Spring 2-13-2017

Remote Handled Disposal Enhancement at the Waste Isolation Pilot Plant

Philip Theisen

Philip Theisen
Candidate

Nuclear Engineering
Department

This thesis is approved, and it is acceptable in quality
and form for publication:

Approved by the Thesis Committee:

Dr. Cassiano, De Oliveira, Chairperson

Dr. Patrick McDaniel

Dr. Youho Lee

REMOTE HANDLED DISPOSAL ENHANCEMENT AT THE WASTE ISOLATION PILOT PLANT

BY

PHILIP THEISEN

B.S. ARCHITECTURAL ENGINEERING

THESIS

Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

Nuclear Engineering

The University of New Mexico
Albuquerque, New Mexico

May, 2017

ACKNOWLEDGEMENTS

I heartily acknowledge Dr. Cassiano De Oliveira, my advisor and Thesis chair, for continuing to encourage me through the years of classroom teachings and his assistance in helping me with my project. I believe the knowledge and skills I learned from this project will benefit me throughout my career.

I also thank my committee members, Dr. Patrick McDaniel, and Dr. Youho Lee, for their valuable recommendations pertaining to this study and assistance in my professional development. Gratitude is also extended to the Department of Energy for the funding to pursue this research. As part of an Integrated Project Team lead by the Carlsbad Field Office, I would like to thank the Field Element at the Waste Isolation Pilot Plant for the opportunity to participate on their team and for the opportunity to continue on with my efforts during my graduate studies.

REMOTE HANDLED DISPOSAL ENHANCEMENT AT THE WASTE ISOLATION PILOT PLANT

By

Philip Theisen

B.S. Architectural Engineering, Illinois Institute of Technology, 2013

ABSTRACT

The Waste Isolation Pilot Plant (WIPP) is a deep underground facility for the disposal of Transuranic Defense Waste located in Southeastern New Mexico. Transuranic (TRU) Waste is defined as any radionuclides with an atomic number greater than that of Uranium, has a half-life greater than 20 years, and activity greater than 100nanocuries. According to the 'Land Withdrawal Act' (LWA), WIPP is licensed to dispose of 6.2million cubic feet of waste.

TRU waste is categorized into two types: Contact Handled (CH) and Remote Handled (RH). CH waste is any waste that does not have a surface dose rate that exceeds 200mrem per hour; while RH waste is defined as any waste with a surface dose rate greater than 200mrem per hour.

WIPP's current emplacement process for disposing of CH waste is to stack in rows along the floor of the underground panel drift. RH waste is emplaced by the borehole method in the ribs (walls) of the mine via a Horizontal Emplacement Machine (HEM).

The primary dilemma presented by the emplacement rates between CH and RH waste is the inefficiency with meeting the Volume of Record specified in the LWA. WIPP is allowed to dispose of 6.2 million CF of TRU waste. The facility is progressing through the disposal panels in the Underground (UG) at a rate in which available real estate for disposal will be filled before the Volume of Record is reached; and in doing so, disrupting the process for shipping hazardous TRU waste off of the generator sites throughout the Department of Energy (DOE) and into a permanent location for long term disposal.

An investigation will be conducted into a more efficient method for disposing of the RH waste from around the DOE Complex with the intent of dedicating a single panel to strictly RH waste. The concept will allow for the better utilization of RH real estate in the UG assisting the solution to meeting the Volume of Record.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

The WIPP is a deep underground repository for the disposal of Transuranic Defense Waste located in Southeastern New Mexico. WIPP belongs to what has been nicknamed the "Nuclear Corridor" of southeastern New Mexico. URENCO's enrichment facility in Eunice, New Mexico provides fuel for nuclear power utilities and Waste Control Specialists (WCS) in Andrews, Texas provides nuclear power plants with a low level waste facility. WIPP's focus is to permanently dispose of TRU Waste from around the DOE complex generated during nation's nuclear weapon defense program beginning in the early 1940's. WIPP is licensed to permanently isolate the waste in an underground facility 2,150 feet below the surface for the next 10,000 years. TRU Waste is defined as any radionuclides with an atomic number greater than that of Uranium, has a half-life greater than 20 years, and activity greater than 100nanocuries per gram.

The waste disposed at WIPP is bounded by the requirements per the LWA in terms of Dose Rates and Volume. Due to the complexity of Hot Cell Operations at the Generator Sites, an inefficiency exists between the amount of waste that is need of being disposed and the real estate available in the WIPP UG. The purpose of this project is to establish a methodology for disposing of RH more efficiently; utilizing the existing facility processes and provide shielding calculations that fit within the bounds of Regulations and the elements of the Facility.

HISTORY

In the 1950's, the National Academy of Sciences proposed the idea of deep geological disposal for long lived radionuclides. The government spent time during the 1960's researching potential sites around the nation, which eventually narrowed down to Southeastern New Mexico. Exploratory work for WIPP's repository location began in 1974 with Construction operations taking place from 1982 until 1988. In 1979 Congress authorized WIPP as a Research and Development project for radioactive waste disposal. President Bush signed the LWA of 1992, a bill to allow the transfer public lands belonging to the State of New Mexico to the DOE. After receiving Certification from the EPA and the HWFP issued by the State of New Mexico for the Resource Conservation and Recovery Act (RCRA), WIPP's opening occurs and receives their first shipment in 1999 from Los Alamos. To date, five of the ten disposal panels in WIPP's underground have been undergone final closure.

WIPP started to receive waste in 1999; this was strictly CH waste at the time. In 2007, WIPP received its first RH waste. The first panel to dispose of RH waste was Panel 4; the first three were exclusively CH waste. Since then, WIPP has completely filled six of the ten panels; Panels 9 and 10 being located in the main drifts traversing north and south. Panel 7 just began disposal.

GEOLOGY

The geographical region assigned, the Delaware Basin, was chosen as the most suitable form of long term radioactive disposal. The salt, in which the waste is buried in at WIPP, provides a range of advantages for disposing of radioactive waste. For starters, Salt is for all intents and purposes, impermeable. The salt basin at WIPP has existed since the Permian Era, 250 million years ago. This fact has provided enough assurance that free flowing ground water will not flow to the waste causing a radioactive effluent. Salt is also considered "self-healing". This entails the healing of fractures that might be seen in the formation. If a fracture exists, the salt will close (or creep) filling in the cavity and then bond to the adjacent surfaces. This is an important characteristic to WIPP's operations. The radioactive waste disposed of at WIPP is emplaced into disposal rooms that are isolated by permanent bulkheads, over time the weight of the ground above the rooms will eventually lead to the a permanent encasing of waste to shield it for the 10,000 year timespan.

SALT DEFENSE DISPOSAL INVESTIGATIONS

SDDI were experiments conducted on Defense High Level Waste (DHLW) to better understand the impact of in-drift emplacement of radioactive waste on the salt; particularly the thermal characteristics observed in the salt. These experiments were conducted in specified drifts of WIPP's UG. Heaters were used to study the thermal properties from in-drift emplacement. This was seen as operationally beneficial compared to the borehole method described above mainly due to the fact that it is more time efficient. The SDDI concluded that the salt may potentially be an excellent medium to dispose of HLW. Modeling has been performed and the development of test plans is still ongoing.

SURFACE FACILITY

The Surface of WIPP comprises of two primary components to perform waste disposal operations: the four shafts and the Waste Handling Building (WHB). The first shaft is the Air Intake Shaft (AIS). This allows a channel for the airflow to the UG to enter. The air is then pulled through the UG facility via the fans located at the top of the Exhaust Shaft (ES). The airflow will then enter a filtration system before exiting into the environment. The SHS was developed to assist in the mining operations of the UG.

When a new panel is mined a salt haul truck will transport run of mine salt (ROM) to the Salt Handling Shaft (SHS) where it will be carried out of the UG. The last shaft at WIPP is the Waste Handling Shaft (WHS) for waste handling operations. Sections 1.6 and 1.7 describe the CH and RH process used at WIPP, part of which is downloading the waste to the UG after unloading from the shipping containers. Once the waste reaches the bottom of the WHS, a forklift or Transporter will retrieve the waste.

UNDEGROUND FACILITY

The WIPP UG facility is split into three sections: shaft pillar area, north experimental area, and waste disposal area. The shaft pillar area is the defined area from which the ground must be protected due to the location of the shafts providing an exit and source of ventilation. The north experimental area is dedicated to research; and the disposal area is made up of eight panels each with 7 rooms that once filled are then segregated by bulkhead closure. Panels 9A and 10A encompass the main drifts and are planned to be filled upon completion of the first eight panels. Figure 1represents the basic layout of WIPP.

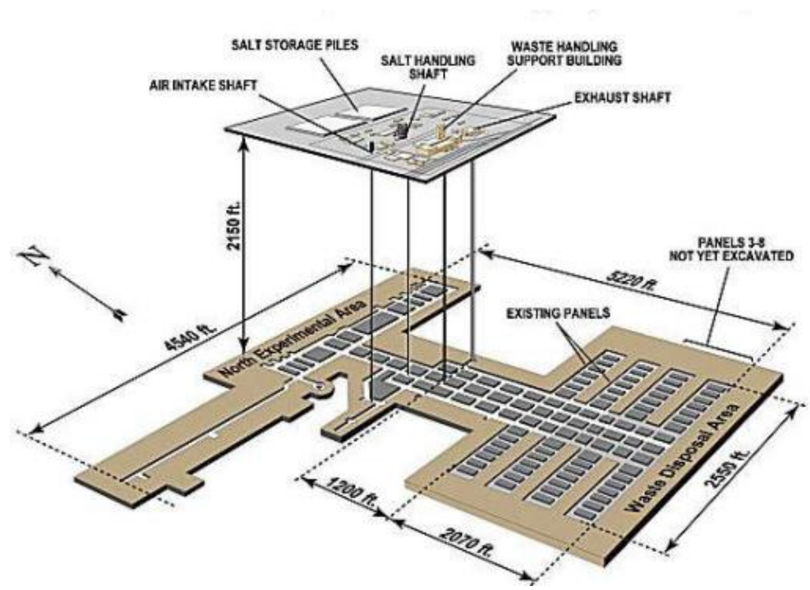

Figure 1: WIPP Surface and UG Layout

CONTACT HANDLED WASTE PROCESS

The primary waste disposed of at WIPP is solely TRU Waste. These are categorized into two types at WIPP: CH and RH. CH waste is any waste that does not have a surface dose rate that exceeds 200mrem per hour; while RH waste is defined as any waste with a surface dose rate greater than 200mrem per hour. Both sets of waste are received and processed at WIPP within the confinement of the WHB. This facility is split between a CH Bay and RH Bay. The CH Bay provides a confined area to unload a CH package from the shipping containers: Transuranic Packaging Transporter (TRUPACT) II and TRUPACT III. Half Pacts are also a shipping container approved for receipt and is essentially the same as TRUPACT II except transports half as much in a package. From here the packages are then downloaded via the Waste Handling Shaft to the UG. A vehicle known as the Transporter will then deliver the waste package to the disposal room where a forklift will emplace. The containers are disposed of in a honeycomb pattern along the floor of the disposal room. Approximately 96% of the waste at WIPP is CH.

REMOTE HANDLED WASTE PROCESS

RH waste undergoes a different process as seen in Figure 12. The Shipping Cask is brought into the RH Bay of the WHB and processed through what is called the transfer cell to a Facility Cask. Due to the higher levels of radioactive material within the RH Canisters, the only time it is exposed outside of a cask is in the transfer cell which lined with appropriate concrete shielding. Any other time throughout the process, RH waste is contained within a Cask. This Cask reduces the Dose Rate to 200mrem/hr, same as CH, which allows operators to process without additional precautions. The Facility Cask is then downloaded via the Waste Hoist to the underground where it meets the 41 Ton Forklift to be delivered to the disposal room. RH waste is emplaced by the borehole method in the ribs (walls) of the mine via a Horizontal Emplacement Machine (HEM).

REGULATORY REQUIREMENTS

WIPP's primary regulating body is the DOE. However, other agencies such as NMED and EPA have jurisdiction over WIPP's operations, administering the HWFP and Certification, respectively. The HWFP drives the WIPP's ability to dispose of hazardous waste according to RCRA at the state level. WIPP's Certification verifies that WIPP's waste disposal regulations are compliant with 40 CFR. Congress requires that WIPP be recertified every five years until the end of its operational lifetime.

In 1992 Congress set forth the LWA, licensing WIPP to dispose of 6.2million cubic feet of waste. Here CH waste is defined as being less than 200 mrem/hr and RH is greater than 200 mrem/hr but less than 1,000 rem/hr. Only 5% of WIPP's waste is allowed to be greater than 1,000 mrem/hr.

Before waste operations could commence, WIPP was required to implement a DSA. This is , is a in depth hazard analysis that describes WIPP's site, the facility and equipment, the hazard analysis associated with CH and RH accidents, the SSC's used for controls, and programmatic descriptions.

Other documents important to this project include: the TRAMPAC, and the WAC. The TRAMPAC documents govern all shipments in TRUPACT II's, Half Pacts, TRUPACT III's, and RH-72 Type-B shipping containers. The Waste Acceptance Criteria (WAC) defines the criteria for which the National TRU Program (NTP) generator sites can ship waste to WIPP. These two documents assist in defining the contents and construction of the shipping containers.

The RH Safety Analysis Report (SAR) was also referenced; this document, similar to the Design Safety Analysis (DSA), provides a description of the RH-72 Type-B Shipping Container and the Hazard Accident Conditions (HAC) associated with RH waste. The vital piece of information in this document is the method for deriving the shielding requirements for an RH canister.

CHAPTER 2: IN SCOPE

The primary dilemmas both these methods offer is the inability to meet the Volume of Record specified by the LWA; At WIPP's current pace, many of the waste panels in the mine will be full before all the Defense TRU Waste around the DOE Complex has been permanently disposed. One cause of this problem is the inefficiency of the borehole method due to the difference of shipment rates between RH and CH waste. Many of the drilled boreholes stay vacant due to the quicker rate of CH floor emplacement compared to the RH emplacement. The LWA specifies that WIPP shall not exceed any more than 5% of the total volume disposed with a surface dose rate higher 100rem per hour. This makes 95% of the waste received by definition CH waste. The process for mining uses the Just-In-Time concept; a panel is mined at the same time the panel previously mined is being used for waste emplacement. This allows the process the most time possible to utilize for disposal before the weight of the salt (or ground above) creeps in too much to the point of collapsing prematurely. The Just-In-Time method allows workers to emplace waste with the least amount of maintenance during emplacement. Once arrays of CH packages are emplaced, the ground behind it is unable to be maintained. Within the disposal panel RH boreholes are drilled in one room, RH waste canisters are emplaced within the previous room, and CH waste is emplaced in the room previous to RH emplacement. Once again, this utilized the Just-In-Time method to dispose of the waste; but if the process was prolonged to allow for additional RH waste, the rooms would be more difficult to maintain.

The Volume of Record mentioned above, refers to the volume of waste allowed by the LWA to be disposed of at WIPP. This value is based on the volume of containers shipped and not the actual volume of waste packaged in the container. Through radiography, it was discovered that due to the inefficient method of packaging the containers using glove boxes, only about 10% of the containers were being filled with waste. The overarching problem is due to the fact that the CH shipping rates are much quicker than RH and only a small percentage of the waste around the complex is being disposed of, DOE runs the risk of filling up WIPP long before the nation's laboratories are cleaned up. The following discusses the shipping rates between CH and RH waste per the Supplemental Environmental Impact Statement (SEIS) prepared by DOE.

- CH TRU Waste Rates
  - TRUPACT II Unloading Dock (TRUDOCKS) handling capacity = 50 TRUPACTs/week
  - Assumed 80% efficiency due to worker impact analysis = 40 TRUPACTs/week or 13-14trucks/ week (from SEIS)

- 3 TRUPACTs/ Truck
- 3 TRUPACTs fills ~ 2 full positions in disposal room

- RH TRU Waste Rates
  - 2007-2009 = 2.1/week
  - 2009-2010 = 2.8/week
  - 2010-2011 = 3.1/week
  - 2011-1012 = 1.9/week
- RH TRU Borehole Emplacement Rates
  - Panel 1- Panel 3 = None
  - Panel 4 = 198 boreholes filled
  - Panel 5 = 264 boreholes filled
  - Panel 6 = 85 boreholes filled
  - Total Capacity/ Panel = 730 boreholes filled

The floor configuration for emplacing RH canisters was explored by the SDDI studied the impact of heat generated from HLW on the surrounding salt. This study will look into the equipment specifications that would support the SDDI concept. The SDDI concluded that using retreat emplacement and horizontally emplaced canisters directly on to the floor using a Remote Operated Vehicle (ROV). The primary focus of this project is the shielding design of that ROV and defining process that the canister will undergo from point of receipt to final disposal. The intent of the conceptual process is to utilize as much of WIPP's current facilities, equipment and processes as possible.

The goal of this project is to design the shielding of a piece of equipment capable of disposing of RH TRU waste within the geometric parameters of the existing facility and without violating the regulatory bounds that will assist with the overall efficiency towards reaching the volume of record. The conclusion of this project will provide a series of dose calculations and equipment specifications along with a conceptual process.

CHAPTER 3: OUT OF SCOPE

In February of 2014, WIPP experienced two major events: the February 5th fire event and the February 14th Radiological Release. Due to recovery operations, WIPP is not currently open (waste is not being accepted or disposed of). As a result of the accidents, changes are being made to the Safety Basis. Much of the Waste Disposal area in the underground is categorized as Contaminated Areas and Radiation Areas. Panels 9A and 10A are located within these areas as well as the remainder of Panel 7. Currently Panel 8 is the only clean panel and has not been completely mined as of today.

Other items that will not be considered include the process of packaging the waste. As this would provide an alternative solution, the focus of this project will be on the step carried out at WIPP to dispose of the waste in its final resting place.

CHAPTER 4: INITIAL ASSUMPTIONS

The use of a dedicated RH Panel/ Rooms would require under the current conditions of the underground, assuming both CH and RH operations continue, that new panels be mined. This project will not be looking at the alternatives to expanding the mine. It will be assumed that the process used will be operated under a clean environment.

Regarding the Volume of Record, each drum disposed is not full to maximum capacity and hence most of the 6.2million cubic feet disposed will not be Transuranic Waste. The majority of these drums are made up of approximately 90% air and only 10% waste due to glove box operations. This is a result of the generator site processes and will not be considered in this project.

The waste received at WIPP is required to meet the WAC. This specifies the chemical, radiological, nuclear, and physical limits of the waste being shipped to WIPP. The presumption will be that these limits will not be exceeded and anytime they are, it will be considered an abnormal event.

This design will assume that both the current borehole method and new floor emplacement method will be utilized simultaneously. The floor emplacement method will be reserved for RH waste greater than 100 rem/hr but less than the LWA limit of 1,000 rem/hr. These canisters will be emplaced in a dedicated RH Panel. All waste less than 100 rem/hr (includes both CH and RH) will be disposed of by the same process currently in place at WIPP. The borehole method provides sufficient means to shield the RH Canister from personnel disposing of waste; a new dedicated RH Panel will be a means to dispose of RH with higher Dose Rates in a more efficient way and also relieve the varying rates between CH and RH waste under the current process. The range for the Source Strength will be from 100 rem/hr to 1,000 rem/hr. The process will calculate the thickness required for the Cask needed to reduce the maximum Source limit of 1,000 rem/hr to 200 mrem/hr. The results will then be used to generate the lower Dose Rate with the same thickness but with a Source strength of 100 rem/hr. This will be the Dose Rate range exhibited by the Cask.

CHAPTER 5: METHODOLOGY

The method used for this project will be the *Optimization Toolbox* in Matlab. The Optimization Toolbox allows for solving functions with a very distinct set of constraints. The solutions can be minimized or maximized based on the intent. Specifically for this project, the optimal objectives include: shielding requirements and equipment specifications.

Before the optimization runs, manual iterations using trial by error will be completed to approximate the range for the independent variable. This independent variable will be the lead layer. The inner and outer stainless steel layer will be approximated with the manual iterations. The Source strength will be constant; however, after solving for the shielding thickness, a lower Source strength will be used with the same thickness. This will provide the range of Dose rates that will be observed. The buildup factor and mean free path will also vary due to the fact that they are dependent on the thickness.

Since the manual Matlab Iterations provide an approximated range and expected value, the optimization run will provide the exact value needed to obtain a surface dose rate of 200mrem/hr.

CHAPTER 6: CONSTRAINTS

The shielding of the RH equipment allows the waste to be processed as CH. Only when the canister is removed from either the Shipping Cask or Facility Cask does it require a shielded hot cell configuration; which is the transfer cell in this process. The surface dose rate specified by the LWA is 200mrem/hr. The calculations will use a range of shield thicknesses for Lead and Stainless Steel 304 to acquire a dose rate that will then be truncated at 200mrem/hr.

After surface processing, the newly designed cask will download the waste into the mine via the Waste Hoist Shaft. The Waste Hoist is a friction type hoist with a counterweight that is used to raise and lower the conveyance. The conveyance has a 45 ton maximum capacity for RH waste. The new cask design will need to meet both the dose rate limits and the weight capacity; the 8,000 lb loaded canister will be taken into account as well.

Another important bound that needs to be accounted for is the dimensions of the drifts. The Disposal Rooms are approximately 13 feet high, 33 feet wide and 300 feet long. The entrance into the Panel is specified by the DSA as being 14 feet wide. These dimensions will bound the overall turning radii needed by the forklift.

CHAPTER 7: INPUT PARAMETERS

The Shielding Design Calculation will utilize the Dose Rate Equation with a defined set of ranges to generate a Dose Rate. This Dose Rate will then be truncated at the 200 mrem/hr limit.

ENERGY SOURCE

The output of interest for the RH shielding calculations are primarily a dose rate that is within the required limits established by the LWA for both gamma and neutron energies. The energy range specified in the RH-TRU 72-B SAR, will be utilized for the design of the Cask shielding thickness. This range is from 0.1MeV up to 5MeV. All the calculations will be set at the 5MeV bound.

RADIONUCLIDE INVENTORY

Both CH and RH waste received at WIPP are TRU waste from the Cold War Era from around the nuclear production sites. Most of which consists of clothing, tools, rags, residues, debris, etc. Table 1 is an in depth list of the radionuclide inventory as specified by the RH-TRU 72-B SAR. However, the only ten radionuclides comprise of 95% of the radioactive hazard. These are called the Ten WIPP-Tracked Radionuclides as seen in Table 2.

^{3}H	^{88}Zr	^{126m}Sb	^{153}Gd	^{222}Rn	^{240m}Np
^{10}Be	^{90}Zr	^{123}Te	^{160}Tb	^{221}Fr	^{236}Pu
^{14}C	^{90m}Zr	^{125m}Te	^{166m}Ho	^{223}Fr	^{238}Pu
^{22}Na	^{93}Zr	^{127}Te	^{168}Tm	^{223}Ra	^{239}Pu
^{32}P	^{95}Zr	^{127m}Te	^{182}Ta	^{224}Ra	^{240}Pu
^{33}P	^{93m}Nb	^{129}Te	^{198}Au	^{225}Ra	^{241}Pu
^{35}S	^{94}Nb	^{129m}Te	^{207}Tl	^{226}Ra	^{242}Pu
^{45}Ca	^{95m}Nb	^{125}I	^{208}Tl	^{228}Ra	^{243}Pu
^{46}Sc	^{99}Tc	^{131}I	^{209}Tl	^{225}Ac	^{244}Pu
^{49}V	^{99m}Tc	^{134}Cs	^{209}Pb	^{227}Ac	^{241}Am
^{51}Cr	^{103}Ru	^{135}Cs	^{210}Pb	^{228}Ac	^{242}Am
^{54}Mn	^{106}Ru	^{137}Cs	^{211}Pb	^{227}Th	^{242m}Am
^{55}Fe	^{103m}Rh	^{133}Ba	^{212}Pb	^{228}Th	^{243}Am
^{59}Fe	^{106}Rh	^{137m}Ba	^{214}Pb	^{229}Th	^{245}Am
^{57}Co	^{107}Pd	^{141}Ce	^{207}Bi	^{230}Th	^{240}Cm
^{58}Co	^{108}Ag	^{142}Ce	^{210}Bi	^{231}Th	^{242}Cm
^{60}Co	^{108m}Ag	^{144}Ce	^{211}Bi	^{232}Th	^{243}Cm
^{59}Ni	^{109m}Ag	^{143}Pr	^{212}Bi	^{234}Th	^{244}Cm
^{63}Ni	^{110}Ag	^{144}Pr	^{214}Bi	^{231}Pa	^{245}Cm
^{64}Cu	^{110m}Ag	^{144m}Pr	^{209}Po	^{233}Pa	^{246}Cm
^{65}Zn	^{109}Cd	^{146}Pr	^{210}Po	^{234}Pa	^{247}Cm
^{73}As	^{113m}Cd	^{147}Pr	^{211}Po	^{234m}Pa	^{248}Cm
^{79}Se	^{115m}Cd	^{148}Pr	^{212}Po	^{232}U	^{250}Cm
^{85}Kr	^{114}In	^{148m}Pr	^{213}Po	^{233}U	^{247}Bk
^{86}Rb	^{115m}In	^{146}Sm	^{214}Po	^{234}U	^{249}Bk
^{87}Rb	^{119m}Sn	^{147}Sm	^{215}Po	^{235}U	^{250}Bk
^{89}Sr	^{121m}Sn	^{151}Sm	^{216}Po	^{236}U	^{249}Cf
^{90}Sr	^{123}Sn	^{150}Eu	^{218}Po	^{237}U	^{250}Cf
^{88}Y	^{126}Sn	^{152}Eu	^{211}At	^{238}U	^{251}Cf
^{90}Y	^{124}Sb	^{154}Eu	^{217}At	^{239}U	^{252}Cf
^{90m}Y	^{125}Sb	^{155}Eu	^{219}Rn	^{240}U	^{254}Cf
^{91}Y	^{126}Sb	^{152}Gd	^{220}Rn	^{237}Np	^{252}Es
				^{238}Np	^{253}Es
				^{239}Np	^{254}Es
				^{240}Np	^{254m}Es

Table 1: WIPP Radionuclide Inventory

^{241}Am	^{240}Pu	^{234}U	^{137}Cs
^{238}Pu	^{242}Pu	^{238}U	
^{239}Pu	^{233}U	^{90}Sr	

Table 2: Ten WIPP Tracked Radionuclides

SHIELDING MATERIAL

The shielding will comprise of an outer layer of Type 304 Stainless Steel, a layer of Lead, and an inner layer of Type 304 Stainless Steel. The composition and properties of these materials are provided in Table 3 and will be used in the calculation of the mass attenuation coefficients needed for the Mean Free Paths (mfp).

Element	Stainless Steel Type 304		Lead	
	Percent Composition	**Partial Density (g/cc)**	**Percent Composition**	**Partial Density (g/cc)**
Silicon	1%	0.0801	-	-
Chromium	19%	1.5224	-	-
Manganese	2%	0.1603	-	-
Iron	68%	5.4487	-	-
Nickel	10%	0.8013	-	-
Lead	-	-	100%	11.35
Total	100%	8.0128	100%	11.35

Table 1: Summary of Shield Regional Densities

SHIELDING THICKNESS

The layers that can be observed in the Clamshell Cask design will include an outer layer of Stainless Steel Type 304, a middle layer of Lead, and an inner layer of Stainless Steel Types 304. The Stainless Steel layers ranged from 1cm, 2cm, 4cm, 6cm, 8cm, and 9cm. The Lead layer was ranged from 0.06cm to 17cm. Only ten Matlab iterations were explored for each Stainless Steel layer to achieve the most accurate solution.

CHAPTER 8: RESULTS

The following illustrates the conceptual design of the equipment and process for the enhancing RH disposal. Both the conceptual designs integrated with the current facility and processes at WIPP and the shielding calculations are provided below. The Shielding calculations were also used to derive the dimensions and the net weight of the Cask. These values contributed to the basic capacity and the turning radius of the forklift.

CLAMSHELL CAKS DESIGN

The Clamshell Cask (Figure 2) is a shielded transfer device for RH-TR 72-B canisters. Based on the calculations seen in Table 7, the Cask length ranges from 10'-9" to 11'-11"; the canister is 10' in length. The diameter of the Cask from the Table 7 is an approximate range of 2'-10" to 4'and the canister has a set diameter of 2'-2".

The Cask has a Clamshell design is a cylindrical container capable of retracting within itself to allow for access to the inner cavity. The RH Canister will be suspended while the Cask encloses and by doing so encases the Canister. Once in the underground, the Cask opens by the same mechanism as exhibited on the surface except in a horizontal orientation for floor emplacement.

Due to the dimensions of the WHS, the Clamshell Cask will not fit appropriately unto the hoist if placed perpendicularly. The Cask will need the capabilities of rotating 90 degrees for optimal fit. A Clamshell Cask Actuator with a remote gear system will allow for the horizontal rotation of the Cask.

Once delivered to the WHS, the Clamshell Cask poses the issue of rolling. To eliminate rolling, a stabilizing rack (Figure 7) will be utilized on the waste hoist for convenient transporting of the Cask.

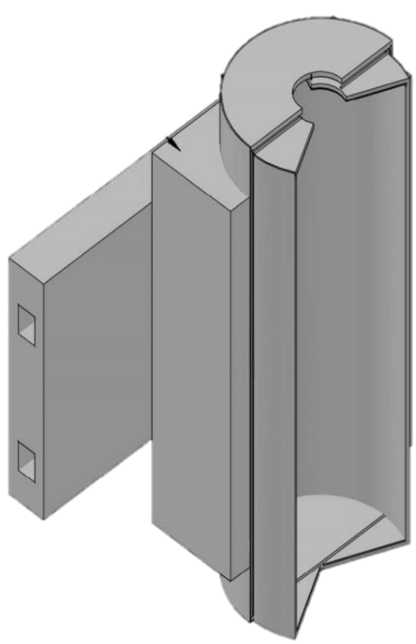

Figure 2: Empty Clamshell Cask Design

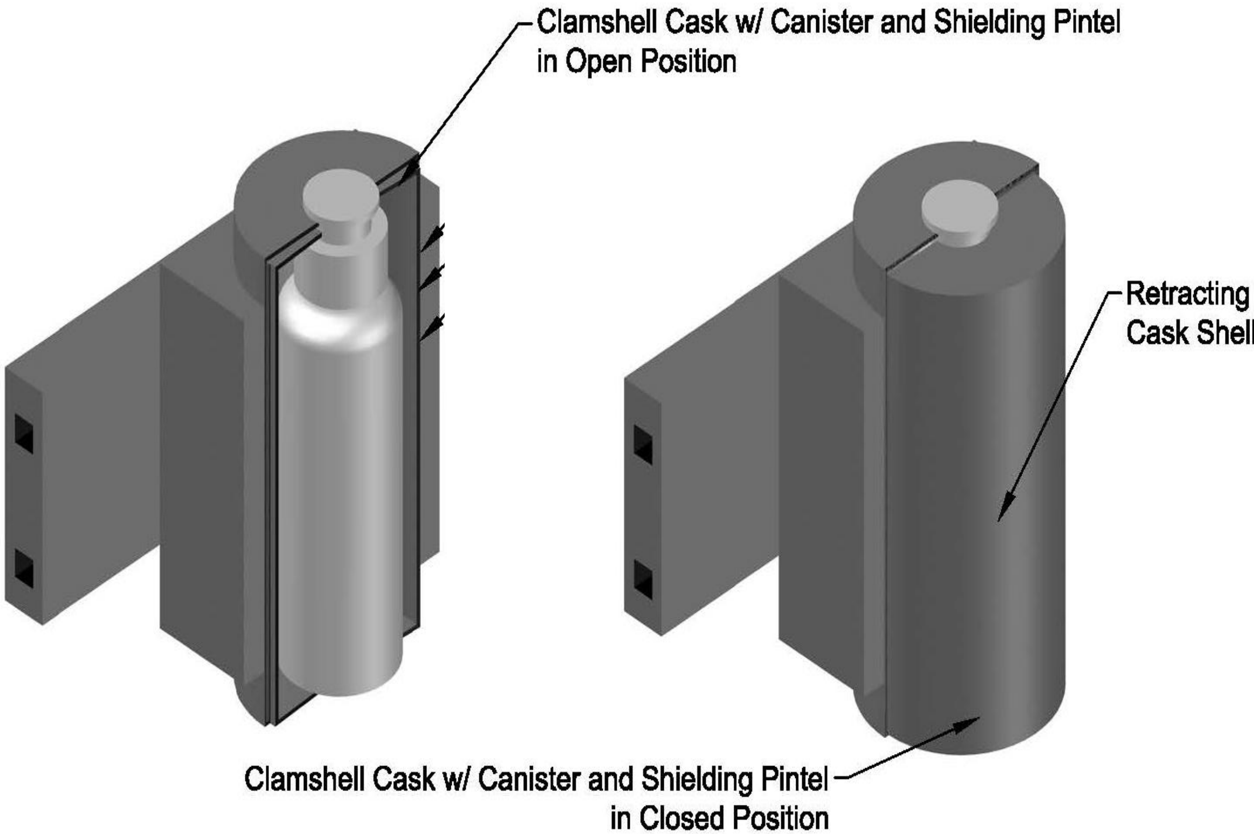

Figure 3: Loaded Clamshell Cask Design

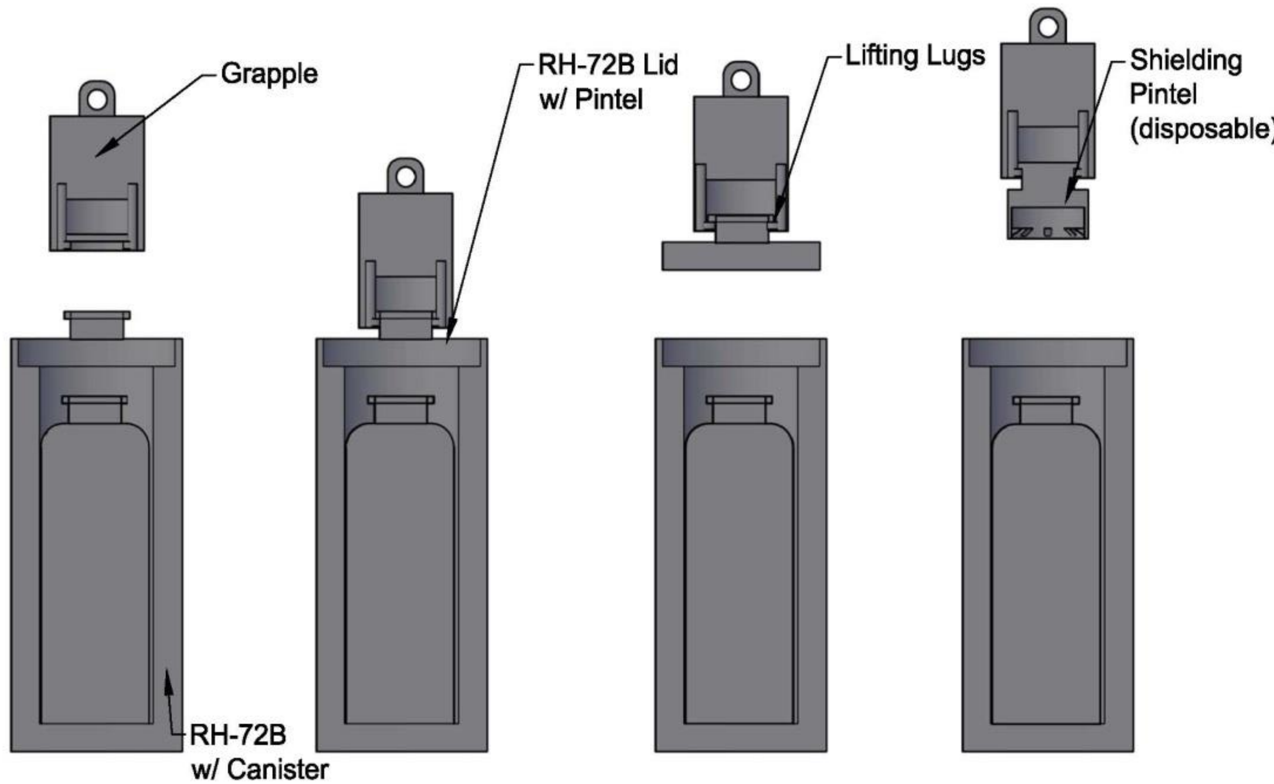

Figure 4: RH-TRU 72-B Canister Extraction Phase

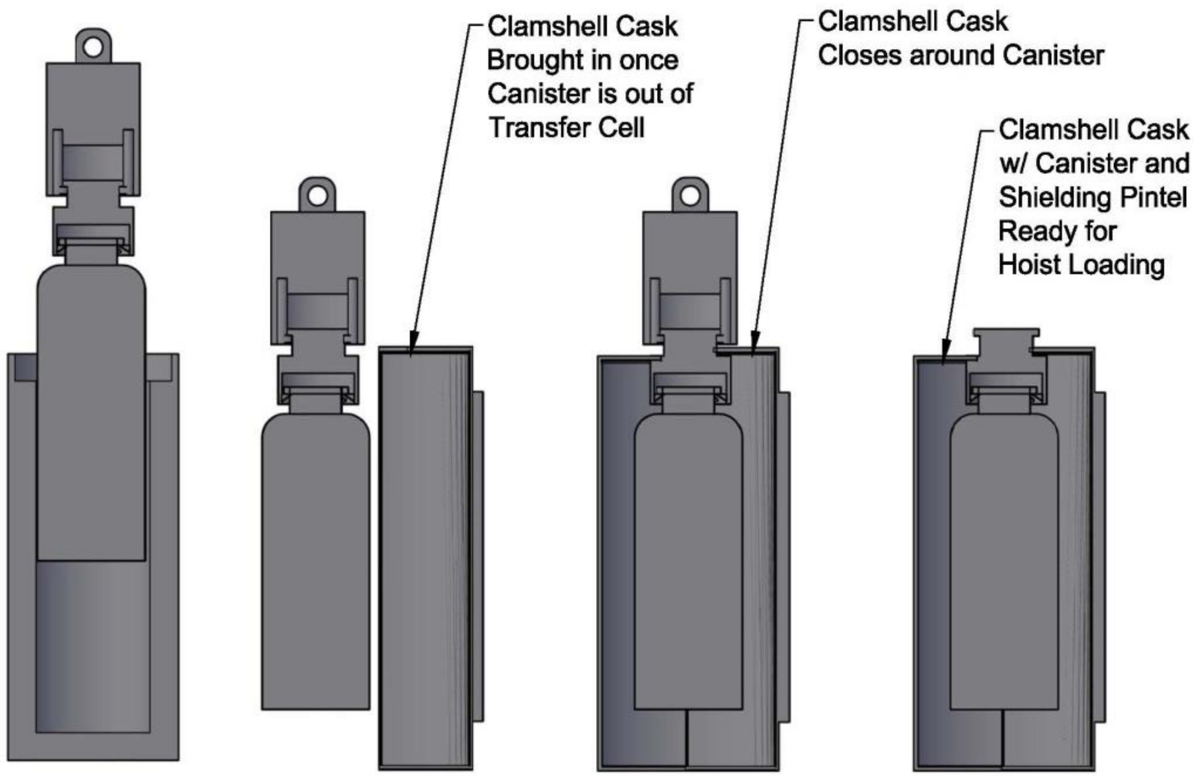

Figure 5: RH-TRU 72-BCanister Loading Phase

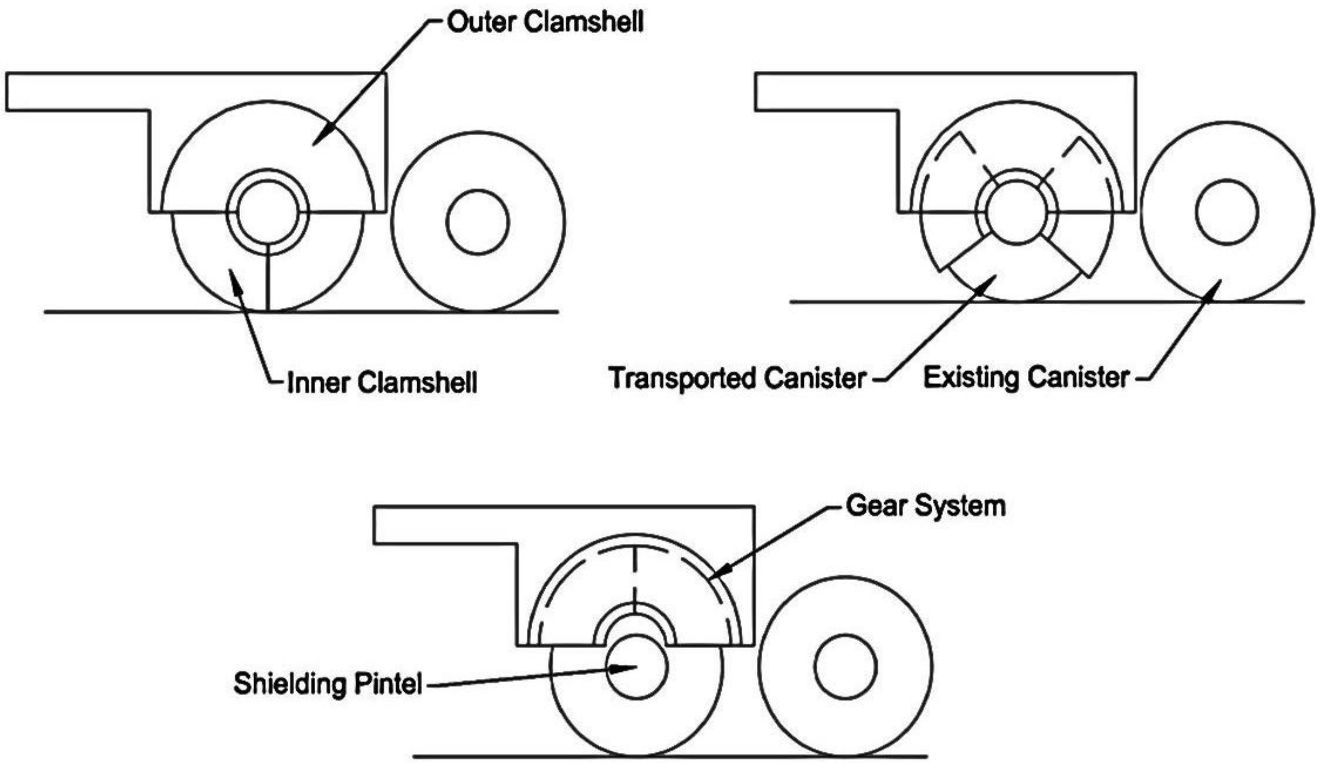

Figure 6: Clamshell Cask Retraction Schematic

Figure 7: Stabilizing Rack Design

SHIELDING PINTEL DESIGN

The RH-TRU 72-B will undergo the same process for horizontal in drift floor emplacement as that of the borehole emplacement up until the loading from the Transfer Cell. The shield bell will be attached to a shielding pintel (Figure 1), which will also be disposable, will be used to grapple the canister and load into the Clamshell Cask. One way lugs will provide the grasping mechanism needed for attaching to the RH canister pintel to pull up into the cask. The shielding pintel will also offer the necessary shielding for the gap. Figure 4 and Figure 5 display the various extraction and loading stages the RH-TRU 72-B Canister will experience in the Transfer Cell and Cask Loading Room.

REMOTE OPERATING VEHICLE DESIGN

An ROV as seen in Figure 4 is the primary piece of equipment that will be used in delivering the Clamshell Cask to its final resting place in the horizontal emplacement process. There will be three separate units needed; one surface unit for transporting the Cask in the Cask Loading Room to the Waste Hoist and two in the Underground; one for transporting the Cask from the Waste Hoist to the RH dedicated Panel airlock and the other to retrieve from the airlock and deliver to its emplacement position.

The forklift apparatus used for lifting the Clamshell Cask will also contain a rotational aspect to allow the Cask to be revolved from the orientation necessary for the RH canister loading to the orientation necessary for placement on the hoist. A vertical rotation allows the Cask to be moved from the loading position to the stabilizing rack in the Waste Hoist. This movement will also be used when retrieving the Cask from the Waste Hoist in the underground. The vertical translation represents the basic mechanism of a forklift in terms of reaching different heights, which will also be needed when staging the Cask on the stabilizing rack. The final orientation that the Cask provides is a horizontal rotation for final disposal on the floor of the RH dedicated room.

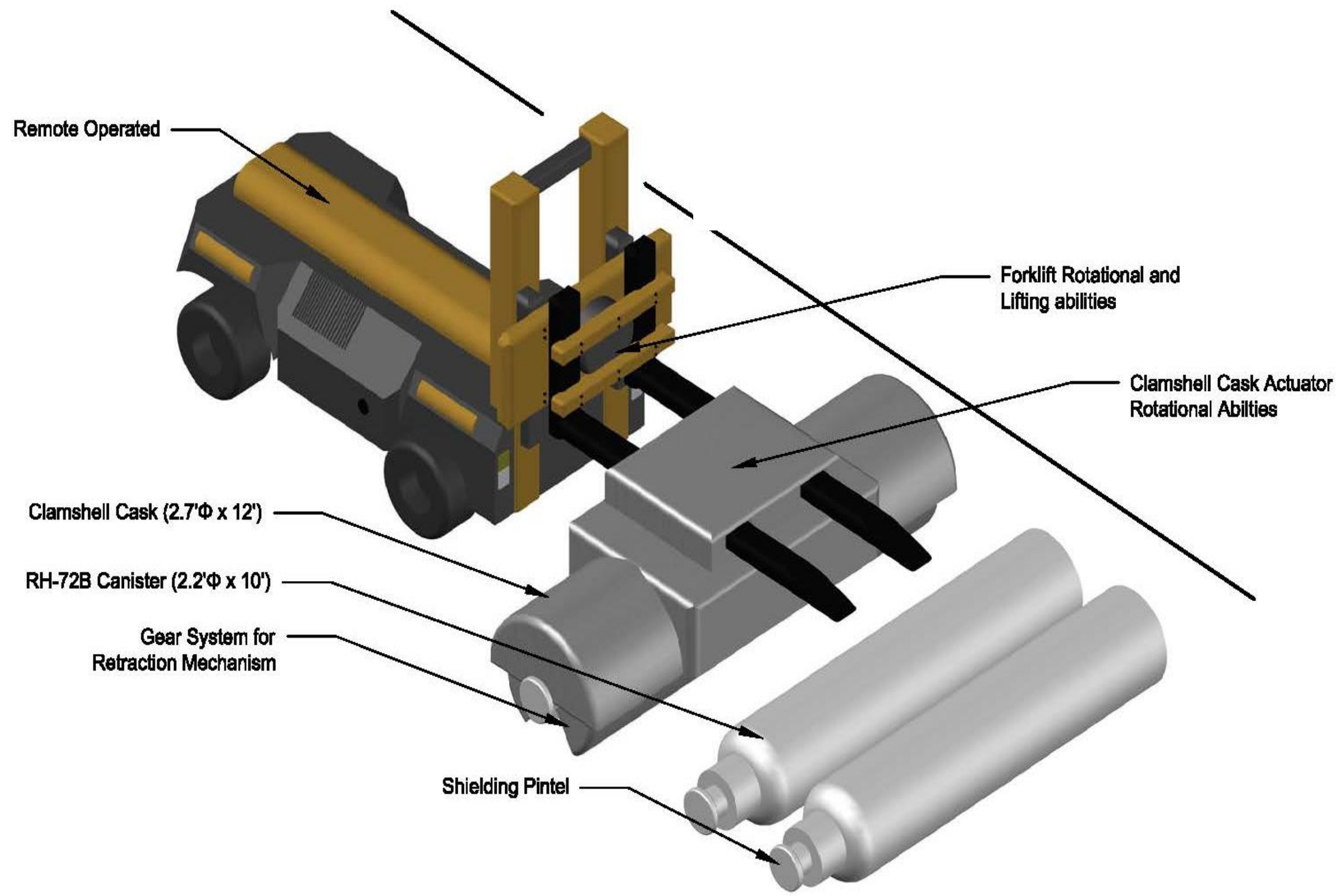
Remote Operated
Forklift Rotational and
Lifting abilities
Clamshell Cask Actuator
Rotational Abilties
Clamshell Cask (2.7'Φ x 12')
RH-72B Canister (2.2'Φ x 10')
Gear System for
Retraction Mechanism
Shielding Pintel

Figure 8: ROV

A. Horizontal Rotation	B. Vertical Rotation	C. Vertical Translation

Figure 9: ROV Maneuvering Capabilities

SURFACE REMOTE HANLED PROCESS

As seen in Figure 9, once the RH-TRU 72-B container has been conveyed through the Transfer Cell, the facility grapple will remove the lid of the container and attach to the pintel of the shielding pintel. The shielding pintel will be lowered and permanently attached to the pintel of the RH canister. It is important to note that the shielding pintel is a disposable piece of equipment that will accompany the RH canister for the remainder of its disposal lifetime.

Once the RH canister has been drawn out of the Transfer Cell, the Clamshell Cask will close around the canister as a remote operation. The HEM will approach the Cask and will slide the forks into the fork holes located on the Clamshell Cask Actuator. The Actuator will then rotate the Cask forward until it is in a horizontal alignment. From this position, the forklift will be remotely turned so the Cask can be properly positioned onto the stabilizing rack for transportation down the WHS.

UNDERGROUND REMOTE HANDLED PROCESS

Upon arrival of the Clamshell Cask to the UGvia the WHS, an additional ROV will approach the hoist and lift the Cask out of the Stabilizing Rack and off of the hoist. It will then proceed to reverse into the drift and forward towards the RH dedicated panel.

As the ROV reaches the disposal room, the Clamshell Cask Actuator will realign the Clamshell Cask to a perpendicular orientation. The forklift will lower the Cask to the floor while the gear system activates the opening of the outer cask shell. The Clamshell Cask will be emplaced on the floor of the drift and the ROV will reverse out of the room to retrieve additional canisters (Figure 10). The option of stacking the RH canisters will also be available, however not a necessity to the process.

RUN OF MINE SALT PROCESS

After an appropriate amount of RH canisters have been emplaced on the RH dedicated room floor, a remote operated conveyor system with an attached hopper will approach the waste. This hopper will be prefilled with ROM salt by the LHD. The conveyor belt will contain a swiveling end piece for greater range.

The ROM salt will be cascaded onto the RH canisters to provide shielding for a safe work environment for the upcoming shift. These steps will be repeated until the RH dedicated room has been completely filled and closed off (Figure 11).

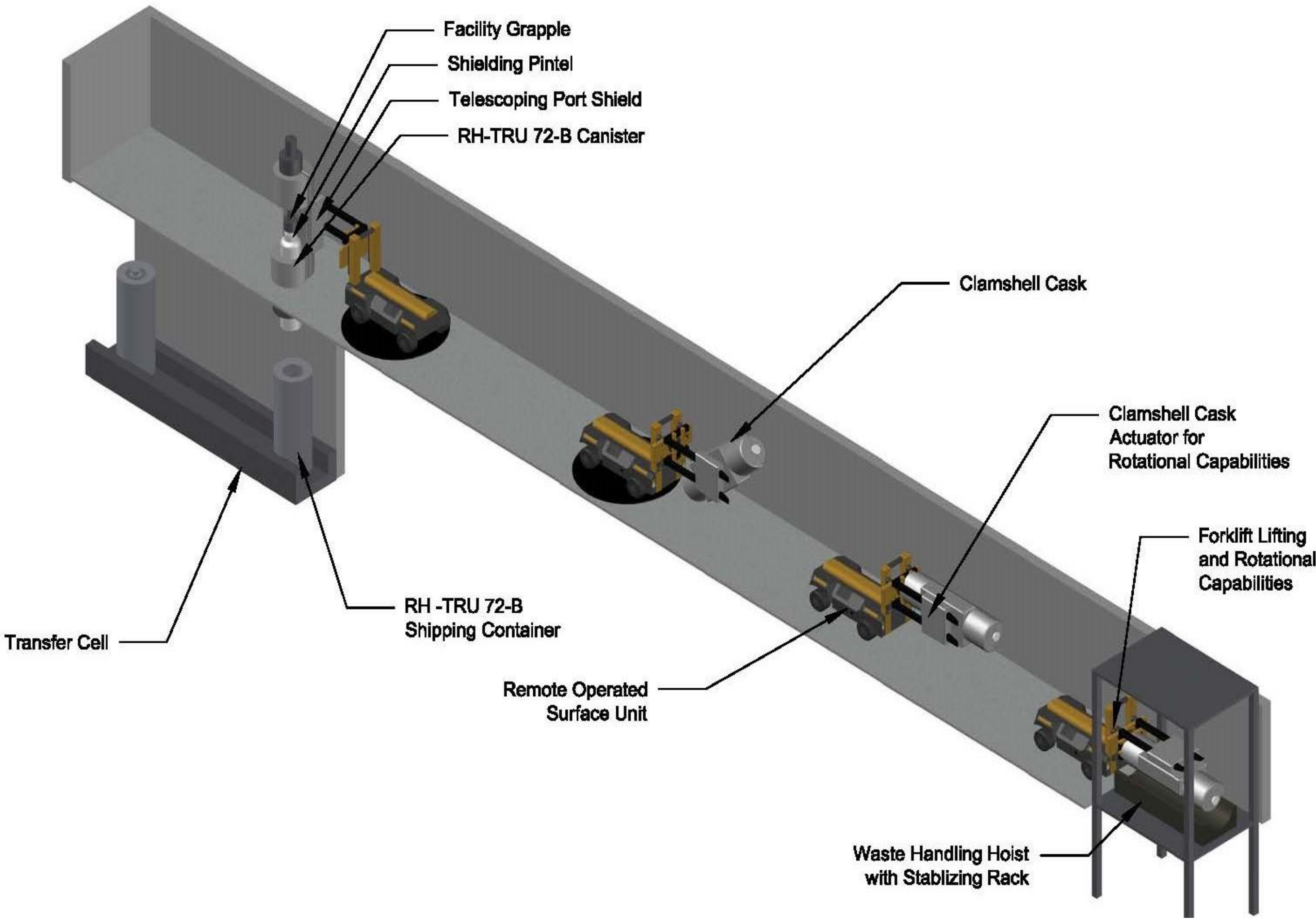

Figure 10: Surface RH Process

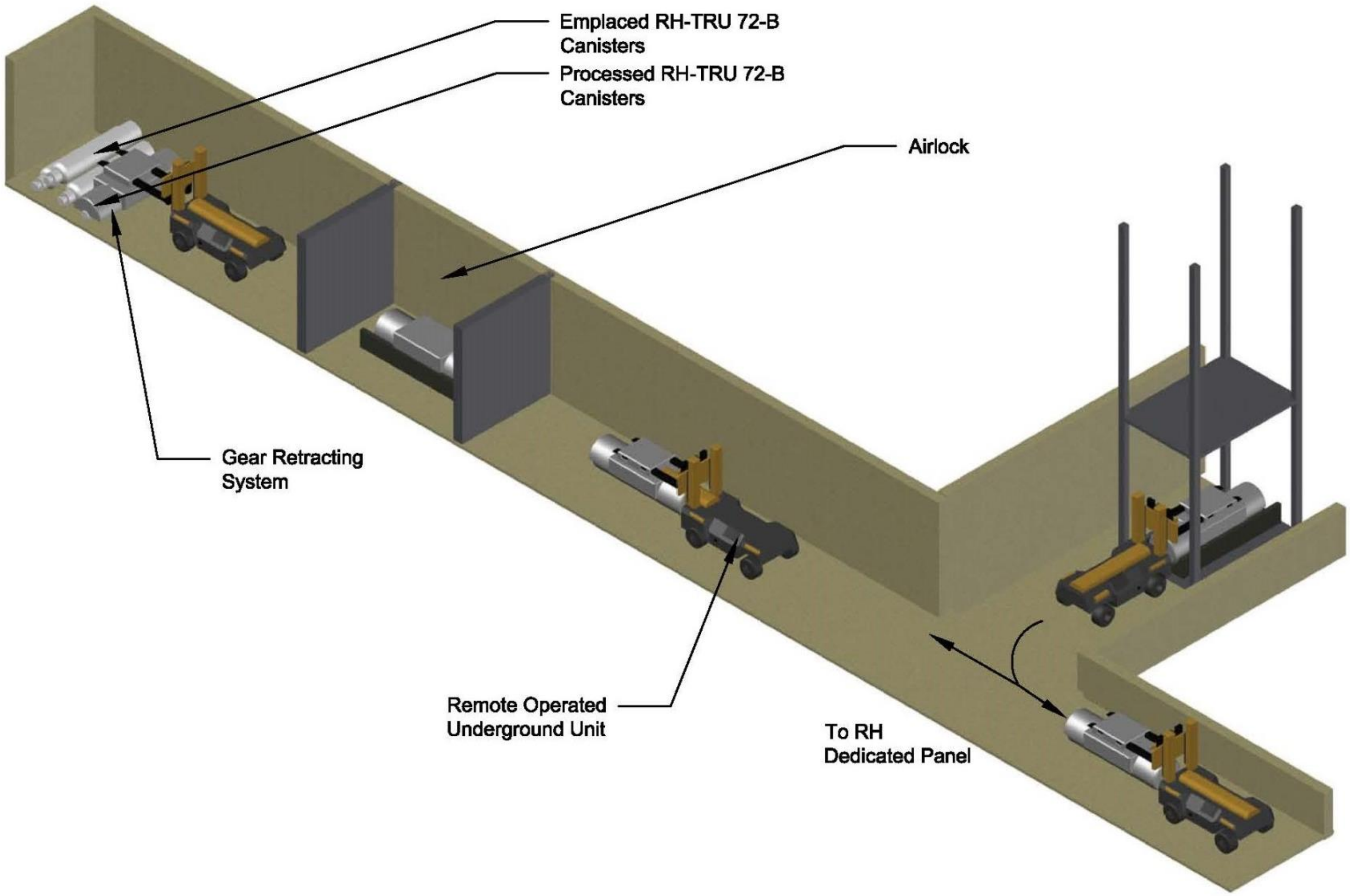

Figure 11: UG RH Process

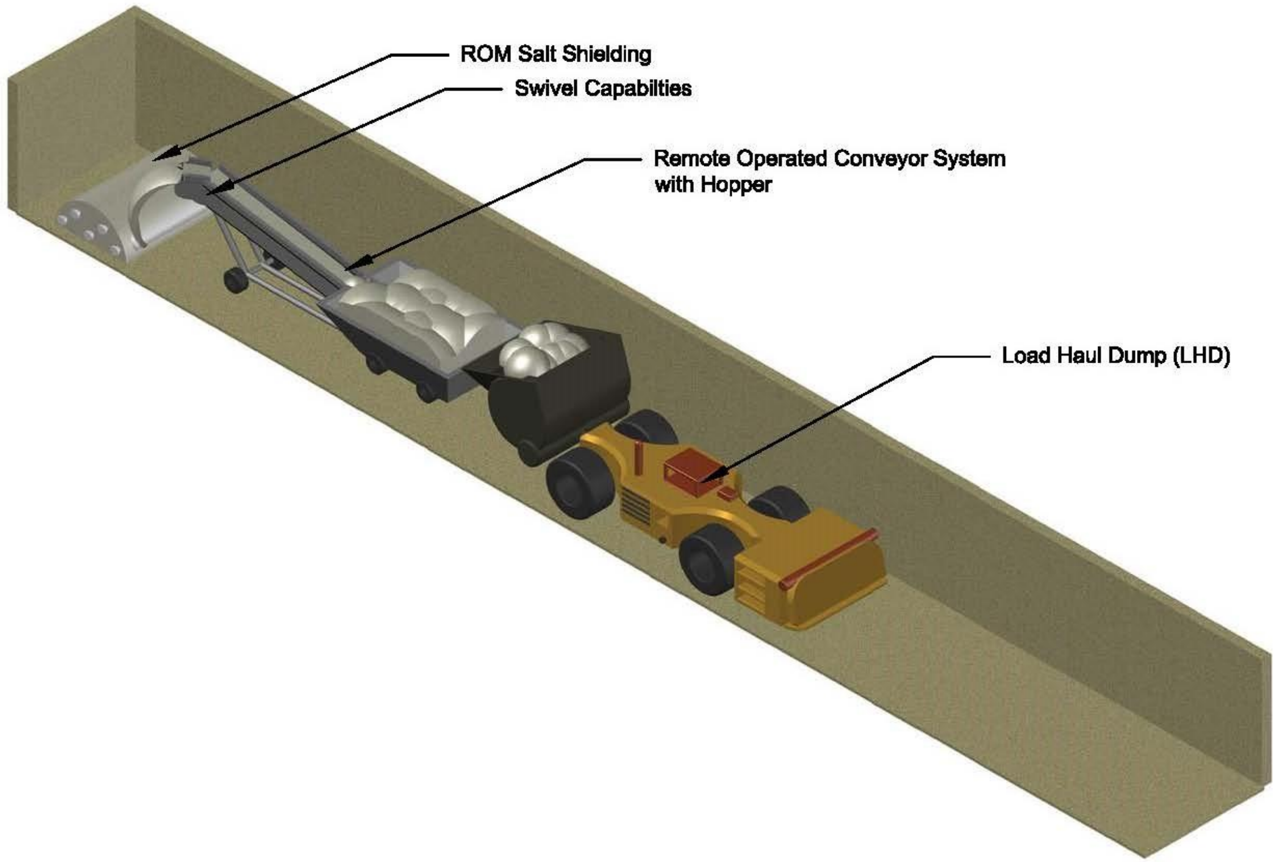

Figure 12: ROM Salt Shielding Process

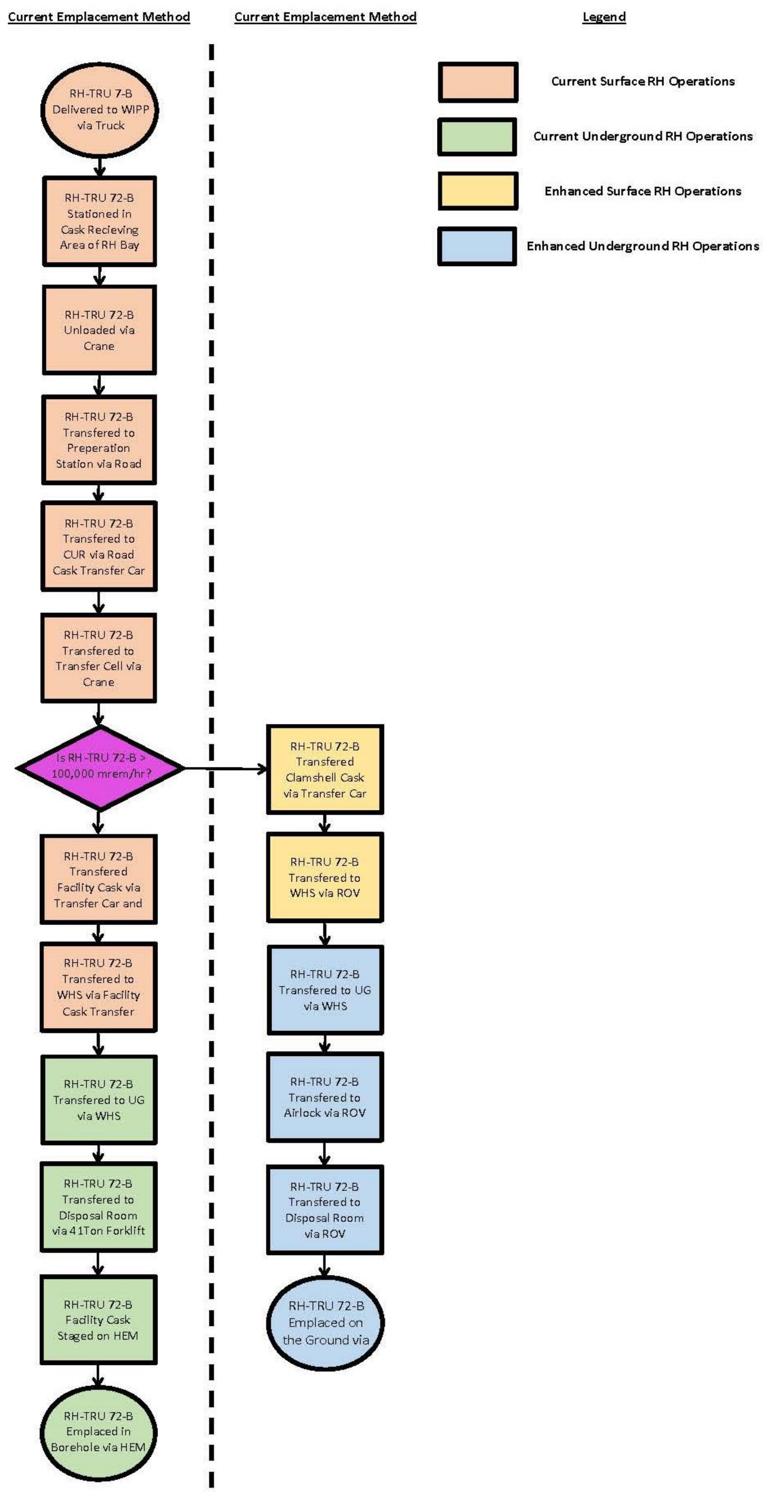

Figure 13: RH Processing Flow Chart

DOSE RATE CALCULATIONS

The approach to calculating the surface dose rate seen on the Clamshell Cask was based on a point source within the Canister. This point source allows for a more conservative value as it is making the assumption that the entirety of the radiation is being experienced at a single point adjacent to the inner edge of the cask; as seen in figure 12.

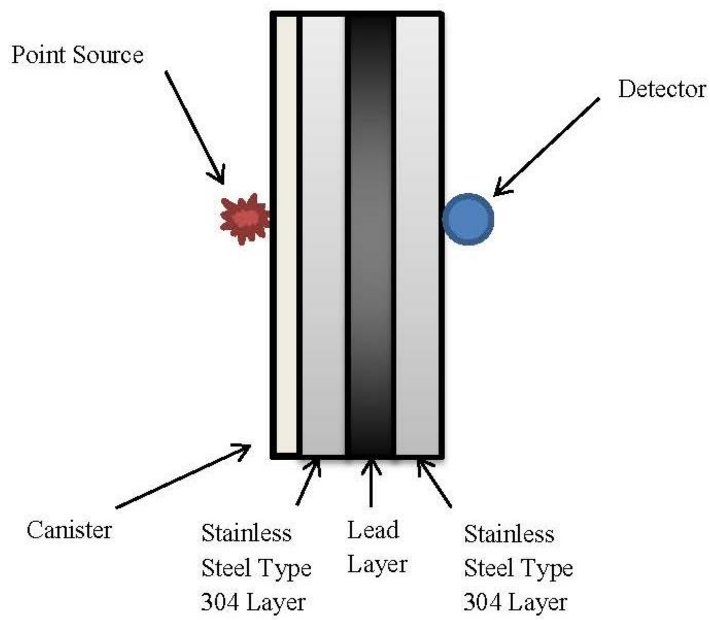

Figure 14: Point Source Geometry

Both Gamma and Neutron calculations were taken into consideration. For gamma, the isotropic point source dose rate function is Equation 1. Due to the fact that this is a surface dose rate calculation, the Range, R, will simply be the sum of each thickness used in the cask. This is expressed in Equation 2.

$$D(E) = \frac{S(E)B(E)K(E)}{4\pi R^2} e^{-x} \qquad \text{Equation 1}$$

$$R = \sum t_{Pb} + 2t_{SS} \qquad \text{Equation 2}$$

The Dose Rate, D(E), will be the final value of interest and will be truncated at 200mrem/hr as per the LWA. The Source, S(E), will be varied at two dose rates that would be seen on the Canister within the Clamshell Cask. Per the LWA, the maximum surface dose rate the can be experienced by RH waste is 1,000,000 mrem/hr. The LWA also specifies that only a 5% by volume may be greater than 100,000 mrem/hr. The remaining 95% needs to be greater than 200 mrem/hr but less than the 100,000 mrem/hr. The current borehole method of disposal will still be utilized but restricted to the 95% bin of waste and the process explored for this project will be exclusively for the upper range. The 5% bin will represent the range for the calculations demonstrating a conservative approach with the 1,000,000 mrem/hr and the most efficient approach possible with the 100,000 mrem/hr.

The Build-Up Factor, B(E), is determined from the Geometric Progression function from the ANSI/ANS 1991. Equation 3 and Equation 4 represent the Buildup Factor; Equation 5 is the K_x factor for used in determining the correct Build-Up Factor equation.

$$B(E) = 1+(b-1)\left(\frac{(k^X-1)}{k-1}\right), \text{ for } K\neq 1 \qquad \text{Equation 3}$$

$$B(E) = 1+(b-1)x, \text{ for } K=1 \qquad \text{Equation 4}$$

$$K_x = cx^a + d\left(\frac{(\tanh\left(\frac{x}{2}\right)-2)-(\tanh(-2))}{1-\tanh(-2)}\right) \qquad \text{Equation 5}$$

The Build-Up Factor is predominantly is for deep penetrations, particularly for mean free paths greater than 20. The Iron Exposure Build-Up Factor Coefficients for a, b, c, d, and K_x are listed in Table 3. For conservative purposes, the Build-Up Factor will assume Lead to be the primary source of shielding; therefore, Table 3 only includes Leads Iron Exposure Coefficients.

It was determined that for all the mean free path's, K_x yielded a value not equal to one; therefore, Equation 4 was omitted from all calculations in Matlab. Table 3 demonstrates this using the values from Table 4. The mfp's used were derived from the coding calculations provided through Matlab.

Trial	t_Pb [cm]	t_SS [cm]	total t [cm]	x	b	c	a	Xk	d	K
1	8	1	12	0.0682	1.483	1.009	0.012	13.120	-0.258	1.109
2	9	1	10	0.0720	1.483	1.009	0.012	13.120	-0.258	1.109
3	10	1	11	0.0758	1.483	1.009	0.012	13.120	-0.258	1.109
4	11	1	12	0.0795	1.483	1.009	0.012	13.120	-0.258	1.110
5	12	1	13	0.0833	1.483	1.009	0.012	13.120	-0.258	1.110
6	13	1	14	0.0870	1.483	1.009	0.012	13.120	-0.258	1.110
7	14	1	15	0.0908	1.483	1.009	0.012	13.120	-0.258	1.110
8	15	1	16	0.0945	1.483	1.009	0.012	13.120	-0.258	1.111
9	16	1	17	0.0983	1.483	1.009	0.012	13.120	-0.258	1.111
10	17	1	18	0.1020	1.483	1.009	0.012	13.120	-0.258	1.111
11	8	2	12	0.1065	1.483	1.009	0.012	13.120	-0.258	1.111
12	9	2	11	0.1102	1.483	1.009	0.012	13.120	-0.258	1.112
13	10	2	12	0.1140	1.483	1.009	0.012	13.120	-0.258	1.112
14	11	2	13	0.1177	1.483	1.009	0.012	13.120	-0.258	1.112
15	12	2	14	0.1215	1.483	1.009	0.012	13.120	-0.258	1.112
16	13	2	15	0.1252	1.483	1.009	0.012	13.120	-0.258	1.112
17	14	2	16	0.1290	1.483	1.009	0.012	13.120	-0.258	1.112
18	15	2	17	0.1327	1.483	1.009	0.012	13.120	-0.258	1.112
19	16	2	18	0.1365	1.483	1.009	0.012	13.120	-0.258	1.112
20	17	2	19	0.1403	1.483	1.009	0.012	13.120	-0.258	1.112

Table 4: K_x Determination

Trial	t_Pb [cm]	t_SS [cm]	total t [cm]	x	b	c	a	Xk	d	K
21	8	4	12	0.1829	1.483	1.009	0.012	13.120	-0.258	1.113
22	9	4	13	0.1867	1.483	1.009	0.012	13.120	-0.258	1.113
23	10	4	14	0.1904	1.483	1.009	0.012	13.120	-0.258	1.113
24	11	4	15	0.1942	1.483	1.009	0.012	13.120	-0.258	1.113
25	12	4	16	0.1979	1.483	1.009	0.012	13.120	-0.258	1.113
26	13	4	17	0.2017	1.483	1.009	0.012	13.120	-0.258	1.113
27	14	4	18	0.2054	1.483	1.009	0.012	13.120	-0.258	1.113
28	15	4	19	0.2092	1.483	1.009	0.012	13.120	-0.258	1.113
29	16	4	20	0.2129	1.483	1.009	0.012	13.120	-0.258	1.113
30	17	4	21	0.2167	1.483	1.009	0.012	13.120	-0.258	1.113
31	8	6	14	0.2594	1.483	1.009	0.012	13.120	-0.258	1.112
32	9	6	15	0.2631	1.483	1.009	0.012	13.120	-0.258	1.112
33	10	6	16	0.2669	1.483	1.009	0.012	13.120	-0.258	1.112
34	11	6	17	0.2706	1.483	1.009	0.012	13.120	-0.258	1.112
35	12	6	18	0.2744	1.483	1.009	0.012	13.120	-0.258	1.112
36	13	6	19	0.2781	1.483	1.009	0.012	13.120	-0.258	1.112
37	14	6	20	0.2819	1.483	1.009	0.012	13.120	-0.258	1.111
38	15	6	21	0.2856	1.483	1.009	0.012	13.120	-0.258	1.111
39	16	6	22	0.2894	1.483	1.009	0.012	13.120	-0.258	1.111
40	17	6	23	0.2931	1.483	1.009	0.012	13.120	-0.258	1.111

Table 4: K_x Determination (continued)

Trial	t_Pb [cm]	t_SS [cm]	total t [cm]	x	b	c	a	Xk	d	K
41	1	8	9	0.3095	1.483	1.009	0.012	13.120	-0.258	1.111
42	2	8	10	0.3133	1.483	1.009	0.012	13.120	-0.258	1.111
43	3	8	11	0.3170	1.483	1.009	0.012	13.120	-0.258	1.111
44	4	8	12	0.3208	1.483	1.009	0.012	13.120	-0.258	1.111
45	5	8	13	0.3245	1.483	1.009	0.012	13.120	-0.258	1.110
46	6	8	14	0.3283	1.483	1.009	0.012	13.120	-0.258	1.110
47	7	8	15	0.3321	1.483	1.009	0.012	13.120	-0.258	1.110
48	8	8	16	0.3358	1.483	1.009	0.012	13.120	-0.258	1.110
49	9	8	17	0.3396	1.483	1.009	0.012	13.120	-0.258	1.110
50	10	8	18	0.3433	1.483	1.009	0.012	13.120	-0.258	1.110
51	0.06	9	9	0.3442	1.483	1.009	0.012	13.120	-0.258	1.110
52	0.07	9	9	0.3443	1.483	1.009	0.012	13.120	-0.258	1.110
53	0.08	9	9	0.3443	1.483	1.009	0.012	13.120	-0.258	1.110
54	0.09	9	9	0.3443	1.483	1.009	0.012	13.120	-0.258	1.110
55	0.10	9	9	0.3444	1.483	1.009	0.012	13.120	-0.258	1.110
56	0.11	9	9	0.3444	1.483	1.009	0.012	13.120	-0.258	1.110
57	0.12	9	9	0.3444	1.483	1.009	0.012	13.120	-0.258	1.110
58	0.13	9	9	0.3445	1.483	1.009	0.012	13.120	-0.258	1.110
59	0.14	9	9	0.3445	1.483	1.009	0.012	13.120	-0.258	1.110
60	0.15	9	9	0.3446	1.483	1.009	0.012	13.120	-0.258	1.110
61	**0.1216**	**9**	**9**	**0.1756**	**1.483**	**1.009**	**0.012**	**13.120**	**-0.258**	**1.113**

Table 4: K_x Determination (Continued)

γ-Energy (MeV)	b	c	a	X_k	d
0.1	1.389	0.557	0.144	14.11	-0.0791
0.15	1.660	0.743	0.079	14.12	-0.0476
0.2	1.839	0.911	0.034	13.23	-0.0334
0.3	1.973	1.095	-0.009	11.86	-0.0183
0.4	1.992	1.187	-0.027	10.72	-0.0140
0.5	1.967	1.240	-0.039	8.34	-0.0074
0.6	1.947	1.247	-0.040	8.20	-0.0096
0.8	1.906	1.233	-0.038	7.93	-0.0110
1.0	1.841	1.250	-0.048	19.49	0.0140
1.5	1.750	1.197	-0.040	15.90	0.0110
2.0	1.712	1.123	-0.021	7.97	-0.0057
3.0	1.627	1.059	-0.005	11.99	-0.0132
4.0	1.553	1.026	0.005	12.93	-0.0191
5.0	1.483	1.009	0.012	13.12	-0.0258

Table 5: Iron Exposure Build-Up Factors. ANSI/ANS 6.4.3-1991

The Mean Free Paths, x, consists of the sum of attenuation coefficients per partial densities and multiplied by the thickness; therefore, μ_{Pb}, μ_{Si}, μ_{Cr}, μ_{Mg}, μ_{Fe}, and μ_{Ni} are the attenuation coefficients for Lead, Silicon, Chromium, Manganese, Iron, and Nickel respectively. The partial densities are also ρ_{Pb}, ρ_{Si}, ρ_{Cr}, ρ_{Mg}, ρ_{Fe}, and ρ_{Ni}. Equation 6, Equation 7, and Equation 8 list the mfp and the attenuation coefficient for lead and Stainless Steel Type 304. Table 4 contains the material densities, and present of composition, C, for Stainless Steel Type 304 and for Lead. The Cask will be designed with an outer layer of Stainless Steel Type 304, a layer of Lead, and an inner layer of Stainless Steel Type 304. Table 5 lists the mass attenuation coefficients for the different elements observed throughout the layers of the shielding.

$$x=\sum \mu_{Pb}t_{Pb} + 2\mu_{SS}t_{SS} \quad \text{Equation 6}$$

$$\mu_{SS} = \frac{\mu_{Si}}{\rho_{Si}}C_{Si}+\frac{\mu_{Cr}}{\rho_{Cr}}C_{Cr}+\frac{\mu_{Mg}}{\rho_{Mg}}C_{Mg} + \frac{\mu_{Fe}}{\rho_{Fe}}C_{Fe} + \frac{\mu_{Ni}}{\rho_{Ni}}C_{Ni} \quad \text{Equation 7}$$

$$\mu_{Pb} = \frac{\mu_{Pb}}{\rho_{Pb}}C_{Pb} \quad \text{Equation 8}$$

γ-Energy (MeV)	Silicon	Chromium	Manganese	Iron	Nickel	Lead
0.1	1.73E-01	2.92E-01	3.10E-01	3.43E-01	4.10E-01	5.36E+00
0.15	1.40E-01	1.67E-01	1.72E-01	1.83E-01	2.05E-01	1.92E+00
0.2	1.25E-01	1.31E-01	1.32E-01	1.38E-01	1.49E-01	9.43E-01
0.3	1.07E-01	1.04E-01	1.03E-01	1.06E-01	1.11E-01	3.77E-01
0.4	9.54E-02	9.04E-02	8.95E-02	9.20E-02	9.53E-02	2.17E-01
0.5	8.70E-02	8.17E-02	8.07E-02	8.28E-02	8.55E-02	1.51E-01
0.6	8.04E-02	7.52E-02	7.42E-02	7.61E-02	7.84E-02	1.18E-01
0.8	7.06E-02	6.57E-02	6.49E-02	6.64E-02	6.83E-02	8.47E-02
1.0	6.34E-02	5.90E-02	5.82E-02	5.96E-02	6.12E-02	6.84E-02
1.5	5.17E-02	4.81E-02	4.75E-02	4.86E-02	4.99E-02	5.10E-02
2.0	4.47E-02	4.20E-02	4.15E-02	4.25E-02	4.37E-02	4.54E-02
3.0	3.67E-02	3.55E-02	3.51E-02	3.61E-02	3.73E-02	4.20E-02
4.0	3.23E-02	3.23E-02	3.20E-02	3.30E-02	3.44E-02	4.18E-02
5.0	2.96E-02	3.05E-02	3.04E-02	3.14E-02	3.28E-02	4.26E-02

Table 6: Mass Attenuation Coefficients. ANSI/ANS 6.4.3-1991

The Gamma-Flux-to-Dose Rate Conversion Factor, K(E), provides a conversion when the activity in the canister is known. For these calculations, the constraints will be bound by the limits provided in the LWA; therefore, the Gamm-Flux-to-Dose Rate Conversion Factor will not be applied due to the fact that the source is in unit's mrem/hr.

The following code summarizes the manual test iterations through Matlab to achieve a Surface Dose Rate by using matrices to establish the varying ranges for the thickness of both Lead and Stainless Steel Type 304.

MATLAB ITERATION'S RESULTS

Appendix A provides the various iterations used to calculate the shielding requirements through trial and error in order to reduce the range of the different shielding layers. Each iteration varied the stainless steel type 304 thickness and the range for the lead thickness. Ten values of Lead were calculated for each value of Stainless Steel. The results provided are the dose rates that each corresponding lead thickness. Iterations 1-10 were for a Stainless Steel thickness of 1cm; Iterations 11-20 were for 2cm, Iterations 21-30 were for 4cm, Iterations 31-40 were for 6cm, Iterations 41-50 were for 8cm, and Iterations 51-60 were for 9cm. The last Iteration was generated to provide a more accurate estimation based on the lowest Cask weight that still met the 200 mrem/hr limit.

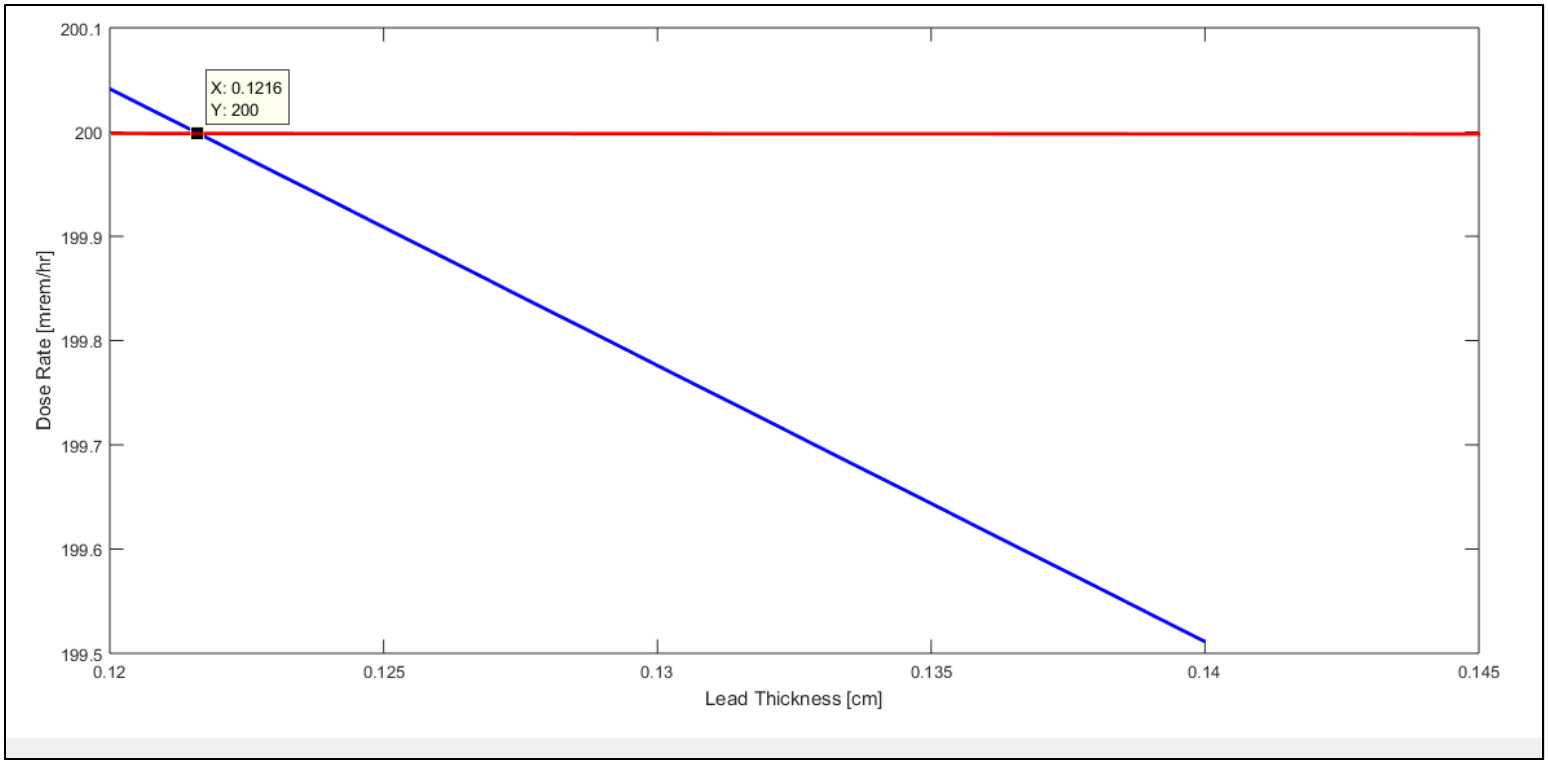

Figure 15: Dose Rate vs Lead Thickness

Trial	t_Pb [cm]	t_SS [cm]	total t [cm]	t_Pb [in]	t_SS [in]	total t [in]	p_Pb [lb/in3]	p_SS [lb/in3]
1	8	1	12	3	0	4	0.41	0.29
2	9	1	10	4	0	4	0.41	0.29
3	10	1	11	4	0	5	0.41	0.29
4	11	1	12	4	0	5	0.41	0.29
5	12	1	13	5	0	6	0.41	0.29
6	13	1	14	5	0	6	0.41	0.29
7	14	1	15	6	0	6	0.41	0.29
8	15	1	16	6	0	7	0.41	0.29
9	16	1	17	6	0	7	0.41	0.29
10	17	1	18	7	0	7	0.41	0.29
11	8	2	12	3	1	5	0.41	0.29
12	9	2	11	4	1	5	0.41	0.29
13	10	2	12	4	1	6	0.41	0.29
14	11	2	13	4	1	6	0.41	0.29
15	12	2	14	5	1	6	0.41	0.29
16	13	2	15	5	1	7	0.41	0.29
17	14	2	16	6	1	7	0.41	0.29
18	15	2	17	6	1	7	0.41	0.29
19	16	2	18	6	1	8	0.41	0.29
20	17	2	19	7	1	8	0.41	0.29
21	8	4	12	3	2	6	0.41	0.29
22	9	4	13	4	2	7	0.41	0.29
23	10	4	14	4	2	7	0.41	0.29
24	11	4	15	4	2	7	0.41	0.29
25	12	4	16	5	2	8	0.41	0.29
26	13	4	17	5	2	8	0.41	0.29
27	14	4	18	6	2	9	0.41	0.29
28	15	4	19	6	2	9	0.41	0.29
29	16	4	20	6	2	9	0.41	0.29
30	17	4	21	7	2	10	0.41	0.29

Table 7: Shielding Material Characteristics

Trial	t_Pb [cm]	t_SS [cm]	total t [cm]	t_Pb [in]	t_SS [in]	total t [in]	p_Pb [lb/in3]	p_SS [lb/in3]
31	8	6	14	3	2	8	0.41	0.29
32	9	6	15	4	2	8	0.41	0.29
33	10	6	16	4	2	9	0.41	0.29
34	11	6	17	4	2	9	0.41	0.29
35	12	6	18	5	2	9	0.41	0.29
36	13	6	19	5	2	10	0.41	0.29
37	14	6	20	6	2	10	0.41	0.29
38	15	6	21	6	2	11	0.41	0.29
39	16	6	22	6	2	11	0.41	0.29
40	17	6	23	7	2	11	0.41	0.29
41	1	8	9	0	3	7	0.41	0.29
42	2	8	10	1	3	7	0.41	0.29
43	3	8	11	1	3	7	0.41	0.29
44	4	8	12	2	3	8	0.41	0.29
45	5	8	13	2	3	8	0.41	0.29
46	6	8	14	2	3	9	0.41	0.29
47	7	8	15	3	3	9	0.41	0.29
48	8	8	16	3	3	9	0.41	0.29
49	9	8	17	4	3	10	0.41	0.29
50	10	8	18	4	3	10	0.41	0.29
51	0.06	9	9	0	4	7	0.41	0.29
52	0.07	9	9	0	4	7	0.41	0.29
53	0.08	9	9	0	4	7	0.41	0.29
54	0.09	9	9	0	4	7	0.41	0.29
55	0.10	9	9	0	4	7	0.41	0.29
56	0.11	9	9	0	4	7	0.41	0.29
57	0.12	9	9	0	4	7	0.41	0.29
58	**0.1216**	**9**	**9**	**0**	**4**	**7**	**0.41**	**0.29**
59	0.13	9	9	0	4	7	0.41	0.29
60	0.14	9	9	0	4	7	0.41	0.29
61	0.15	9	9	0	4	7	0.41	0.29

Table 7: Shielding Material Characteristics (Continued)

Trial	h_Inner Cask [in]	r_Inner Cask [in]	V_Inner Cask [in3]	h_Inner SS Layer [in]	r_Inner SS Layer [in]	V_SSI [in3]	h_Outter SS Layer [in]	r_Outter SS Layer [in]	V_SSO [in3]	total V_SS [in3]
1	120	13	63711	121	13	4361	128	17	5972	10333
2	120	13	63711	121	13	4361	129	17	6163	10524
3	120	13	63711	121	13	4361	129	18	6356	10717
4	120	13	63711	121	13	4361	130	18	6551	10912
5	120	13	63711	121	13	4361	131	19	6748	11109
6	120	13	63711	121	13	4361	132	19	6948	11309
7	120	13	63711	121	13	4361	133	19	7150	11511
8	120	13	63711	121	13	4361	133	20	7354	11715
9	120	13	63711	121	13	4361	134	20	7561	11922
10	120	13	63711	121	13	4361	135	20	7770	12131
11	120	13	63711	122	14	8892	129	18	12518	21411
12	120	13	63711	122	14	8892	130	18	12906	21798
13	120	13	63711	122	14	8892	131	19	13299	22191
14	120	13	63711	122	14	8892	132	19	13696	22588
15	120	13	63711	122	14	8892	133	19	14098	22990
16	120	13	63711	122	14	8892	133	20	14504	23396
17	120	13	63711	122	14	8892	134	20	14915	23807
18	120	13	63711	122	14	8892	135	20	15331	24223
19	120	13	63711	122	14	8892	136	21	15751	24643
20	120	13	63711	122	14	8892	137	21	16175	25068
21	120	13	63711	123	15	18473	133	19	27397	45869
22	120	13	63711	123	15	18473	133	20	28200	46673
23	120	13	63711	123	15	18473	134	20	29013	47485
24	120	13	63711	123	15	18473	135	20	29835	48307
25	120	13	63711	123	15	18473	136	21	30666	49138
26	120	13	63711	123	15	18473	137	21	31506	49979
27	120	13	63711	123	15	18473	137	22	32355	50828
28	120	13	63711	123	15	18473	138	22	33214	51687
29	120	13	63711	123	15	18473	139	22	34082	52555
30	120	13	63711	123	15	18473	140	23	34959	53432

Table 8: Stainless Steel Type 304 Geometric Results

Trial	h_Inner Cask [in]	r_Inner Cask [in]	V_Inner Cask [in3]	h_Inner SS Layer [in]	r_Inner SS Layer [in]	V_SSI [in3]	h_Outter SS Layer [in]	r_Outter SS Layer [in]	V_SSO [in3]	total V_SS [in3]
31	120	13	63711	125	15	28760	136	21	44763	73524
32	120	13	63711	125	15	28760	137	21	46010	74770
33	120	13	63711	125	15	28760	137	22	47270	76031
34	120	13	63711	125	15	28760	138	22	48545	77305
35	120	13	63711	125	15	28760	139	22	49833	78593
36	120	13	63711	125	15	28760	140	23	51135	79895
37	120	13	63711	125	15	28760	140	23	52450	81210
38	120	13	63711	125	15	28760	141	24	53780	82540
39	120	13	63711	125	15	28760	142	24	55123	83883
40	120	13	63711	125	15	28760	143	24	56480	85240
41	120	13	63711	126	16	39773	133	20	53241	93014
42	120	13	63711	126	16	39773	134	20	54830	94603
43	120	13	63711	126	16	39773	135	20	56437	96210
44	120	13	63711	126	16	39773	136	21	58062	97835
45	120	13	63711	126	16	39773	137	21	59706	99479
46	120	13	63711	126	16	39773	137	22	61368	101141
47	120	13	63711	126	16	39773	138	22	63049	102822
48	120	13	63711	126	16	39773	139	22	64748	104521
49	120	13	63711	126	16	39773	140	23	66465	106238
50	120	13	63711	126	16	39773	140	23	68201	107974
51	120	13	63711	127	17	45557	134	20	60910	106466
52	120	13	63711	127	17	45557	134	20	60927	106484
53	120	13	63711	127	17	45557	134	20	60945	106502
54	120	13	63711	127	17	45557	134	20	60963	106520
55	120	13	63711	127	17	45557	134	20	60981	106538
56	120	13	63711	127	17	45557	134	20	60999	106556
57	120	13	63711	127	17	45557	134	20	61017	106574
58	**120**	**13**	**63711**	**127**	**17**	**45557**	**134**	**20**	**61020**	**106577**
59	120	13	63711	127	17	45557	134	20	61035	106592
60	120	13	63711	127	17	45557	134	20	61053	106610
61	120	13	63711	127	17	45557	134	20	61071	106627

Table 8: Stainless Steel Type 304 Geometric Results (Continued)

Trial	h_Pb Layer [in]	r_Pb Layer [in]	V_Pb [in3]	total V_Pb [in3]
1	127	17	41196	41196
2	128	17	47168	47168
3	129	17	53331	53331
4	129	18	59686	59686
5	130	18	66237	66237
6	131	19	72985	72985
7	132	19	79933	79933
8	133	19	87083	87083
9	133	20	94437	94437
10	134	20	101998	101998
11	128	17	42637	42637
12	129	17	48800	48800
13	129	18	55155	55155
14	130	18	61706	61706
15	131	19	68454	68454
16	132	19	75402	75402
17	133	19	82552	82552
18	133	20	89906	89906
19	134	20	97467	97467
20	135	20	105237	105237
21	129	18	45575	45575
22	130	18	52126	52126
23	131	19	58874	58874
24	132	19	65822	65822
25	133	19	72971	72971
26	133	20	80326	80326
27	134	20	87886	87886
28	135	20	95656	95656
29	136	21	103637	103637
30	137	21	111832	111832

Table 9: Lead Geometric Results

Trial	h_Pb Layer [in]	r_Pb Layer [in]	V_Pb [in3]	total V_Pb [in3]
31	131	19	48586	48586
32	132	19	55534	55534
33	133	19	62684	62684
34	133	20	70038	70038
35	134	20	77599	77599
36	135	20	85369	85369
37	136	21	93350	93350
38	137	21	101544	101544
39	137	22	109955	109955
40	138	22	118583	118583
41	127	17	5784	5784
42	128	17	11756	11756
43	129	17	17919	17919
44	129	18	24275	24275
45	130	18	30825	30825
46	131	19	37574	37574
47	132	19	44521	44521
48	133	19	51671	51671
49	133	20	59026	59026
50	134	20	66586	66586
51	127	17	353	353
52	127	17	412	412
53	127	17	471	471
54	127	17	530	530
55	127	17	589	589
56	127	17	648	648
57	127	17	707	707
58	**127**	**17**	**716**	**716**
59	127	17	766	766
60	127	17	825	825
61	127	17	884	884

Table 9: Lead Geometric Results (Continued)

Trial	W_Pb [lbs]	W_SS [lbs]	W_Canister (lbs)	Total weight [lb]	Total weight [tons]	Weight Limit	Weight Limit Violated	Dose Rate	Dose Rate Limit	Dose Limit Violated	Solution
1	16892	2986	8000	27878	13.94	45	1	767.72	200	0	_
2	19341	3041	8000	30382	15.19	45	1	633.20	200	0	_
3	21868	3097	8000	32965	16.48	45	1	531.00	200	0	_
4	24474	3154	8000	35628	17.81	45	1	451.53	200	0	_
5	27160	3211	8000	38371	19.19	45	1	388.54	200	0	_
6	29927	3268	8000	41196	20.60	45	1	337.78	200	0	_
7	32776	3327	8000	44103	22.05	45	1	296.27	200	0	_
8	35708	3386	8000	47094	23.55	45	1	261.91	200	0	_
9	38723	3445	8000	50169	25.08	45	1	233.14	200	0	_
10	41824	3506	8000	53330	26.66	45	1	208.82	200	0	_
11	17483	6188	8000	31671	15.84	45	1	522.23	200	0	_
12	20010	6300	8000	34310	17.15	45	1	444.07	200	0	_
13	22616	6413	8000	37029	18.51	45	1	382.11	200	0	_
14	25302	6528	8000	39830	19.92	45	1	332.18	200	0	_
15	28069	6644	8000	42713	21.36	45	1	291.36	200	0	_
16	30918	6762	8000	45680	22.84	45	1	257.55	200	0	_
17	33850	6880	8000	48730	24.37	45	1	229.26	200	0	_
18	36866	7000	8000	51866	25.93	45	1	205.34	200	0	_
19	39966	7122	8000	55088	27.54	45	1	184.93	200	1	Accept
20	43152	7245	8000	58396	29.20	45	1	167.39	200	1	Accept
21	18688	13256	8000	39944	19.97	45	1	281.59	200	0	_
22	21374	13488	8000	42862	21.43	45	1	248.91	200	0	_
23	24141	13723	8000	45864	22.93	45	1	221.55	200	0	_
24	26990	13961	8000	48951	24.48	45	1	198.43	200	1	Accept
25	29922	14201	8000	52123	26.06	45	1	178.70	200	1	Accept
26	32937	14444	8000	55381	27.69	45	1	161.74	200	1	Accept
27	36037	14689	8000	58727	29.36	45	1	147.06	200	1	Accept
28	39223	14938	8000	62161	31.08	45	1	134.27	200	1	Accept
29	42496	15188	8000	65684	32.84	45	1	123.05	200	1	Accept
30	45856	15442	8000	69298	34.65	45	1	113.16	200	1	Accept

Table 10: Clamshell Cask Specification Results

Trial	W_Pb [lbs]	W_SS [lbs]	W_Canister (lbs)	Total weight [lb]	Total weight [tons]	Weight Limit	Weight Limit Violated	Dose Rate	Dose Rate Limit	Dose Limit Violated	Solution
31	19923	21248	8000	49171	24.59	45	1	172.55	200	1	Accept
32	22771	21609	8000	52380	26.19	45	1	156.17	200	1	Accept
33	25703	21973	8000	55676	27.84	45	1	141.99	200	1	Accept
34	28719	22341	8000	59060	29.53	45	1	129.63	200	1	Accept
35	31819	22713	8000	62532	31.27	45	1	118.79	200	1	Accept
36	35005	23090	8000	66095	33.05	45	1	109.24	200	1	Accept
37	38278	23470	8000	69747	34.87	45	1	100.78	200	1	Accept
38	41638	23854	8000	73492	36.75	45	1	93.25	200	1	Accept
39	45086	24242	8000	77328	38.66	45	1	86.52	200	1	Accept
40	48624	24634	8000	81259	40.63	45	1	80.48	200	1	Accept
41	2372	26881	8000	37253	18.63	45	1	231.98	200	0	_
42	4821	27340	8000	40161	20.08	45	1	206.47	200	0	_
43	7348	27805	8000	43152	21.58	45	1	184.90	200	1	Accept
44	9954	28274	8000	46228	23.11	45	1	166.50	200	1	Accept
45	12640	28749	8000	49389	24.69	45	1	150.69	200	1	Accept
46	15407	29230	8000	52637	26.32	45	1	137.00	200	1	Accept
47	18256	29715	8000	55971	27.99	45	1	125.07	200	1	Accept
48	21188	30206	8000	59394	29.70	45	1	114.61	200	1	Accept
49	24203	30703	8000	62906	31.45	45	1	105.39	200	1	Accept
50	27303	31204	8000	66508	33.25	45	1	97.23	200	1	Accept
51	145	30769	8000	38914	19.46	45	1	201.40	200	0	_
52	169	30774	8000	38943	19.47	45	1	201.17	200	0	_
53	193	30779	8000	38972	19.49	45	1	200.95	200	0	_
54	217	30784	8000	39002	19.50	45	1	200.72	200	0	_
55	241	30789	8000	39031	19.52	45	1	200.49	200	0	_
56	266	30795	8000	39060	19.53	45	1	200.27	200	0	_
57	290	30800	8000	39090	19.54	45	1	200.04	200	0	_
58	**294**	**30801**	**8000**	**39094**	**19.55**	**45**	**1**	**199.999**	**200**	**1**	**Accept**
59	314	30805	8000	39119	19.56	45	1	199.82	200	1	Accept
60	338	30810	8000	39148	19.57	45	1	199.59	200	1	Accept
61	362	30815	8000	39178	19.59	45	1	199.37	200	1	Accept

Table 10: Clamshell Cask Specification Results (Continued)

MATLAB OPTIMIZATION RESULTS

After plotting the formula dose rate vs shielding thicknesses, it was concluded that a single local minimum does not exist. The plot below shows that a series of solutions exist along the edge of the surface area representing Dose Rate observed for each configuration of shielding. The solution to Iteration 61 found was validated against the optimization formula generated. Due to the fact, that this solution provided the most acceptable value for fitting the weight limits presented by the Facility, the Shielding Specifications will utilize this value.

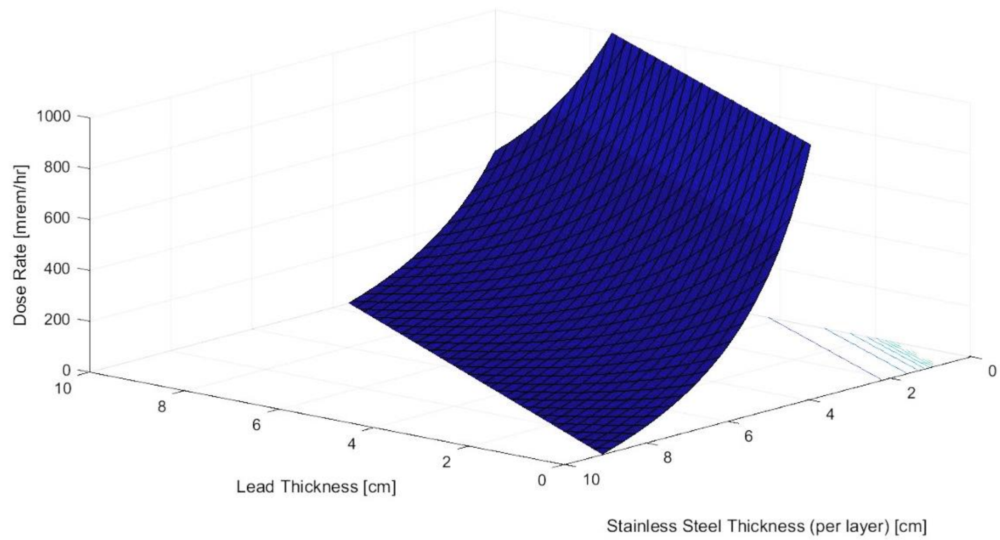

Figure 16: Optimization Plot

REMOTE OPERATED VEHICLE LIFTING CAPACTIY

Based on the information derived from the Matlab Iterations, it was determined that the ideal weight of the cask that still provided sufficient shielding was 39,095 lbs (19.55 tons) and a height of 134 inches (11'-10"). Equation 9 demonstrates the specifications needed for the forklift used on the surface and UG facility. The calculations associated with Figure 13 generate an estimated forklift capacity. This capacity is based on the Clamshell Cask being within the bounds of the limits for the Waste Hoist conveyance, which is 45 tons. The RH-TRU 72-B Canister is specified as 4 tons. The values in the calculations are estimated dimensions of the forklift and are conservative to demonstrate a piece of equipment on the largest scale possible without exceeding the geometry of the drifts in the UG and the maximum capacity of the Waste Hoist conveyance. Using the approximated dimensions of the forklift and the values derived from the shielding calculations (weight and height) the forklift basic capacity was found to be 119 tons. Due to the fact that three total units, 1 surface and 2 underground ROV's, the forklift will not be loaded onto the Waste Hoist at any point during the operation. Therefore, only the weight of the Cask, Canister, and stabilizing rack contribute to the weight applied to the conveyance. Due to the fact that these geometric specifications were conservatively approximated, the forklift is oversized. However, the weight of the ROV will be much lighter since the counterweight accounts for a portion of the total basic capacity.

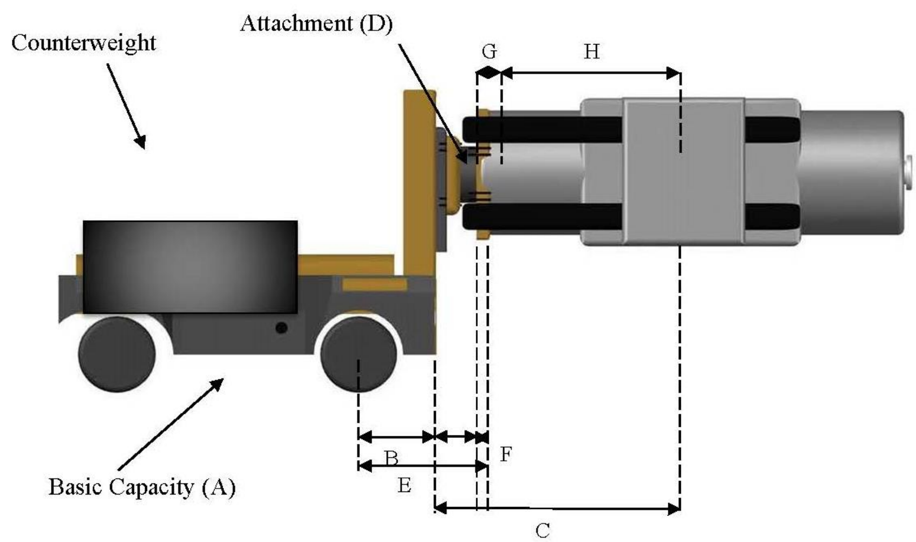

Figure 17: ROV Elevation View

$$Cask\ Weight = \frac{A(B+C)-D(E+F)}{E+G+H} \qquad \text{Equation 9}$$

A= Forklift (Basic Capacity)
B= 2' (Distance from front wheel center line to fork face)
C= x/2+E-B (Distance from fork face to rated load center)
D= 0.5 tons (Weight of attachment)
E= 4' (Distance from front wheel center line to carriage face)
F= 1' (Distance from carriage face to attachment's center of gravity)
G= 1' (Distance from carriage face to rear face of load)
H= x/2 (Distance from rear face of load to center of load)

REMOTE OPERATED VEHICEL TURING RADIUS

Another specification important to the operation is the turning radius. The geometry of the drifts is sized in such a way that it can support the weight of the salt layers above. Based on the diameter of the shafts, each shaft is provided a shaft pillar. This is the radius in which an only 17% of the ground may be mined in order to protect your egress routes. Outside of these radii,

The Underground mine consists of three total facilities: Shaft Pillar Facility, North Experimental Facility, and Disposal Facility. Both CH and RH are downloaded via the Waste Hoist Shaft; they are then transported through the Shaft Pillar Facility to the Disposal Facility where the Disposal Panels are located. Each panel consists of seven Rooms with dimensions of 13 feet high, 33 feet wide, and 300 feet in length. As seen in Figure 10 and Figure 11, the Canisters will be emplaced using the horizontal emplacement method. WIPP's DSA has determined that for borehole drilling the minimum spacing for the RH-TRU 72-B Canisters is 30 inches and is not to exceed 10 Kilowatts per acre. The typical spacing is actually eight feet center-to-center.

The Disposal Panel will be dedicated exclusively to RH floor emplacement. The borehole method will be utilized for RH Canisters closer to the 200mrem/hr limit, while the floor emplacement method will be for Canisters approaching the 1,000,000mrem/hr limit. Since the process is hindering on the RH dedicated panel be used solely for higher dose rates, the Disposal Panels will need to posted as High Radiation Areas (HRA) with the operations being conducted remotely. An airlock at the entry of each Panel will be provided along with a staged Stabilizing Rack. This will allow for the transfer of the Clamshell Cask from a ROV on the clean side to drop off the Canister and have a ROV dedicated to the HRA operations. Both ROV's will need the capability to navigate through the narrow drifts of the underground. Entry ways into the Disposal Panels are typically narrowed to 14 feet wide but expand once the Panel Room has been entered. The turn radii will be based on the fact that Room 1 of a Panel is the immediately after the entrance to a Panel. Therefore the 14 foot limit will be used as the initial drift width followed by a 90 degree turn directly into the 33 foot wide Room. In order to appropriately make these turns in the underground crosscuts (intersections), the ROV will be provided with negative four wheel steering capabilities. The turn radii for each wheel with a maximum deflection angle, δ, of 25^o, which yields a maximum turn radius of 19.8^o for the outer wheels based on the geometry of the drifts. The length, L, was estimated off of the maximum turn radius and the width of the drift assuming a minimum driving distance between the ROV and Rib (technical term for drift wall) is 1'- 1". This was figured from the distance in space between the width of the Rib and the length of the Cask as specified in Equation 15. This yielded an axle-to-axle length of 13 feet using Pythagoreans theorem, Figure 14.

$$R_{IF} = \frac{L}{\sin\theta_{IF}}$$ Equation 10

$$R_{OF} = \frac{L}{\sin\theta_{OF}}$$ Equation 11

$$R_{IR} = \frac{L}{\sin\theta_{IR}}$$ Equation 12

$$R_{OR} = \frac{L}{\sin\theta_{OR}}$$ Equation 13

$$D = \sqrt{2w_1^2}$$ Equation 14

$$W_2 = W_1 - W_{Cask}$$ Equation 15

$\delta = 25°$	(Angle of Deflection)
$\theta_{IF} = 30°$	(Inner Front Wheel Turn Angle)
$\theta_{OF} = 25°$	(Outer Front Wheel Turn Angle)
$\theta_{IR} = 30°$	(Inner Rear Wheel Turn Angle)
$\theta_{OR} = 25°$	(Outer Rear Wheel Turn Angle)
W_1 =14’	(Width of Disposal Panel Rooms)
$W_2 = W_1 - D_2$	(Width of ROV)
W_{Cask} = 11’-10”	(Length of Cask)
D_1 = 19’ – 9.6”	(Maximum Turn Radius)
$D_2 = (W_1 - W_{Cask}) / 2$	(Approximate Driving Distance from Rib)
R_{IF}	(Inner Front Wheel Turn Radius)
R_{OF}	(Outer Front Wheel Turn Radius)
R_{IR}	(Inner Rear Wheel Turn Radius)
R_{OR}	(Outer Rear Wheel Turn Radius)
L	(Axle-to-Axle Distance)L

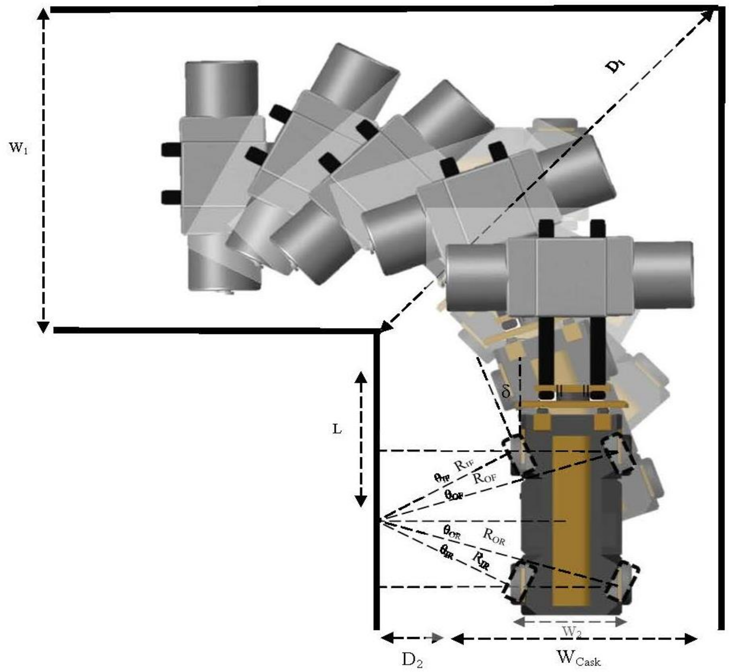

Figure 18: ROV Turning Radius (not to scale)

CHAPTER 9: CONLSUSION

The purpose of this project was to design an ROV capable of applying the in-drift emplacement method at the WIPP to enhance to RH disposal program and help improve the efficiency in utilizing as much of the volume of record as possible. This would require a clamshell cask that is of sufficient thickness to reduce the 1,000,000mrem/hr maximum limit for acceptable RH waste to 200mrem/hr. This allows operators to process the cask as a CH, reducing the need for additional changes to the facility's controls. The cask provides an adequate control from the exchange point between the shipping cask and the clamshell cask, all the way to the final step of in-drift emplacement.

By establishing an RH dedicated panel, in-drift emplacement will be possible since the panel can be bounded as an HRA; only remote operations will be able to be conducted within these bounds. The dynamic movement of the ground will also be easier to maintain if an RH panel is created. Operations can use a Just in Time methodology with the CH waste, mining one panel ahead of the emplacement panel. The same can be applied with an RH dedicated panel.

The shielding calculations provided for the Clamshell Cask were constrained to the regulatory limits as well as the allowable weight on the WHS and the geometry of the drifts. This resulted in a Clamshell Cask length and weight from the minimum thickness required. For meeting the 200 mrem/hr limit, a thickness of 18cm and 0.1216cm were found for Stainless Steel types 304 and Lead, respectively. These values produced an overall thickness of 18.1216cm (7.1345 in). This also resulted in an overall weight of 31,905 lbs empty and 39,905 lbs loaded; equivalent to 19.55 tons. This is well below the WHS limit of 45 tons.

The ROV was also provided with negative four wheal steering. With this capability, maneuvering through the drifts of the UG will not be an issue. The narrowest drift is 14' at the entrance to a panel. The length of the Clamshell Cask was found to be 11'-10". These dimensions were found to be of no hindrance to the ROV's maneuverability.

Overall, it was concluded that the designs specified will satisfy the constraints that bounded the problem and were also within the required limit. Furthermore, the process utilizes as much of the existing facility so as to reduce the impact on the current waste operations. The process also supports the SDDI concept of in-drift emplacement by an ROV, providing the WIPP with a capability to dispose of CH and RH waste in a more effective manner.

Continuation of this project would potentially include the evaluation of reducing the energy levels specified in the RH-TRU 72-B SAR to generate a lighter and smaller Clamshell Cask that will allow for additional degrees of freedom within the facilities bounds. This can also potentially be obtained by varying the two Stainless Steel layers from each other. An evaluation can be performed to treat the Stainless Steel configuration independently and observe the difference in dose rate from that of the investigated configuration demonstrated in this project.

The process defined here was meant to provide WIPP with a solution to more efficiently disposing of RH waste and improve the rate at which the Volume of Record is being approached. However, the concept of floor emplacement and utilizing the Clamshell Cask mechanism is something that can be explored at other repositories. This concept provides a safe way of disposing of canisters in a remotely operated environment and overall, improving the nuclear waste problem around the world. Other facilities would have the opportunity to utilize or improve on the cask design to better fit the process of their facility. The results of this project do not reflect DOE's intentions for the WIPP's waste operations.

APPENDICES

APPENDIX A: MATLAB ITERATIONS

Iterations 1-10

```
%%Function

%%Solve for Dose and truncate at 200mrem/hr.

 function [ D ] = Dose(S,B,x,R)

D = (S .* B .* exp(-x))./(4 * pi .* R.^2);

%% Shielding at 5MeV

%% Source at 1,000,000 mrem/hr

%% t_SS = 1cm

>> t_Pb=[8 9 10 11 12 13 14 15 16 17] %%thickness of lead shielding [cm]

 t_SS=1 %%thickness of Stainless Steel Shielding [cm]

u_Pb=4.26e-2 %%Mass Attenuation Coefficient for Lead [cm^2/g]

 p_Pb=11.35 %%Density of Lead [g/cc]

C_Pb=1.00 %%Percent lComposition of Lead

u_1=u_Pb/p_Pb*C_Pb %%Attenuation Coefficient for Lead

u_Si=2.96e-2 %%Mass Attenuation Coefficient for Silicon [cm^2/g]

 p_Si=0.0801 %%Density of Silicon [g/cc]

C_Si=.01 %%Percent Composition of Silicon

u_2=u_Si/p_Si*C_Si %%Attenuation Coefficient for Silicon

u_Cr=3.05e-2 %%Mass Attenuation Coefficient for Chromium [cm^2/g]

p_Cr=1.5224 %%Density of Chromium [g/cc]

C_Cr=.19 %%Percent Composition of Chromium

u_3=u_Cr/p_Cr*C_Cr %%Attenuation Coefficient for Chromium

u_Mg=3.04e-2 %%Mass Attenuation Coefficient for Manganese [cm^2/g]

 p_Mg=.1663 %%Density of Manganese [g/cc]
```

```
C_Mg=.02  %%Percent Composition  of Mangense

u_4=u_Mg/p_Mg*C_Mg   %%Attenuation Coefficient for Manganese

u_Fe=3.14e-2  %%Mass Attenuation Coefficient  for Iron [cm^2/g]

p_Fe=5.4487   %%Density of Iron [g/cc]

C_Fe=.68  %%Percent Composition  of Iron

u_5=u_Fe/p_Fe*C_Fe  %%Attenuation Coefficient  for Iron

u_Ni=3.28e-2      %%Mass Attenuation Coefficient  for Nickle  [cm^2/g]

p_Ni=.813    %%Density of Nickel [g/cc]

C_Ni=.1  %%Percent Composition  of Nickel

 u_6=u_Ni/p_Ni*C_Ni   %%Attenuation Coefficient  for Nickel

u_7=u_2+u_3+u_4+u_5+u_6    %%Attenuation Coefficient  for Stainless  Steel

x=u_1.*t_Pb+2*u_7*t_SS     %%Mean Free Path (mfp)

b=1.48e0   %%Iron Exposure  Buildup  Factor from ANSI/ANS 6.4.3-1991

c=1.01e0   %%Iron Exposure  Buildup  Factor from ANSI/ANS 6.4.3-1991

a=1.2e-2  %%Iron Exposure  Buildup  Factor from ANSI/ANS 6.4.3-1991

X=1.31e1   %%Iron Exposure  Buildup  Factor from ANSI/ANS 6.4.3-1991

d=-2.58e-2   %%Iron Exposure  Buildup  Factor from ANSI/ANS 6.4.3-1991

K=c.*x.^a+d.*(((tanh(x/X)-2)-(tanh(-2)))/(1-tanh(-2)))       %% Geometric  Progression
Approximation

B_E=1.+(b-1).*((K.^x-1)./(K-1))   %%Build Up Factor

S_E=1000000   %%Source [mrem/hr]

R=2.*t_SS+ t_Pb %%total thickness  of material and range to surface dose rate [cm]

Dose(S_E,B_E,x,R)   %%Dose Rate [mrem/hr]

t_Pb =

  Columns  1 through  8

     8     9    10    11    12    13    14    15
```

```
  Columns 9 through 10

    16    17

t_SS =

     1

u_Pb =

    0.0426

p_Pb =

   11.3500

C_Pb =

     1

u_1 =

    0.0038

u_Si =

    0.0296

p_Si =

    0.0801

C_Si =

    0.0100

u_2 =

    0.0037

u_Cr =

    0.0305

p_Cr =

    1.5224
```

C_Cr =

0.1900

u_3 =

0.0038

u_Mg =

0.0304

p_Mg =

0.1663

C_Mg =

0.0200

u_4 =

0.0037

u_Fe =

0.0314

p_Fe =

5.4487

C_Fe =

0.6800

u_5 =

0.0039

u_Ni =

0.0328

p_Ni =

0.8130

```
C_Ni =

    0.1000

u_6 =

    0.0040

u_7 =

    0.0191

x =

  Columns 1 through 5

    0.0682    0.0720    0.0758    0.0795    0.0833

  Columns 6 through 10

    0.0870    0.0908    0.0945    0.0983    0.1020

b =

    1.4800

c =

    1.0100

a =

    0.0120

X =

   13.1000

d =

   -0.0258

K =

  Columns 1 through 5

    0.9915    0.9921    0.9927    0.9933    0.9938
```

```
  Columns 6 through 10

    0.9944    0.9949    0.9953    0.9958    0.9962

B_E =

  Columns 1 through 5

    1.0329    1.0347    1.0365    1.0383    1.0401

  Columns 6 through 10

    1.0419    1.0437    1.0455    1.0473    1.0491

S_E =

     1000000

R =

  Columns 1 through 8

    10    11    12    13    14    15    16    17

  Columns 9 through 10

    18    19

ans =

  Columns 1 through 5

  767.7220  633.2044  530.9952  451.5322  388.5440

  Columns 6 through 10

  337.7794  296.2741  261.9101  233.1418  208.8198

>>
```

Iterations 11-20

```
%%Function
%%Solve for Dose and truncate at 200mrem/hr.
 function [ D ] = Dose(S,B,x,R)
D = (S .* B .* exp(-x))./(4 * pi .* R.^2);
%% Shielding  at 5MeV
%% Source at 1,000,000  mrem/hr
%% t_SS = 2cm
>>  t_Pb=[8 9 10 11 12 13 14 15 16 17]  %%thickness of lead shielding  [cm]
 t_SS=2   %%thickness of Stainless Steel Shielding  [cm]
u_Pb=4.26e-2 %%Mass Attenuation Coefficient  for Lead [cm^2/g]
 p_Pb=11.35   %%Density of Lead [g/cc]
C_Pb=1.00  %%Percent Composition  of Lead
u_1=u_Pb/p_Pb*C_Pb  %%Attenuation Coefficient for Lead
u_Si=2.96e-2   %%Mass Attenuation Coefficient for Silicon  [cm^2/g]
 p_Si=0.0801   %%Density of Silicon  [g/cc]
C_Si=.01   %%Percent Composition  of Silicon
u_2=u_Si/p_Si*C_Si   %%Attenuation Coefficient for Silicon
u_Cr=3.05e-2   %%Mass Attenuation Coefficient  for Chromium  [cm^2/g]
p_Cr=1.5224  %%Density of Chromium  [g/cc]
C_Cr=.19   %%Percent Composition  of Chromium
u_3=u_Cr/p_Cr*C_Cr  %%Attenuation Coefficient  for Chromium
u_Mg=3.04e-2  %%Mass Attenuation Coefficient  for Manganese [cm^2/g]
 p_Mg=.1663  %%Density of Manganese [g/cc]
C_Mg=.02  %%Percent Composition  of Mangense
```

```
u_4=u_Mg/p_Mg*C_Mg   %%Attenuation Coefficient for Manganese
u_Fe=3.14e-2  %%Mass Attenuation Coefficient  for Iron [cm^2/g]
p_Fe=5.4487   %%Density of Iron [g/cc]
C_Fe=.68  %%Percent Composition  of Iron
u_5=u_Fe/p_Fe*C_Fe  %%Attenuation Coefficient for Iron
u_Ni=3.28e-2     %%Mass Attenuation Coefficient for Nickle [cm^2/g]
p_Ni=.813   %%Density of Nickel [g/cc]
C_Ni=.1  %%Percent Composition  of Nickel
 u_6=u_Ni/p_Ni*C_Ni   %%Attenuation Coefficient for Nickel
u_7=u_2+u_3+u_4+u_5+u_6   %%Attenuation Coefficient  for Stainless Steel
x=u_1.*t_Pb+2*u_7*t_SS     %%Mean Free Path (mfp)
b=1.48e0   %%Iron Exposure Buildup  Factor from ANSI/ANS 6.4.3-1991
c=1.01e0  %%Iron Exposure Buildup  Factor from ANSI/ANS 6.4.3-1991
a=1.2e-2  %%Iron Exposure  Buildup  Factor from ANSI/ANS 6.4.3-1991
X=1.31e1   %%Iron Exposure Buildup  Factor from ANSI/ANS 6.4.3-1991
d=-2.58e-2   %%Iron Exposure Buildup  Factor from ANSI/ANS 6.4.3-1991
K=c.*x.^a+d.*(((tanh(x/X)-2)-(tanh(-2)))/(1-tanh(-2)))      %% Geometric Progression
Approximation
B_E=1.+(b-1).*((K.^x-1)./(K-1))   %%Build Up Factor
S_E=1000000   %%Source [mrem/hr]
R=2.*t_SS+ t_Pb %%total thickness of material and range to surface dose rate [cm]
Dose(S_E,B_E,x,R)    %%Dose Rate [mrem/hr]
t_Pb =

  Columns 1 through 8

    8    9    10    11    12    13    14    15
```

```
  Columns 9 through 10

    16    17

t_SS =

     2

u_Pb =

    0.0426

p_Pb =

   11.3500

C_Pb =

     1

u_1 =

    0.0038

u_Si =

    0.0296

p_Si =

    0.0801

C_Si =

    0.0100

u_2 =

    0.0037

u_Cr =

    0.0305

p_Cr =

    1.5224
```

C_Cr =

0.1900

u_3 =

0.0038

u_Mg =

0.0304

p_Mg =

0.1663

C_Mg =

0.0200

u_4 =

0.0037

u_Fe =

0.0314

p_Fe =

5.4487

C_Fe =

0.6800

u_5 =

0.0039

u_Ni =

0.0328

p_Ni =

0.8130

```
C_Ni =

   0.1000

u_6 =

   0.0040

u_7 =

   0.0191

x =

  Columns 1 through 5

   0.1065    0.1102    0.1140    0.1177    0.1215

  Columns 6 through 10

   0.1252    0.1290    0.1327    0.1365    0.1403

b =

   1.4800

c =

   1.0100

a =

   0.0120

X =

  13.1000

d =

  -0.0258

K =

  Columns 1 through 5

   0.9967    0.9971    0.9975    0.9979    0.9983
```

```
  Columns 6 through 10

    0.9986    0.9990    0.9993    0.9996    0.9999

B_E =

  Columns 1 through 5

    1.0512    1.0530    1.0548    1.0566    1.0584

  Columns 6 through 10

    1.0602    1.0619    1.0637    1.0655    1.0673

S_E =

     1000000

R =

  Columns 1 through 8

    12    13    14    15    16    17    18    19

  Columns 9 through 10

    20    21

ans =

  Columns 1 through 5

  522.2345  444.0705  382.1131  332.1799  291.3550

  Columns 6 through 10

  257.5549  229.2591  205.3369  184.9335  167.3929

>>
```

Iterations 21-30

```
%%Function

%%Solve for Dose and truncate at 200mrem/hr.

 function [ D ] = Dose(S,B,x,R)

D = (S .* B .* exp(-x))./(4 * pi .* R.^2);

%% Shielding  at 5MeV

%% Source at 1,000,000  mrem/hr

%% t_SS = 4cm

>>  t_Pb=[8 9 10 11 12 13 14 15 16 17]  %%thickness of lead shielding  [cm]

 t_SS=4   %%thickness of Stainless Steel Shielding  [cm]

u_Pb=4.26e-2 %%Mass Attenuation Coefficient for Lead [cm^2/g]

 p_Pb=11.35   %%Density of Lead [g/cc]

C_Pb=1.00  %%Percent Composition of Lead

u_1=u_Pb/p_Pb*C_Pb  %%Attenuation Coefficient for Lead

u_Si=2.96e-2   %%Mass Attenuation Coefficient for Silicon  [cm^2/g]

 p_Si=0.0801   %%Density of Silicon  [g/cc]

C_Si=.01   %%Percent Composition of Silicon

u_2=u_Si/p_Si*C_Si   %%Attenuation Coefficient for Silicon

u_Cr=3.05e-2   %%Mass Attenuation Coefficient for Chromium  [cm^2/g]

p_Cr=1.5224  %%Density of Chromium  [g/cc]

C_Cr=.19   %%Percent Composition of Chromium

u_3=u_Cr/p_Cr*C_Cr  %%Attenuation Coefficient for Chromium

u_Mg=3.04e-2  %%Mass Attenuation Coefficient for Manganese [cm^2/g]

 p_Mg=.1663  %%Density of Manganese [g/cc]

C_Mg=.02  %%Percent Composition of Mangense
```

```
u_4=u_Mg/p_Mg*C_Mg  %%Attenuation Coefficient for Manganese
u_Fe=3.14e-2  %%Mass Attenuation Coefficient for Iron [cm^2/g]
p_Fe=5.4487  %%Density of Iron [g/cc]
C_Fe=.68  %%Percent Composition of Iron
u_5=u_Fe/p_Fe*C_Fe  %%Attenuation Coefficient for Iron
u_Ni=3.28e-2     %%Mass Attenuation Coefficient for Nickle [cm^2/g]
p_Ni=.813   %%Density of Nickel [g/cc]
C_Ni=.1  %%Percent Composition of Nickel
 u_6=u_Ni/p_Ni*C_Ni  %%Attenuation Coefficient for Nickel
u_7=u_2+u_3+u_4+u_5+u_6   %%Attenuation Coefficient for Stainless Steel
x=u_1.*t_Pb+2*u_7*t_SS    %%Mean Free Path (mfp)
b=1.48e0  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
c=1.01e0  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
a=1.2e-2  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
X=1.31e1  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
d=-2.58e-2  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
K=c.*x.^a+d.*(((tanh(x/X)-2)-(tanh(-2)))/(1-tanh(-2)))     %% Geometric Progression
Approximation
B_E=1.+(b-1).*((K.^x-1)./(K-1))  %%Build Up Factor
S_E=1000000  %%Source [mrem/hr]
R=2.*t_SS+ t_Pb %%total thickness of material and range to surface dose rate [cm]
Dose(S_E,B_E,x,R)  %%Dose Rate [mrem/hr]
t_Pb =

  Columns 1 through 8

    8     9    10    11    12    13    14    15
```

Columns 9 through 10

16 17

t_SS =

4

u_Pb =

0.0426

p_Pb =

11.3500

C_Pb =

1

u_1 =

0.0038

u_Si =

0.0296

p_Si =

0.0801

C_Si =

0.0100

u_2 =

0.0037

u_Cr =

0.0305

p_Cr =

1.5224

C_Cr =

0.1900

u_3 =

0.0038

u_Mg =

0.0304

p_Mg =

0.1663

C_Mg =

0.0200

u_4 =

0.0037

u_Fe =

0.0314

p_Fe =

5.4487

C_Fe =

0.6800

u_5 =

0.0039

u_Ni =

0.0328

p_Ni =

0.8130

```
C_Ni =

    0.1000

u_6 =

    0.0040

u_7 =

    0.0191

x =

  Columns 1 through 5

    0.1829    0.1867    0.1904    0.1942    0.1979

  Columns 6 through 10

    0.2017    0.2054    0.2092    0.2129    0.2167

b =

    1.4800

c =

    1.0100

a =

    0.0120

X =

   13.1000

d =

   -0.0258

K =

  Columns 1 through 5

    1.0030    1.0033    1.0035    1.0037    1.0040
```

```
  Columns 6 through 10

    1.0042    1.0044    1.0046    1.0048    1.0050

B_E =

  Columns 1 through 5

    1.0877    1.0895    1.0913    1.0931    1.0949

  Columns 6 through 10

    1.0966    1.0984    1.1002    1.1020    1.1038

S_E =

     1000000

R =

  Columns 1 through 8

    16    17    18    19    20    21    22    23

  Columns 9 through 10

    24    25

ans =

  Columns 1 through 5

  281.5894  248.9104  221.5538  198.4263  178.7012

  Columns 6 through 10

  161.7442  147.0620  134.2665  123.0488  113.1605

>>
```

Iterations 31-40

```
%%Function
%%Solve for Dose and truncate at 200mrem/hr.
 function [ D ] = Dose(S,B,x,R)
D = (S .* B .* exp(-x))./(4 * pi .* R.^2);
%% Shielding  at 5MeV
%% Source at 1,000,000  mrem/hr
%% t_SS = 6cm
>>  t_Pb=[8 9 10 11 12 13 14 15 16 17]  %%thickness of lead shielding  [cm]
 t_SS=6   %%thickness of Stainless Steel Shielding  [cm]
u_Pb=4.26e-2 %%Mass Attenuation Coefficient for Lead [cm^2/g]
 p_Pb=11.35   %%Density of Lead [g/cc]
C_Pb=1.00  %%Percent Composition of Lead
u_1=u_Pb/p_Pb*C_Pb  %%Attenuation Coefficient for Lead
u_Si=2.96e-2   %%Mass Attenuation Coefficient for Silicon  [cm^2/g]
 p_Si=0.0801   %%Density of Silicon  [g/cc]
C_Si=.01   %%Percent Composition of Silicon
u_2=u_Si/p_Si*C_Si   %%Attenuation Coefficient for Silicon
u_Cr=3.05e-2   %%Mass Attenuation Coefficient for Chromium  [cm^2/g]
p_Cr=1.5224  %%Density of Chromium  [g/cc]
C_Cr=.19   %%Percent Composition of Chromium
u_3=u_Cr/p_Cr*C_Cr  %%Attenuation Coefficient for Chromium
u_Mg=3.04e-2  %%Mass Attenuation Coefficient for Manganese [cm^2/g]
 p_Mg=.1663  %%Density of Manganese [g/cc]
C_Mg=.02  %%Percent Composition of Mangense
```

```
u_4=u_Mg/p_Mg*C_Mg  %%Attenuation Coefficient for Manganese
u_Fe=3.14e-2  %%Mass Attenuation Coefficient for Iron [cm^2/g]
p_Fe=5.4487  %%Density of Iron [g/cc]
C_Fe=.68  %%Percent Composition of Iron
u_5=u_Fe/p_Fe*C_Fe  %%Attenuation Coefficient for Iron
u_Ni=3.28e-2    %%Mass Attenuation Coefficient for Nickle [cm^2/g]
p_Ni=.813   %%Density of Nickel [g/cc]
C_Ni=.1  %%Percent Composition of Nickel
 u_6=u_Ni/p_Ni*C_Ni  %%Attenuation Coefficient for Nickel
u_7=u_2+u_3+u_4+u_5+u_6   %%Attenuation Coefficient for Stainless Steel
x=u_1.*t_Pb+2*u_7*t_SS    %%Mean Free Path (mfp)
b=1.48e0  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
c=1.01e0  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
a=1.2e-2  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
X=1.31e1  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
d=-2.58e-2  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
K=c.*x.^a+d.*(((tanh(x/X)-2)-(tanh(-2)))/(1-tanh(-2)))     %% Geometric Progression
Approximation
B_E=1.+(b-1).*((K.^x-1)./(K-1))  %%Build Up Factor
S_E=1000000  %%Source [mrem/hr]
R=2.*t_SS+ t_Pb %%total thickness of material and range to surface dose rate [cm]
Dose(S_E,B_E,x,R)  %%Dose Rate [mrem/hr]
t_Pb =

  Columns 1 through 8

    8    9   10   11   12   13   14   15
```

Columns 9 through 10

16 17

t_SS =

6

u_Pb =

0.0426

p_Pb =

11.3500

C_Pb =

1

u_1 =

0.0038

u_Si =

0.0296

p_Si =

0.0801

C_Si =

0.0100

u_2 =

0.0037

u_Cr =

0.0305

p_Cr =

1.5224

C_Cr =

0.1900

u_3 =

0.0038

u_Mg =

0.0304

p_Mg =

0.1663

C_Mg =

0.0200

u_4 =

0.0037

u_Fe =

0.0314

p_Fe =

5.4487

C_Fe =

0.6800

u_5 =

0.0039

u_Ni =

0.0328

p_Ni =

0.8130

```
C_Ni =

    0.1000

u_6 =

    0.0040

u_7 =

    0.0191

x =

  Columns 1 through 5

    0.2594    0.2631    0.2669    0.2706    0.2744

  Columns 6 through 10

    0.2781    0.2819    0.2856    0.2894    0.2931

b =

    1.4800

c =

    1.0100

a =

    0.0120

X =

   13.1000

d =

   -0.0258

K =

  Columns 1 through 5

    1.0071    1.0073    1.0075    1.0076    1.0078
```

```
  Columns 6 through 10

    1.0079    1.0081    1.0082    1.0084    1.0086

B_E =

  Columns 1 through 5

    1.1242    1.1260    1.1277    1.1295    1.1313

  Columns 6 through 10

    1.1331    1.1349    1.1367    1.1385    1.1403

S_E =

     1000000

R =

  Columns 1 through 8

    20    21    22    23    24    25    26    27

  Columns 9 through 10

    28    29

ans =

  Columns 1 through 5

  172.5528  156.1725  141.9901  129.6304  118.7949

  Columns 6 through 10

  109.2439  100.7828   93.2525   86.5218   80.4819

>>
```

Iterations 41-50

```
%%Function
%%Solve for Dose and truncate at 200mrem/hr.
 function [ D ] = Dose(S,B,x,R)
D = (S .* B .* exp(-x))./(4 * pi .* R.^2);
%% Shielding at 5MeV
%% Source at 1,000,000 mrem/hr
%% t_SS = 8cm
>> t_Pb=[1 2 3 4 5 6 7 8 9 10] %%thickness of lead shielding [cm]
 t_SS=8 %%thickness of Stainless Steel Shielding [cm]
u_Pb=4.26e-2 %%Mass Attenuation Coefficient for Lead [cm^2/g]
 p_Pb=11.35 %%Density of Lead [g/cc]
C_Pb=1.00 %%Percent Composition of Lead
u_1=u_Pb/p_Pb*C_Pb %%Attenuation Coefficient for Lead
u_Si=2.96e-2 %%Mass Attenuation Coefficient for Silicon [cm^2/g]
 p_Si=0.0801 %%Density of Silicon [g/cc]
C_Si=.01 %%Percent Composition of Silicon
u_2=u_Si/p_Si*C_Si %%Attenuation Coefficient for Silicon
u_Cr=3.05e-2 %%Mass Attenuation Coefficient for Chromium [cm^2/g]
p_Cr=1.5224 %%Density of Chromium [g/cc]
C_Cr=.19 %%Percent Composition of Chromium
u_3=u_Cr/p_Cr*C_Cr %%Attenuation Coefficient for Chromium
u_Mg=3.04e-2 %%Mass Attenuation Coefficient for Manganese [cm^2/g]
 p_Mg=.1663 %%Density of Manganese [g/cc]
C_Mg=.02 %%Percent Composition of Mangense
```

```
u_4=u_Mg/p_Mg*C_Mg  %%Attenuation Coefficient for Manganese
u_Fe=3.14e-2  %%Mass Attenuation Coefficient for Iron [cm^2/g]
p_Fe=5.4487  %%Density of Iron [g/cc]
C_Fe=.68  %%Percent Composition of Iron
u_5=u_Fe/p_Fe*C_Fe  %%Attenuation Coefficient for Iron
u_Ni=3.28e-2     %%Mass Attenuation Coefficient for Nickle [cm^2/g]
p_Ni=.813   %%Density of Nickel [g/cc]
C_Ni=.1  %%Percent Composition of Nickel
 u_6=u_Ni/p_Ni*C_Ni  %%Attenuation Coefficient for Nickel
u_7=u_2+u_3+u_4+u_5+u_6   %%Attenuation Coefficient for Stainless Steel
x=u_1.*t_Pb+2*u_7*t_SS     %%Mean Free Path (mfp)
b=1.48e0  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
c=1.01e0  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
a=1.2e-2  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
X=1.31e1  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
d=-2.58e-2  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
K=c.*x.^a+d.*(((tanh(x/X)-2)-(tanh(-2)))/(1-tanh(-2)))      %% Geometric Progression
Approximation
B_E=1.+(b-1).*((K.^x-1)./(K-1))  %%Build Up Factor
S_E=1000000  %%Source [mrem/hr]
R=2.*t_SS+ t_Pb %%total thickness of material and range to surface dose rate [cm]
Dose(S_E,B_E,x,R)   %%Dose Rate [mrem/hr]
t_Pb =

  Columns 1 through 8

     1     2     3     4     5     6     7     8
```

```
  Columns  9 through  10

     9    10

t_SS =

     8

u_Pb =

    0.0426

p_Pb =

   11.3500

C_Pb =

     1

u_1 =

    0.0038

u_Si =

    0.0296

p_Si =

    0.0801

C_Si =


    0.0100

u_2 =

    0.0037

u_Cr =

    0.0305

p_Cr =

    1.5224
```

C_Cr =

0.1900

u_3 =

0.0038

u_Mg =

0.0304

p_Mg =

0.1663

C_Mg =

0.0200

u_4 =

0.0037

u_Fe =

0.0314

p_Fe =

5.4487

C_Fe =

0.6800

u_5 =

0.0039

u_Ni =

0.0328

p_Ni =

0.8130

```
C_Ni =

   0.1000

u_6 =

   0.0040

u_7 =

   0.0191

x =

  Columns 1 through 5

   0.3095    0.3133    0.3170    0.3208    0.3245

  Columns 6 through 10

   0.3283    0.3321    0.3358    0.3396    0.3433

b =

   1.4800

c =

   1.0100

a =

   0.0120

X =

  13.1000

d =

  -0.0258

K =

  Columns 1 through 5

   1.0092    1.0093    1.0095    1.0096    1.0097
```

```
  Columns 6 through 10

    1.0099    1.0100    1.0101    1.0103    1.0104

B_E =

  Columns 1 through 5

    1.1481    1.1499    1.1517    1.1535    1.1553

  Columns 6 through 10

    1.1571    1.1589    1.1606    1.1624    1.1642

S_E =

     1000000

R =

  Columns 1 through 8

    17    18    19    20    21    22    23    24

  Columns 9 through 10

    25    26

ans =

  Columns 1 through 5

  231.9780  206.4651  184.8973  166.5032  150.6912

  Columns 6 through 10

  137.0011  125.0708  114.6119  105.3931   97.2264

>>
```

Iterations 51-60

%%Function

%%Solve for Dose and truncate at 200mrem/hr.

```
function [ D ] = Dose(S,B,x,R)

D = (S .* B .* exp(-x))./(4 * pi .* R.^2);
```

%% Shielding at 5MeV

%% Source at 1,000,000 mrem/hr

%% t_SS = 9cm

```
>> t_Pb=[0.06 0.07 0.08 0.09 0.1 0.11 0.12 0.13 0.14 0.15]  %%thickness of lead shielding [cm]

t_SS=9   %%thickness of Stainless Steel Shielding [cm]

u_Pb=4.26e-2 %%Mass Attenuation Coefficient for Lead [cm^2/g]

p_Pb=11.35   %%Density of Lead [g/cc]

C_Pb=1.00  %%Percent Composition of Lead

u_1=u_Pb/p_Pb*C_Pb  %%Attenuation Coefficient for Lead

u_Si=2.96e-2   %%Mass Attenuation Coefficient for Silicon [cm^2/g]

p_Si=0.0801   %%Density of Silicon [g/cc]

C_Si=.01   %%Percent Composition of Silicon

u_2=u_Si/p_Si*C_Si   %%Attenuation Coefficient for Silicon

u_Cr=3.05e-2   %%Mass Attenuation Coefficient for Chromium [cm^2/g]

p_Cr=1.5224   %%Density of Chromium [g/cc]

C_Cr=.19   %%Percent Composition of Chromium

u_3=u_Cr/p_Cr*C_Cr  %%Attenuation Coefficient for Chromium

u_Mg=3.04e-2  %%Mass Attenuation Coefficient for Manganese [cm^2/g]

p_Mg=.1663  %%Density of Manganese [g/cc]

C_Mg=.02  %%Percent Composition of Mangense
```

```
u_4=u_Mg/p_Mg*C_Mg  %%Attenuation Coefficient for Manganese
u_Fe=3.14e-2  %%Mass Attenuation Coefficient for Iron [cm^2/g]
p_Fe=5.4487  %%Density of Iron [g/cc]
C_Fe=.68  %%Percent Composition of Iron
u_5=u_Fe/p_Fe*C_Fe  %%Attenuation Coefficient for Iron
u_Ni=3.28e-2     %%Mass Attenuation Coefficient for Nickle [cm^2/g]
p_Ni=.813   %%Density of Nickel [g/cc]
C_Ni=.1  %%Percent Composition of Nickel
 u_6=u_Ni/p_Ni*C_Ni  %%Attenuation Coefficient for Nickel
u_7=u_2+u_3+u_4+u_5+u_6   %%Attenuation Coefficient for Stainless Steel
x=u_1.*t_Pb+2*u_7*t_SS    %%Mean Free Path (mfp)
b=1.48e0  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
c=1.01e0  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
a=1.2e-2  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
X=1.31e1  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
d=-2.58e-2  %%Iron Exposure Buildup Factor from ANSI/ANS 6.4.3-1991
K=c.*x.^a+d.*(((tanh(x/X)-2)-(tanh(-2)))/(1-tanh(-2)))     %% Geometric Progression
Approximation
B_E=1.+(b-1).*((K.^x-1)./(K-1))  %%Build Up Factor
S_E=1000000  %%Source [mrem/hr]
R=2.*t_SS+ t_Pb %%total thickness of material and range to surface dose rate [cm]
Dose(S_E,B_E,x,R)  %%Dose Rate [mrem/hr]
t_Pb =

  Columns 1 through 5

    0.0600    0.0700    0.0800    0.0900    0.1000
```

```
  Columns 6 through 10

    0.1100    0.1200    0.1300    0.1400    0.1500

t_SS =

     9

u_Pb =

    0.0426

p_Pb =

   11.3500

C_Pb =

     1

u_1 =

    0.0038

u_Si =

    0.0296

p_Si =

    0.0801

C_Si =

    0.0100

u_2 =

    0.0037

u_Cr =

    0.0305

p_Cr =

    1.5224
```

C_Cr =

0.1900

u_3 =

0.0038

u_Mg =

0.0304

p_Mg =

0.1663

C_Mg =

0.0200

u_4 =

0.0037

u_Fe =

0.0314

p_Fe =

5.4487

C_Fe =

0.6800

u_5 =

0.0039

u_Ni =

0.0328

p_Ni =

0.8130

```
C_Ni =

    0.1000

u_6 =

    0.0040

u_7 =

    0.0191

x =

  Columns 1 through 5

    0.3442    0.3443    0.3443    0.3443    0.3444

  Columns 6 through 10

    0.3444    0.3444    0.3445    0.3445    0.3446

b =

    1.4800

c =

    1.0100

a =

    0.0120

X =

   13.1000

d =

   -0.0258

K =

  Columns 1 through 5

    1.0104    1.0104    1.0104    1.0104    1.0104
```

```
 Columns 6 through 10

   1.0104    1.0104    1.0104    1.0104    1.0104

B_E =

  Columns 1 through 5

   1.1647    1.1647    1.1647    1.1647    1.1647

  Columns 6 through 10

   1.1648    1.1648    1.1648    1.1648    1.1648

S_E =

     1000000

R =

  Columns 1 through 5

  18.0600   18.0700   18.0800   18.0900   18.1000

  Columns 6 through 10

  18.1100   18.1200   18.1300   18.1400   18.1500

ans =

  Columns 1 through 5

  201.4009  201.1736  200.9466  200.7201  200.4939

  Columns 6 through 10

  200.2681  200.0427  199.8177  199.5930  199.3687

>>
```

Iteration 61

```
%%Solve for Dose and truncate at 200mrem/hr.

function [ D ] = Dose(t)

D = (1000000) .* (1 + (1.48 - 1) .* (( ((1.01) .* ((0.038) .* t + (0.019) *18) .^ (0.012) +
(0.0258) .* (((tanh(((0.038) .* t + (0.019) * 18) / 13.1) - 2) - (tanh(-2))) ./ (1-tanh(-2)))) .^
((0.038) .* t + (0.019) .* 18) - 1) ./ ( ((1.01) .* ((0.038) .* t + (0.019) .* 18) .^ (0.012) +
(0.0258) .* (((tanh(((0.038) .* t + (0.019) * 18) / 13.1) - 2) - (tanh(-2))) ./ (1 - tanh(-2)))) -
1))) .* exp(-((0.038) .* t + (0.019) .* 18)) ./ (4 * pi .* (18 + t) .^ 2);

x= .1756

%% Shielding at 5MeV

%% Source at 1,000,000 mrem/hr

%% t_SS = 9cm

t= [0.12:0.0001:0.14]

t =

  Columns 1 through 5

    0.1200    0.1201    0.1202    0.1203    0.1204

  Columns 6 through 10

    0.1205    0.1206    0.1207    0.1208    0.1209

  Columns 11 through 15

    0.1210    0.1211    0.1212    0.1213    0.1214

  Columns 16 through 20

    0.1215    0.1216    0.1217    0.1218    0.1219

  Columns 21 through 25

    0.1220    0.1221    0.1222    0.1223    0.1224

  Columns 26 through 30

    0.1225    0.1226    0.1227    0.1228    0.1229
```

Columns 31 through 35

0.1230 0.1231 0.1232 0.1233 0.1234

Columns 36 through 40

0.1235 0.1236 0.1237 0.1238 0.1239

Columns 41 through 45

0.1240 0.1241 0.1242 0.1243 0.1244

Columns 46 through 50

0.1245 0.1246 0.1247 0.1248 0.1249

Columns 51 through 55

0.1250 0.1251 0.1252 0.1253 0.1254

Columns 56 through 60

0.1255 0.1256 0.1257 0.1258 0.1259

Columns 61 through 65

0.1260 0.1261 0.1262 0.1263 0.1264

Columns 66 through 70

0.1265 0.1266 0.1267 0.1268 0.1269

Columns 71 through 75

0.1270 0.1271 0.1272 0.1273 0.1274

Columns 76 through 80

0.1275 0.1276 0.1277 0.1278 0.1279

Columns 81 through 85

0.1280 0.1281 0.1282 0.1283 0.1284

Columns 86 through 90

0.1285 0.1286 0.1287 0.1288 0.1289

Columns 91 through 95

0.1290	0.1291	0.1292	0.1293	0.1294

Columns 96 through 100

0.1295	0.1296	0.1297	0.1298	0.1299

Columns 101 through 105

0.1300	0.1301	0.1302	0.1303	0.1304

Columns 106 through 110

0.1305	0.1306	0.1307	0.1308	0.1309

Columns 111 through 115

0.1310	0.1311	0.1312	0.1313	0.1314

Columns 116 through 120

0.1315	0.1316	0.1317	0.1318	0.1319

Columns 121 through 125

0.1320	0.1321	0.1322	0.1323	0.1324

Columns 126 through 130

0.1325	0.1326	0.1327	0.1328	0.1329

Columns 131 through 135

0.1330	0.1331	0.1332	0.1333	0.1334

Columns 136 through 140

0.1335	0.1336	0.1337	0.1338	0.1339

Columns 141 through 145

0.1340	0.1341	0.1342	0.1343	0.1344

Columns 146 through 150

0.1345	0.1346	0.1347	0.1348	0.1349

Columns 151 through 155

0.1350 0.1351 0.1352 0.1353 0.1354

Columns 156 through 160

0.1355 0.1356 0.1357 0.1358 0.1359

Columns 161 through 165

0.1360 0.1361 0.1362 0.1363 0.1364

Columns 166 through 170

0.1365 0.1366 0.1367 0.1368 0.1369

Columns 171 through 175

0.1370 0.1371 0.1372 0.1373 0.1374

Columns 176 through 180

0.1375 0.1376 0.1377 0.1378 0.1379

Columns 181 through 185

0.1380 0.1381 0.1382 0.1383 0.1384

Columns 186 through 190

0.1385 0.1386 0.1387 0.1388 0.1389

Columns 191 through 195

0.1390 0.1391 0.1392 0.1393 0.1394

Columns 196 through 200

0.1395 0.1396 0.1397 0.1398 0.1399

Column 201

0.1400

Dose(t)

ans_1 =

Columns 1 through 5

200.0415 200.0389 200.0362 200.0336 200.0309

Columns 6 through 10

200.0282 200.0256 200.0229 200.0203 200.0176

Columns 11 through 15

200.0150 200.0123 200.0097 200.0070 200.0043

Columns 16 through 20

200.0017 199.9990 199.9964 199.9937 199.9911

Columns 21 through 25

199.9884 199.9858 199.9831 199.9804 199.9778

Columns 26 through 30

199.9751 199.9725 199.9698 199.9672 199.9645

Columns 31 through 35

199.9619 199.9592 199.9566 199.9539 199.9512

Columns 36 through 40

199.9486 199.9459 199.9433 199.9406 199.9380

Columns 41 through 45

199.9353 199.9327 199.9300 199.9274 199.9247

Columns 46 through 50

199.9220 199.9194 199.9167 199.9141 199.9114

Columns 51 through 55

199.9088 199.9061 199.9035 199.9008 199.8982

Columns 56 through 60

199.8955 199.8929 199.8902 199.8875 199.8849

Columns 61 through 65

199.8822 199.8796 199.8769 199.8743 199.8716

Columns 66 through 70

199.8690 199.8663 199.8637 199.8610 199.8584

Columns 71 through 75

199.8557 199.8531 199.8504 199.8478 199.8451

Columns 76 through 80

199.8424 199.8398 199.8371 199.8345 199.8318

Columns 81 through 85

199.8292 199.8265 199.8239 199.8212 199.8186

Columns 86 through 90

199.8159 199.8133 199.8106 199.8080 199.8053

Columns 91 through 95

199.8027 199.8000 199.7974 199.7947 199.7921

Columns 96 through 100

199.7894 199.7868 199.7841 199.7815 199.7788

Columns 101 through 105

199.7762 199.7735 199.7708 199.7682 199.7655

Columns 106 through 110

199.7629 199.7602 199.7576 199.7549 199.7523

Columns 111 through 115

199.7496 199.7470 199.7443 199.7417 199.7390

Columns 116 through 120

199.7364 199.7337 199.7311 199.7284 199.7258

Columns 121 through 125

199.7231 199.7205 199.7178 199.7152 199.7125

Columns 126 through 130

199.7099 199.7072 199.7046 199.7019 199.6993

Columns 131 through 135

199.6966 199.6940 199.6913 199.6887 199.6860

Columns 136 through 140

199.6834 199.6807 199.6781 199.6754 199.6728

Columns 141 through 145

199.6701 199.6675 199.6648 199.6622 199.6595

Columns 146 through 150

199.6569 199.6542 199.6516 199.6489 199.6463

Columns 151 through 155

199.6436 199.6410 199.6383 199.6357 199.6330

Columns 156 through 160

199.6304 199.6277 199.6251 199.6225 199.6198

Columns 161 through 165

199.6172 199.6145 199.6119 199.6092 199.6066

Columns 166 through 170

199.6039 199.6013 199.5986 199.5960 199.5933

Columns 171 through 175

199.5907 199.5880 199.5854 199.5827 199.5801

```
  Columns 176 through 180

  199.5774   199.5748   199.5721   199.5695   199.5668

  Columns 181 through 185

  199.5642   199.5615   199.5589   199.5563   199.5536

  Columns 186 through 190

  199.5510   199.5483   199.5457   199.5430   199.5404

  Columns 191 through 195

  199.5377   199.5351   199.5324   199.5298   199.5271

  Columns 196 through 200

  199.5245   199.5218   199.5192   199.5165   199.5139

  Column 201

  199.5113

find(ans<200)

ans =

  Columns 1 through 9

    17    18    19    20    21    22    23    24    25

  Columns 10 through 18

    26    27    28    29    30    31    32    33    34

  Columns 19 through 27

    35    36    37    38    39    40    41    42    43

  Columns 28 through 36

    44    45    46    47    48    49    50    51    52

  Columns 37 through 45

    53    54    55    56    57    58    59    60    61
```

Columns 46 through 54

62 63 64 65 66 67 68 69 70

Columns 55 through 63

71 72 73 74 75 76 77 78 79

Columns 64 through 72

80 81 82 83 84 85 86 87 88

Columns 73 through 81

89 90 91 92 93 94 95 96 97

Columns 82 through 90

98 99 100 101 102 103 104 105 106

Columns 91 through 99

107 108 109 110 111 112 113 114 115

Columns 100 through 108

116 117 118 119 120 121 122 123 124

Columns 109 through 117

125 126 127 128 129 130 131 132 133

Columns 118 through 126

134 135 136 137 138 139 140 141 142

Columns 127 through 135

143 144 145 146 147 148 149 150 151

Columns 136 through 144

152 153 154 155 156 157 158 159 160

Columns 145 through 153

161 162 163 164 165 166 167 168 169

```
Columns 154 through 162

  170   171   172   173   174   175   176   177   178

 Columns 163 through 171

  179   180   181   182   183   184   185   186   187

 Columns 172 through 180

  188   189   190   191   192   193   194   195   196

 Columns 181 through 185

  197   198   199   200   201
```

min(ans)

ans_2 =

17

t(17)

ans _3=

0.1216

ans_4(17) =

199.9990

APPENDIX B: MATLAB OPTIMIZATION CODING

The optimization technique used in Matlab was to provide a more concise solution to the shielding calculation formula for the Clamshell Cask. The process used was to set the formula equal to zero, then optimize the solution with x and y resembling the Lead thickness and Stainless Steel thickness, respectively. The following was the formula used:

```
>>f = @(x,y) ((1000000) .* (1 + (1.48 - 1) .* (( ((1.01) .* ((0.038) .* x + (0.019) .*2.*y)
.^ (0.012) + (0.0258) .* (((tanh(((0.038) .* x + (0.019) .* 2.*y) ./ 13.1) - 2) - (tanh(-2))) ./
(1-tanh(-2)))) .^ ((0.038) .* x + (0.019) .* 2.*y) - 1) ./ ( ((1.01) .* ((0.038) .* x + (0.019)
.* 2.*y) .^ (0.012) + (0.0258) .* (((tanh(((0.038) .* x + (0.019) .* 2.*y) ./ 13.1) - 2) -
(tanh(-2))) ./ (1 - tanh(-2)))) - 1))) .* exp(-((0.038) .* x + (0.019) .* 2.*y)) ./ (4 .* pi .*
(2.*y + x) .^ 2))-200;
```

The formula was then modeled against the two materials' thicknesses so as to establish the range for which the optimization local minimum exists.

```
>>fsurf (f,[0,10],'showcontours','on');
```

APPENDIX C: ACRONYMS

AIS – Air Intake Shaft

C.F.R – Code of Federal Regulation

CH – Contact Handled

cm – Centimeters

DHLW – Defense High Level Waste

DOE –Department of Energy

DSA –Design Safety Analysis

EPA - Environmental Protection Agency

ES – Exhaust Shaft

Ev – Electron Volt

HAC – Hazardous Accident Condition

HEM – Horizontal Emplacement Machine

HLW – High Level Waste

HRA – High Radiation Area

HWFP – Hazardous Waste Facility Permit

in – Inch

in3 – Cubic Inches

lb – Pound

LHD – Load Haul Dump

LWA – Land Withdrawal Act

Matlab –Matrix Laboratory

MeV – Mega Electron Volt

mfp – Mean Free Path

mrem/hr – Millirem per Hour

NMED – New Mexico Environmental Department

RCRA – Resource Conservation and Recovery Act

RH – Remote Handled

ROM – Run of Mine

ROV – Remotely Operated Vehicle

SDDI – Salt Defense Disposal Investigations

SAR – Safety Analysis Report

SEIS – Supplemental Environmental Impact Statement

SHS – Salt Handling Shaft

TRAMPAC – TRU Waste Authorized Methods for Payload Control

TRU – Transuranic

TRUPACT – Transuranic Packaging Transporter

TRUDOCK – TRUPACT II Unloading Dock

UG – Underground

WAC – Waste Acceptance Criteria

WCS – Waste Control Specialist

WHB – Waste Handling Building

WHS – Waste Hoist Shaft

REFRENCES

Development of Four Wheel Steering System for a Car. K. Lohith, Dr. S. R. Shankapal, M.H. Monish Gowda. 2013.

DOE/CBFO-12-3485, *A Conceptual Plan For Salt Defense Disposal Investigations for Disposal of DOE-EM Managed Wastes, Revision 0. U.S. Department of Energy, Carlsbad Field Office*. June 2012

DOE/EIS-0026-S-2, *Waste Isolation Pilot Plant Disposal Phase Final Supplemental Environmental Impact Statement*, Volume I, Chapters 1-6. Department of Energy, Carlsbad Area office. September 2997.

DOE/WIPP-02-3122, *TRANSURANIC Waste Acceptance Criteria for the Waste Isolation Pilot Plant*, Revision 8. July 2016. U.S Department of Energy, Carlsbad Field Office.

DOE/WIPP-07-3372, *the WIPP Design Safety Analysis*, Revision 5. May 2016.

RH-TRU 72-B Safety Analysis Report, Revision 5. February 2011.

The CH-TRAMPAC, Revision 4. April 2012.

The RH-TRAMPAC, Revision 0. June 2006.

The WIPP Land Withdrawal Act, P.L. 102-579, as amended by P.L 104-201.

Truck Capacity Calculation. https://www.cascorp.com/americas/en/capacitycalcintro. Cascade Corporation. 2016.

TRUPACT-II Safety Analysis Report, Revision 21. May 2005.

TRUPACT-III Safety Analysis Report, Revision 5. December 2011.

Waste Isolation Pilot Plant Hazardous Waste permit. January 2016

Waste Isolation Pilot Plant. http://www.wipp.energy.gov/wipprecovery/about.html. U.S. Department of Energy. February 2016.