Heat Transfer Analysis in a Shielding Layer of TRUPACT-II Container using COMSOL Multiphysics

Noor-Al-Din

Department of Nuclear Science and Engineering, Military Institute of Science and Technology, Bangladesh

ABSTRACT

Radioactive Waste production is one of the major drawbacks of nuclear energy. These radioactive wastes emit harmful ionizing radiation, which may significantly damage the environment and all living creatures. A substantial part of these waste inventories is comprised of transuranic radionuclides. Due to having a long half-life, these transuranic radio nuclides generate a significant amount of heat, which makes the consideration of the thermal properties of material very crucial while developing a transuranic waste container. This study investigates the thermal performance of the TRUPACT-II container, a widely used container for transuranic waste storage. This type of container uses Lead as shielding material and Steel as an outer layer. A two-dimensional steady-state heat transfer simulation uses COMSOL Multiphysics to conduct this research. Heat transfer is solid and is opted as the physics to study. The assigned material was Lead covered with a thin layer of Steel. The prime motivation behind this work is to visualize the thermal shielding effectiveness of the shielding material of the TRUPACT-II container when high-level transuranic wastes are stored by analyzing temperature distribution, heat flux, and maximum/minimum temperatures within the lead shielding layer. The result is validated by running simulation in different mesh element size. Visualization of this result will aid in optimizing material selection and design consideration for future radioactive waste container development. Above all, the findings of this research will make an impactful contribution to the efficient management of radioactive wastes in case of risk associated with heat generation and thermal stress.

Keywords: COMSOL, Heat Flux, Temperature, Heat transfer

1) Introduction

Nuclear is considered one of the promising solutions for future energy demand due to its almost zero-carbon footprint. But application of nuclear energy produces harmful radioactive waste, which is one of the key challenges for the application of nuclear energy. To face this challenge effective management of these wastes is mandatory.

Radioactive waste can be stated as by-products which contain highly radioactive isotopes generated from Nuclear and Radiological facilities. Some common sources of radioactive waste are:

➢ Nuclear Power Plant
  ➢ Nuclear Weapon Testing
  ➢ Medical Application of Nuclear Technology

There is a total of five types of radioactive waste:

Table-1: Types of Radioactive Wastes

Type	General Source
Low-Level Waste	Industries
Transuranic Waste	Nuclear Weapon Production

Uranium Mill Tailings	Uranium Ore milling and mining
Spent Nuclear Fuel	Reactor and Reprocessing Plants
Naturally Occurring Radioactive Materials	Nature

The primary background of this study arises from management of Transuranic wastes [1].

Atomic Number	• More than 92
Half lives	• More than 20 years
Specific Activity	• More than 100 nCi/gm

Transuranic waste production began since the development of atom bomb. According to DOE order 435.1, Transuranic waste is defined as the materials having alpha emitting

radioisotopes which have the following general characteristics.

Besides Nuclear Weapon production, Transuranic waste also generates from decommissioning and decontamination procedures. Transuranic wastes further classified as:

➢ Remote handled waste: Dose rate> 20 mrem/hour
➢ Contact handled waste: Dose rate< 20 mrem/hour

Transuranic Wastes are handled at Waste Isolation Pilot plant at United States. Maintaining the following conditions is crucial for packaging and transporting Transuranic waste:

➢ Containment and protection must be ensured in the overall waste management system
➢ Vent and other measures must be installed to prevent pressurization and gas concentration
➢ Defense and non-defense waste should be separated if possible
➢ Transuranic waste containers should be marked to identify their components [2].

A radioactive waste package comprises waste form, containers and internal barriers. Waste forms may be homogeneous or heterogeneous, encompassing a variety of materials and objects according to their physical state. The objective of the waste container is to physically shield, contain, and/or radiologically shield the waste form during the several actions that take place from conditioning to the placement and shut-down of a disposal facility. Thermal impact, chemical and corrosive attacks and long term cumulative radioactive wastes are the main inclusions regarding this objective [3].

In recent studies these containers of radioactive waste packages are studied broadly in the basis of radiation shielding capability. But, in case of transuranic waste container development, considering thermal impact is crucial as these wastes generate a significant amount of heat. But specific thermal analysis in transuranic waste containers is seldom carried out. The focus of this study is the analysis of Heat transfer in the shielding layer of TRUPACT-II container to examine thermal shielding effectiveness of the lead shielding layer of the container.

2) TRUPACT-II wastes container shielding material

TRUPACT-II is a reusable shipping container developed by the Department of Energy (DOE) in accordance with the National Regulatory Commission (NRC). The capacity of each TRUPACT-II is 3182 kg. Loaded into fourteen drums, each drum contains 55 gallons of waste. It has a 1-inch-thick layer of Lead, including an additional 1/8-inch-thick boundary layer of carbon steel as shielding material.
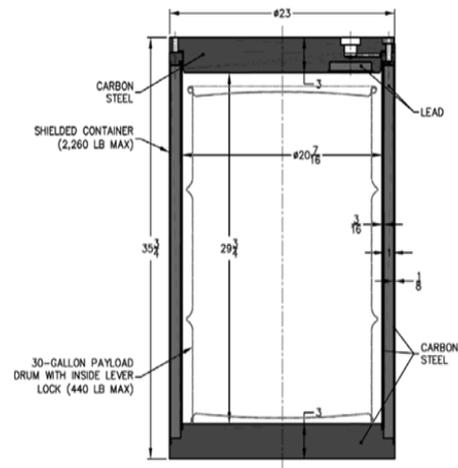

Fig.1 Shielding layer of TRUPACT-II container

Generally, the temperature outside each transuranic waste drum is 333.15 k [4].

3) Methodology

The result of this study is computed by following the governing equation

Energy Balance Equation in case of Heat Transfer in a wall

$$Q_{in} - Q_{out} = \frac{dE_{wall}}{dt} \dots \dots (1)$$

Furriers Law of Heat Conduction

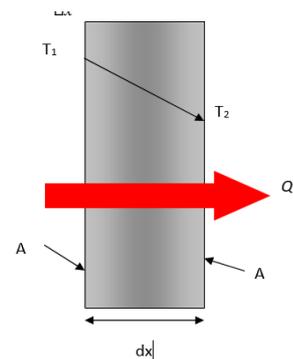$$\dot{Q}_{cond} = kA \frac{dT}{dx} \dots \dots (2)$$

Fig.2: Heat Conduction in a plane wall [5]

COMSOL is a powerful interactive tool to solve many scientific and engineering problems. Three different types of physics interface are available in COMSOL which includes stationary and time dependent studies, linear and nonlinear studies and Eigenfrequency, modal, and frequency response studies. The notable fields for conducting studies with COMSOL are Heat Transfer, Fluid Mechanics, Bioscience, Rotor Dynamics, Semiconductor devices, Photonics and so on [6].

COMSOl has a very efficient tool to analyze Heat Transfer phenomena in test objects which is known as Heat Transfer Module. Heat Transfer in solid is opted as physics under this module for this research. In Heat Transfer in solids, this

module solves the following equation to acquire the results [7].

$$\rho C_p \left(\frac{\partial T}{\partial t} + u_{trans} . \nabla T \right) + \nabla . (q + q_r)$$
$$= -\alpha T \frac{dS}{dt} + Q \dots \dots \dots (3)$$

In this study physics-controlled mesh is applied to the specified geometry. It is a specified meshing feature in COMSOl which automatically generates suitable mesh with user define element size according to the physics and geometry for a particular study [8].
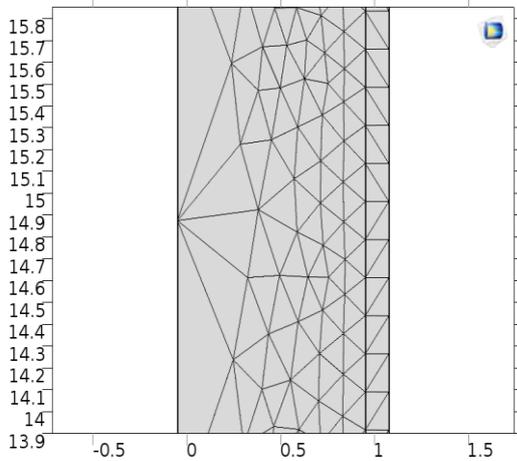

Fig.3: Physics controlled mesh of the geometry with normal mesh element size
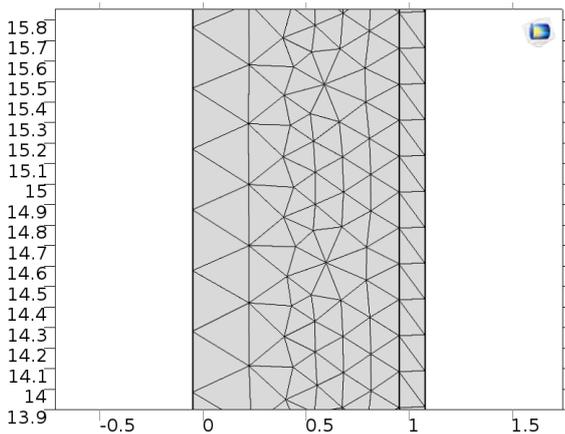

Fig.4: Physics controlled mesh of the geometry with extremely fine mesh element size

In this study this is assumed that TRUPACT-II containers contain a single 55-Gallon drum full of transuranic wastes. The maximum temperature of this can be up to 100 degrees centigrade (373.15 K) [9]. In this study the external temperature of the waste drum is considered as 313.15(K) for moderate analysis. This external temperature of the waste drum is given input as inlet temperature in the shielding layer as well as room temperature is entered as outlet temperature because these containers will be transported in normal environment. This inlet and outlet temperature is considered as boundary conditions in this study.

Table-2: Material specification

Material	Layer thickness in Geometry (in)	Thermal Conductivity (W/m.K)	Density (kg/m³)	Specific Heat at Constant pressure (J/kg.K)
Lead	1	35.3	11340	125.6
Carbon Stell	0.125	44	7850	470

4) Results
Temperature profile

Temperature profile and Distribution plot show that the maximum temperature is 333.15 K, and the minimum is 298.15 K. The straight-line graph indicates that Heat Transfer is the steady state heat conduction. Two differently sized mesh depicts same temperature curve which validates the simulation
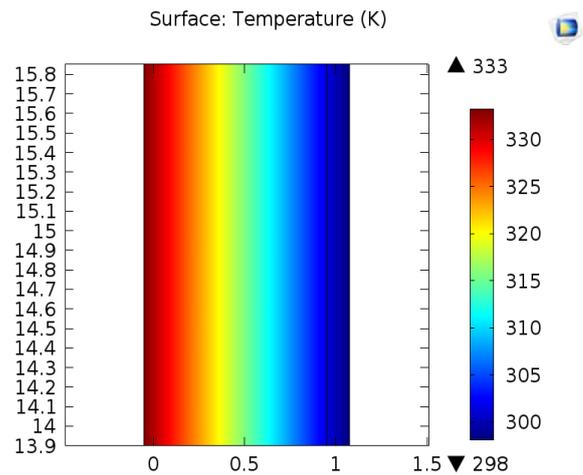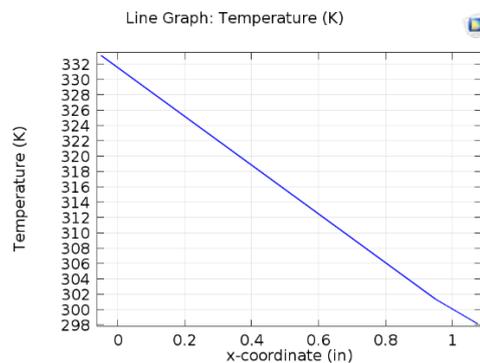

Fig.5: Temperature Distribution

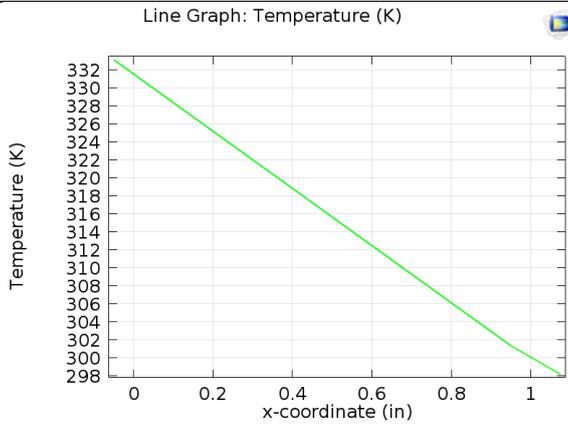Fig.6: Temperature Line graph with normal meshing

Fig.7: Temperature Line graph with extremely meshing

Heat Flux

According to the benchmarks of thermal properties of transuranic waste container, the shielding layer must be capable of resisting and reducing heat transfer. Hence it is proved by this simulation that the design of shielding layer of TRUPACT-II container meets the design criteria of Transuranic waste container based on thermal properties.
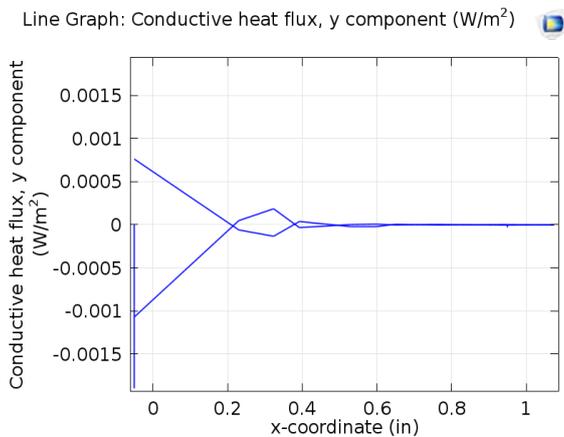

Fig.8: Heat Flux graph

5) Conclusions:
➢ This simulation depicts the thermal shielding effectiveness of the shielding layer of TRUPACT-II container hence proves the effectiveness of the layer
➢ The shielding layer of TRUPACT-II container is enough thick to resist huge amounts of Heat Transfer
➢ The result is validated by simulation of physics-controlled mesh with setting different mesh element size
➢ This simulation is done with 2-D geometry for simplicity of this study. A 3-D geometry simulation in this regard may show more precise

➢ results. As the concerned geometry is there dimensional in real world. In the case of Heat Transfer simulation with 3-D geometry can reduce the impact of edge effect. Moreover, 3-D simulations can account for a variety of material properties which may not be possible in case of 2-D simulations

References

[1] S. S. K. Dr. Hansa Jeswani, "A Review of Radioactive Waste Management," in *International Conference on Technologies for Sustainable Development (ICTSD-2015),*, Mumbai, 2015.

[2] U. D. O. ENERGY, RADIOACTIVE WASTE MANAGEMENT MANUAL, 1999.

[3] I. A. E. A. Waste Technology Section, IAEA-TECDOC-1515, Development of specification for radioactive waste packages, Vienna: IAEA, 2006.

[4] J. Walsh, Review of DOE Planned Change Request for Shielded Containers for Remote-Handled Transuranic Waste,, Vienna, Virginia: S. Cohen & Associates, 2010.

[5] ". 3. (. S. C. H. T. 1. S. H. C. S. F. U. M. Bahrami, ""ENSC 388 (F09) Steady Conduction Heat Transfer 1 Steady Heat Conduction,," Simon Fraser University.

[6] COMSOL, COMSOL Multiphysics Reference Manual, www.comsol.com.

[7] COMSOL, Heat Transfer Module Users Guide, www.comsol.com.

[8] T. G. S. F. T. H. S. C. A. A. E. d. A. Normando P. B. Souto, "Steady-state heat conduction in a nuclear fuel pin:analytical and numerical analysis," in *Semana Nacional de Engenharia Nuclear e da Energia e Ciências das Radiações – VI SENCIR*, Belo Horizonte, 2022.

[9] F. J. P. J. G. F. B. N. G. Alfredo Iranzo, "Cooling Process Analysis of a 5-Drum System for Radioactive Waste Processing," *Energies,* 2018.

NOMENCLATURE:
➢ K: Thermal Conductivity of material
➢ A: Area,
➢ $Q^{.}_{cond}$: amount of heat transfers due to conduction
➢ dT/dx: Temperature Gradient
➢ ρ: density of material (SI unit: kg/m^3)
➢ Cp: specific heat capacity at constant stress (SI unit: $J/(kg·K)$
➢ T: absolute temperature (SI unit: K)
➢ u_{trans}: velocity vector of translational motion (SI unit: m/s)
➢ Q: heat flux by conduction (SI unit: W/m^2)
➢ q_r: heat flux by radiation (SI unit: W/m^2)
➢ α: the coefficient of thermal expansion (SI unit: 1/K)
➢ S: second Piola-Kirchhoff stress tensor (SI unit: Pa)
➢ Q: contain additional heat sources (SI unit: W/m^3)