Modeling Shielding for Nuclear fission Powered Aircrafts

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Abstract

Global carbon emissions are increasing every year, and we need clean energy alternatives. This research focuses on modeling a simplified shielding structure for nuclear fission powered aircraft using OpenMC, a simulation software used to simulate neutron transport in nuclear reactors . A Constructive Solid Geometry (CSG) spherical model was used to represent the shielding, and the reactor structure, making high-level assumptions about the model.Nuclear fission-powered aircrafts, demonstrated in the 1950s were used for propulsion, but this was put to a stop due to the nonproliferation and global security concerns. Furthermore, there was not enough shielding to protect the passengers and avionics from harmful radiations, and the government no longer had a need for these aircrafts so they defunded this field. This is important because as we approach the future, CO2 emission rates increase year by year, ultimately worsening climate change. New methods of clean energy and sustainability must be discovered and one method would be through using nuclear reactors however these reactors do produce radioactive waste. However, due to recent technologies that can reprocess the radioactive waste, which is recycled and produced into nuclear fuel, making fission powered aircrafts a sustainable way to travel. Additionally it is an efficient form of travel as nuclear fuel can produce a significant amount of energy. While this is a efficient and cleaner method of air travel, there are safety measures that must be taken to ensure that this type of reactor propulsion technology is safe to operate without portraying any risks to those onboard or any damage to avionics. This paper models a simple geometry using OpenMC, using uranium-238 as our reactor fuel source, and polyethylene and lead as our shielding material. The goal from testing in OpenMC is to assess the effectiveness of shielding to minimize radiation being emitted from the reactor.

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I. Historical Introduction to Fission-Powered Planes

The concept of nuclear fission-powered planes date all the way back to the 1950s with the first idea coming up in 1946 to develop a nuclear fission aircraft. There were two projects back then, the first project had focused on developing a civilian aircraft that can be powered by nuclear fission.The other project was known as Project Pluto, which focused on making a nuclear powered missile. This was a very important turning point in the field of energy as advanced developments were being made in both civilian and military crafts. [1]

The primary focus would be on the nuclear fission power plane however. In an document from NASA explaining how these nuclear reactors were able to power planes, air first entered the engine through the compressor, it then went to the reactor, acting as a coolant, in which the air got heated to relatively high temperatures and then got exhausted from the nozzle behind, in return providing thrust. This system was known as a direct cycle configuration, which was used in nuclear ramjets. It was first tested in 1956 at Idaho National Laboratory, using General Electric J47 turbojet engine which was modified to be compatible with a reactor. The unclassified documents by National Aeronautics and Space Administration (NASA), explains as to why they had chosen Beryllium Oxide as the material for the core, due to its high heat resistance, temperatures, light weight, which would act as a good moderator[1]

Shielding is used in reactors to weaken and block out any harmful radiation that can pose a risk on humans and avionic systems, as a result the aircraft required effective shielding but also being lightweight. Hence the shield was divided between the crew area, and the reactor because scattering the shielding was more effective in blocking out radiation as it can be more optimized to place where shielding is the most needed, and helps minimize the weight too, & distribution of weight.[2]

A notable development in fission-powered aircraft was explored in molten salt reactors (MSRs). Its main goal was to create a reactor that can be used in aircraft for propulsion. Unlike traditional reactors which use solid fuel, MSRs utilize liquid fuel which typically consists of molten salts and fissile material. This offers a potential to reduce the reactor size and weight. As the molten salts have a higher heat capacity compared to sodium, the size of the pumps and piping will be substantially smaller. This concept was tested in the early 1960s by the Oak Ridge National Laboratory. [8] MSRs can recycle nuclear fuel by reusing actinides, a group of elements with atomic numbers from 89-103 that are radioactive which have the ability to undergo fission. This in turn would help minimize the radioactive waste. [9]

As climate change worsens, it’s crucial to explore greener solutions for aircraft applications. While nuclear-powered aircraft face safety concerns compared to electric powered aircraft, innovative approaches must be considered to help make a positive impact in the world.

II. Technical Background and Design Considerations

Nuclear fission is the process in which the nucleus of an atom is split apart into two nuclei along with the release of a significant amount of energy which is in the form of heat and radiation. When the nucleus splits it produces additional neutrons and heat. The heat can be then used to produce electricity, in terms of airplanes it can be used to generate propulsion.[5]

The reaction is self-sustaining because the neutrons that are released during fission are used towards fission, thus leading to chain reactions. [3]

The core of the reactor typically contains nuclear fuels, such as uranium, which are surrounded by a moderator and control rods. Control rods are used for controlling the power of the reactor. It can prevent neutrons from causing more reactions by absorbing them. Slower neutrons are more likely to cause fission because they have higher fission probability known as cross section (the probability that a reaction will occur). Hence when fast moving neutrons collide with a moderator it loses its speed and it's more probable to sustain the chain reaction Since the reactor reaches up to high temperatures around 2000 degrees fahrenheit, the components must be cooled down efficiently These efficient cooling systems and control mechanisms are essential for the safe operations of nuclear powered flights ensuring the safety of those onboard. [4]

III. Radiological Considerations:

In nuclear reactors shielding is a vital component to ensure the safety of humans, and any electronic components such as avionics in aircrafts. As reactors generate harmful radiation it poses a threat. Hence shielding is a component that must be taken the most seriously when it comes to reactors to ensure safety of everyone especially when on aircrafts as radiation can cause damage to avionics.

One particular element however, that is particularly strong in blocking out all these levels of radiation, is hydrogen. When neutrons collide with the hydrogen nuclei it ends up experiencing a loss in energy due to the proton's low mass it absorbs a lot of the energy from the neutron, which is why hydrogen is a good material for shielding as well as moderating. However hydrogen is not available in a pure solid form; it is found with polymers such as polyethylene which acts as a very effective shielding material. [6]

In nuclear reactors shielding, two primary materials: polyethylene and lead due to its properties of being able to prevent radiation from penetrating through When high energy neutrons collide with hydrogen nuclei they lose energy through elastic scattering, this reduction in energy helps in preventing any neutron radiation from penetrating through. Lead is another material which is highly effective for shielding due to its high density making it effective for absorbing gamma rays. Its high atomic number increases the odds of interacting with radiation effectively reducing their speed and scattering them, preventing it from breaking through. Benefits of using these materials as shielding will prevent any radiation from penetrating through, ensuring the safety of passengers and avionic equipment. [10]

IV. Modeling and Simulations:

A. Introduction to OpenMC:

OpenMC is a software simulation developed by members of the Computational Reactor Physics Group at Massachusetts Institute of Technology that allows users to perform simulations of neutron photon transport in a 3-D modeled geometry. This software allows users to model the geometry of reactor components, such as fuel assemblies, control rods, or shielding. This software is useful as it allows users to have an understanding of the behavior of neutrons. OpenMC enables collection of data on various aspects, such as measuring neutron flux which can help evaluate the effectiveness of shielding.This data is essential for ensuring reactors are fully optimized and fully safe to use, and improving efficiency in nuclear reactors. [7]

In this simulation the number of particles was set to 15,000 for each batch, as well as ten batches were selected to ensure more reliable results as there are multiple batches with a lot of particles. However, a higher number of particles could lead to higher processing times for outputting results which is why 15,000 particles and 10 batches were selected. Neutron energy was selected 2 Mev (2 million electron volts) because this energy level is suitable for facilitating fission reactions. The neutron source is located at the center of the reactor (reactor core) as that's where the fission reaction gets initiated. Photon transport is turned on in this reaction because gamma rays are a byproduct of a nuclear reaction and it's important to evaluate their effects on the shielding materials.

B. Modeling Assumptions / Simplified Spherical Universe Setup:

This simulation will provide data on neutron flux, radiation, hitting the shielding to determine how effective it will be. By analyzing how neutrons/radiation interacts with the shielding the effectiveness can be calculated. The reactor core will be uranium-238 due to its high probability for fission occurring, and sustaining a chain reaction. The geometry is based on spherical layers with materials assigned with specific dimensions. In this simulation the reactor geometry would consist of five spherical regions along with the following radiuses:

- Fuel Cell: 220 cm
- Fuel outer Wall: 250 cm
- Polyethylene wall: 300 cm
- Final wall surface: 350 cm
- Outer Boundary (Lead): 380 cm

The primary shielding regions polyethylene wall and final wall surface were chosen to have a 50 cm thick radius due to having a thicker shielding region proves to be more effective. Additionally due to these properties materials having a 50 cm radius would ensure a significant reduction & absorption of neutrons. However, space and weight must be concerned as these will be used on aircraft, ensuring that these sizes would not add too much weight and take up space but also make sure it can provide effective shielding is very crucial.

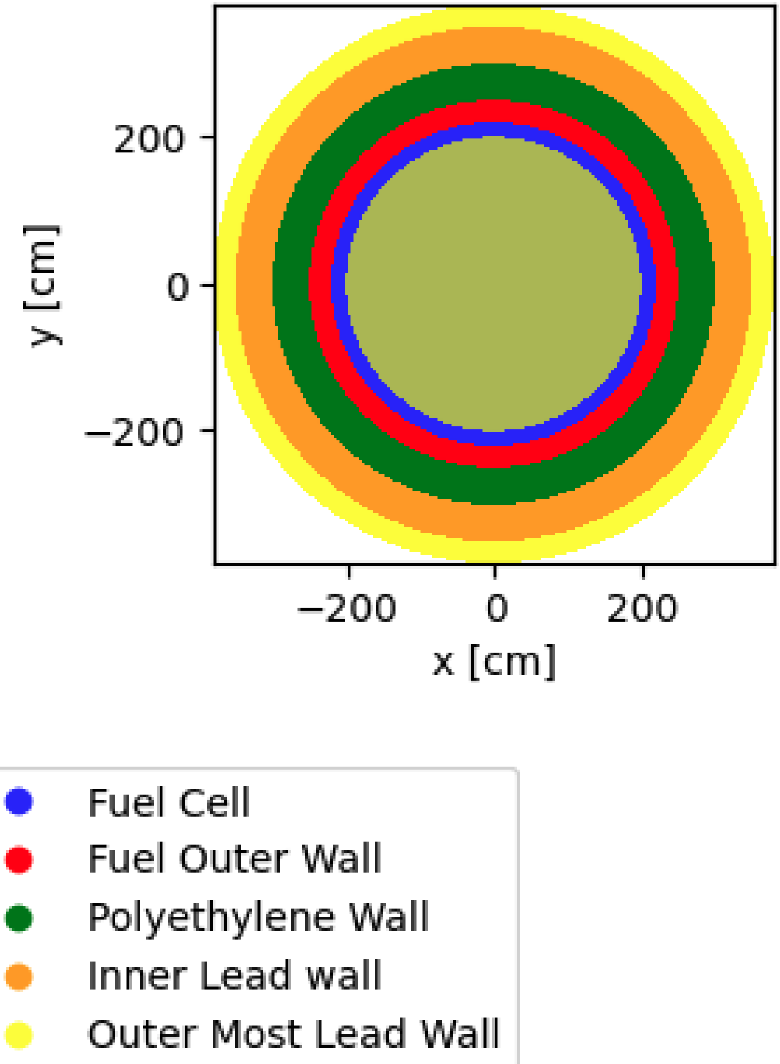

Figure 1: Visual geometry representation of the reactor structure with each color representing a different layer represented in the chart.This structure will be utilized for testing in the simulation performed.

This model assumes a simplified reactor shape, a sphere, rather than a complex shape which is normally found in actual reactors. The volume of this reactor is substantially smaller as this is a scaled down geometry of an actual reactor. Additionally, the simulation assumes the materials being tested are in perfect conditions, ignoring wear and tear, as it can affect the materials performance in blocking neutron radiation from penetrating through. This in turn can increase radiation exposure risk, making it harmful, as well as impacting the reactor's ability to maintain optimal temperatures.

Materials used in simulation:

1. Uranium-238 (Fuel)
    - Selected as the fuel as it can absorb neutrons and convert it into fissile material plutonium-239, which is crucial for sustaining a chain reaction. This material was assigned to the fuel cell.
2. Steel
    - Steel was selected for structural support due to its properties, steel is assigned to the fuel outer wall cell.
3. Polyethylene
    - Polyethylene was selected for shielding as it has a high cross section it allows to slow neutrons by elastic scattering. This property prevents neurons from penetrating past this boundary.
4. Lead
    - Lead was chosen for the outer two most layers due to its excellent properties for radiation shielding, its high density makes it highly effective for absorbing radiation.

Two lead boundaries were chosen to enhance the effectiveness of shielding, as this reactor structure would be used on aircrafts, ensuring minimal radiation leaks is crucial for the safety. The first layer serves as a primary barrier to absorb any radiation such as gamma rays. The outer layer serves as a secondary barrier ensuring any radiation that by chance penetrates the first layer can be stopped. Ensuring as much safety as possible for those onboard and the equipment.

V. Results

Before the actual results are obtained from the simulation, OpenMC first provides results in the units expressed as neutrons per centimeter per source neutron (n-cm/src). However, in order to evaluate and understand the effectiveness of shielding provided by different materials it is necessary to convert these units into neutron flux. Which is typically in the units of neutrons per square centimeter per second:

$$n/cm^2 - s$$

which requires conversion. To convert, the volume of the cell, reactor power, and the energy of each fission reaction are required. Through this the source strength is calculated by dividing energy of each fission reaction by the reactor power. Afterwards, neutron flux can be calculated by dividing the volume of the cell by the flux value outputted by the simulation and multiplying this by the source strength, which will then provide neutron flux.

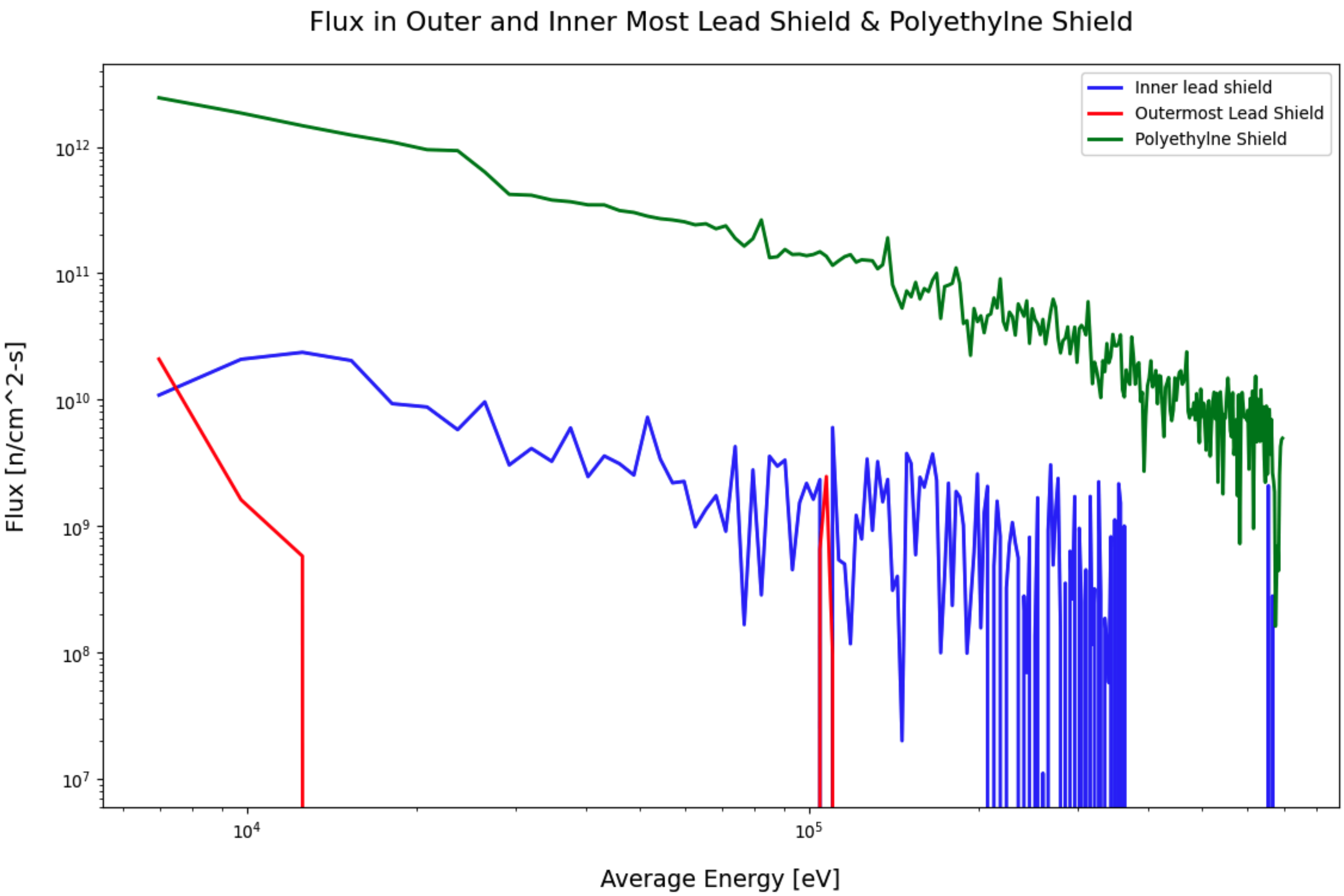

Figure 2: Shows neutron flux distribution of three different materials after the neutrons pass through different shielding materials. Illustrating how each shield type reduces neutron flux

Neutron flux is an important concept in nuclear physics especially in reactor design for shielding as it refers to the number of neutrons that travel through a unit area.
This is typically measured in neutrons per square centimeters per second (n/cm^2-s). Using neutron flux is crucial in understanding the interaction of neutrons with the materials in the reactor, such as shielding. This simulation assesses the effectiveness of shielding structure by analyzing the neutron flux in the last 3 outer regions. The results of the last three regions are depicted in **Figure 2** above. The analysis of the data provided above focuses on how well the shielding material reduced neutron flux as neutrons were passing through each successive layer.

The simulation data revealed that the neutron flux within the polyethylene, the average energy of neutrons had decreased significantly as they passed through the polyethylene layer. This result is expected due to the properties in hydrogen atoms in properties making it effective at slowing down and scattering neutrons. The lead shielding consists of two layers, the first one to absorb radiation and the second one as a safety to capture any radiation that may have penetrated through the first lead layer. The energy of the neutron flux may not be as much of a significant drop as it was in polyethylene. However, the main purpose of lead is to absorb any radiation and since the neutrons had already been slowed down by the polyethylene layer. Therefore, any radiation that makes it in this layer will be absorbed or scattered away. As it can be seen the flux is significantly less in this layer, proving the effectiveness of the shielding. The last layer of this simulation acts to capture any neutrons that make it through the preceding layers. This can be seen in the graph, which shows that the neutron flux is at its lowest point in the outermost region. At energy level 10^4 and 10^5 the cross section for lead is high which is why in **figure 2** the flux is low in the outermost layer.[7] The drop in neutron flux is crucial as it demonstrates the lead's effectiveness in capturing any remaining neutrons. This layer was made to ensure that the minimal amount of radiation escapes beyond the shielding.

The drop in neutron flux in each subsequent layer is essential and should be expected as it demonstrates the materials ability to prevent minimal radiation from escaping through. While this data may be theoretical it provides an idea with expected physical behavior of neutrons giving a sense of accuracy that may occur on prototype models.

VI.Conclusions and Limitations

The model developed simulating nuclear fission in aircraft does demonstrate the effectiveness of shielding designs in reducing the radiation. However, the model does have imitations, simplifications, and assumptions which may not fully reflect the complexities of real world conditions. Mainly the model assumes a scaled spherical geometry for simplicity, however given in the real world a reactor is not a sphere but a complex shape and much larger. Along with the volume calculated in the simulation would be much different compared to real life which would result in different neutron flux values. Additionally the material interaction between the neutrons does not fully capture real world challenges posed by prolonged radiation exposure such as material degradation, or even corrosion.

When considering the realistic implementation of nuclear fission reactors in aircrafts, numerous challenges arise. With the major concern being the reactor's weight because for the plane to be able to support passengers, cargo, the reactor has to be a certain weight in order to fly which would be a challenge as reactors are big, and these reactors would need to be scaled down in order to fit in an aircraft. The shielding materials as well, crucial for safety, add weight too which would require advanced engineering to maintain a balance ensuring everything fits in together. Safety and regulatory hurdles also are a risk, as a reactor malfunction may cause the plane itself to lose engine power, or radiation release into the cabin would pose a huge threat to people. Hence strict guidelines would need to be developed addressing emergency protocols.

VII. Future Work:

Advancing in fission-powered aircraft presents both significant opportunities and challenges. One of the main advantages is its potential to reduce carbon emissions compared to traditional planes, making them a viable option for addressing the impact aviation has on the environment. Nuclear fission produces no greenhouse gasses that offer a cleaner alternative to help mitigate climate change as we advance into the future. Additionally nuclear flight does allow for longer flight ranges without the need for refueling, allowing for long haul flights. Nuclear fission offers a new pathway to long term sustainability in aviation by reducing carbon footprint.

However, there are challenges associated with this technology. Especially radiation which is a safety concern, as protecting passengers, crew, and avionics from harmful exposure to radiation is crucial to ensure a safe flight. This requires advancing shielding material which still has to be further studied into and developed. Additionally nuclear reactors do produce nuclear waste which is a challenge because it must be handled with proper precautions to avoid any contamination with the environment. Regulations may pose a hurdle as governments would need to establish safety protocols before these aircrafts can enter into service. Public perception may pose a significant barrier as well because some people may be hesitant on flying on a nuclear powered plane due to its dangers. Hence this topic hasn't been widely pursued due to safety concerns and challenges. The aviation industry has focused widely on safer air travel more than climate concerns. While we may have diesel powered engines it emits a lot of greenhouse emissions. Safer solutions like electric planes do exist, but the batteries required to power add significant weight relative to the energy they provide, making them unsuitable for long haul flights. As we move towards the future, there is an urgent need to adopt environmentally safe alternatives that can help attain sustainability and reduce emissions.

Approaching the future there are potential for breakthroughs that can make fission powered aircraft a viable solution. Advances in shielding materials & structures, minimizing the size of reactors as much as possible, and advanced safety technology could overcome current limitations. This technology could also benefit space exploration due to its ability to achieve high speeds. While these advances won't be made right away, starting as soon as possible is crucial as it can pave the path for future breakthroughs, making a meaningful environmental impact.

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