00 0.00 20.00 0.00 0.00 0.00 20.00

c

c Material Cards

c

Mode P E

c

m3 1001 -0.143711 \$ HDPE, rho = 0.95
6000 -0.856289

c

m10 1001 -3.386 \$ Electronics Components, rho=3.054 g/cc
6000 -7.175
7014 -0.015
8016 -38.870
11023 -0.086
12000 -0.972
13027 -16.95
14000 -8.948
15031 -0.006
16000 -0.004
20000 -4.217
24000 -2.438
25055 -0.482
26000 -10.753
28000 -1.022
29000 -1.547
30000 -0.669
56138 -2.458
82000 -0.001

c

m22 6000 -0.0015 \$ C Steel conveyor, rho=7.86 g/cc
24000 -0.13 \$ Cr
25055 -0.0125 \$ Mn
14000 -0.01 \$ Si
15031 -0.0006 \$ P
16000 -0.0015 \$ S
26000 -0.8439 \$ Fe

c

m17 82000 -1 \$ Lead, rho=11.34

c

m7 6000 -0.000124 \$ C Air, rho=0.001205 g/cc
7014 -0.755267 \$ N
8016 -0.231781 \$ O
18000 -0.012827 \$ Ar

c

```

m4 13027 -1 $ Al, rho=2.7g/cc
c
c
c bbrem 1 1 46i 100 1
c
c
c sdef pos=240.0 120.0 96.00 $ spatial
c   erg=10 $ energy
c   par=e $ source type
c   vec=0 0 -1 dir=d1 $ direction
c   sur=10.5
c si1 -1 0.970142500 1
c sp1 0 0 1
c
sdef pos=240.0 65.0 75.00 $ spatial
c   erg=10 $ energy
c   par=e $ source type
c   vec=0 0 1 dir=d1 $ direction
c   sur=3.5
si1 -1 0.970142500 1
sp1 0 0 1
c
c
c
F4:P 201 202 226 T
E4: 0.002 100i 10
c
c F2:P 1.3 26.3
c E2: 0.002 100i 10
c
phys:n
phys:p 4j 1
phys:e
c
c
cut:n
cut:p j 0.001
cut:e j 0.001
c
c ctme 10
c
nps 500000
c
c *F8
c
print
rand gen=2 stride=305835
prtmp 3j 2
c
c F4
c
c

```