Adding Boron Compounds to Increase the Neutron Shielding Properties of Materials

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A risk of the nuclear industry is radiation, specifically neutron radiation. In order to maintain a safe work space for workers, better shielding is being developed. Current shielding methods are examined and boron is looked at as a potential material for shielding. Boron, having a large cross section, is combined with other materials in order to obtain the desired material properties to have shielding that can be applicable in different situations. New materials like resins and metals are being created by mixing Boron and other materials to suit the needs different applications within the nuclear industry. Four of these new materials are examined and shown how they are an improvement to current shielding methods used in nuclear reactors. It is concluded that adding Boron to materials is an effective way at increasing the neutron shielding properties. Adding Boron however can cause negative effects on properties such as resistance to high temperatures and the structural properties of materials. By obtaining a balance between these two problems, an ideal neutron shield could be produced to increase the safety of the Nuclear industry.

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I. INTRODUCTION

Radiation exposure is a drawback when working in the nuclear industry or with radioactive material, however shielding has allowed for a safe work environment for Nuclear Energy Workers (NEWs). A more efficient neutron shield would allow for an increased safety in nuclear workers, while reducing the volume of shielding around neutron sources and increasing the flexibility of shielding material. Currently, the main material used for Neutron shielding is Concrete and Lucite (wax). Once these materials are set, there is no practical way to increase the shielding except to add more material, which will reduce usable work spaces around neutron sources in reactors and labs. However, if the neutron shielding when initially placed is not effective or degrades over time, and additional shielding is not added, the risk is increased for NEWs who are working with the neutron source or reactor. A possible method to increasing the stopping power of neutron shielding material is to add a compound of boron. Boron has a large cross section and therefore is a good material for shielding. By adding a boron compound to different materials, the neutron attenuation properties of the material are increased while material properties of the original material can still be utilized.

II. THEORY

Neutrons interacting with matter can be expressed by Eq. (1). $I(x)$ is the intensity of radiation that passed through a material of thickness x, I_o is the initial neutron intensity and Σ is the macroscopic cross section of the material.

$$I(x) = I_o e^{-\Sigma x} \tag{1}$$

The total macroscopic cross section used in this equation is the sum of all of the different neutron interactions with material like scattering, absorption and fission. The macroscopic cross section defined as: $\Sigma = N\sigma$, where σ is the microscopic cross section, which is the cross sectional area that allows neutrons to interact. The microscopic cross section is measured in units of barns or units of area. The higher the cross section of a material, the more the neutron beam is attenuated. N is the density of nuclei in a unit volume. The total macroscopic cross section used in this equation is the sum of all of the different neutron interactions with particles like scattering, absorption, and fission. These interactions are important when selecting a neutron absorbing material as the byproducts of these interactions include other forms of radiation. The total cross section of a atom is dependent on the neutron energy so often an element will be a good thermal neutron absorber, however will not be able to absorb fast neutrons.

When calculating the theoretical cross section of a mixture of two or more elements, the sum of the concentration of each of elements multiplied by the microscopic cross section of the elements.

$$\Sigma = \sum_i \sigma_i N_i \tag{2}$$

Eq. (2) is important as different materials are mixed together to obtain a balance of neutron attenuation properties with other material properties. Other forms of radiation like gamma, alpha and beta radiation can easily be shielded by using lead, but lead shielding does not as well for Neutrons. Neutrons are difficult to shield and detect because the neutrons have an overall neutral charge

TABLE I. Contained in this table is a summary of the data collected from Engineering Physics 3D03 Lab 3: Neutron Material Attenuation, performed in Feburary of 2016.

Material	Thickness (cm)	Counts	Ratio of Counts through the Material/cm
Unattenuated	0	383440	1.0
Steel	2.54	18099	0.0472
Lead	2.54	264027	0.689
Lucite	2.54	531	0.00138
Heavy Water	2.54[a]	85533	0.223
Light Water	2.54[a]	420	0.00110
Boron Rubber	2.40	76	0.000198

[a] The width of the container that holds the water is 0.34 cm, however, this width was neglected for the purposes of the experiment performed

and when absorbed by other materials, other forms of radiation are released. This is why shielding for neutron radiation must be engineered.

A. Boron

In nuclear power plants, boron is used in control rods due to it's high absorption cross section. When the reactivity of the reactor becomes too high, the control rods are dropped into the reactor and the boron rods absorb the neutrons, lowering the reactivity of the reactor, causing it to shutdown. boron (^{10}B) is an ideal choice for shielding materials as it has a high cross section across all energies of neutrons. Boron also does not produce any additional radiation with interactions with neutrons. The reaction products are stable isotopes in the form of Lithium and Helium.

Results where gathered about boron rubber and other types of material and how well those materials are able to attenuate neutrons, Tables I contains a sample of the materials measured. The experiment was performed at the McMaster Nuclear Reactor (MNR) in Hamilton Ontario. The materials where placed in front of a neutron beamport and a detector was placed on the other side of the material. The rubber containing the boron performed much better than the other materials that where used in the lab, even the water. This suggest that it is not just the hydrogen (which is very effective at shielding neutrons) that contributes to this effect.

The second part of the same lab performed looked at several different materials and how well they performed at different thickness at attenuating neutrons. The original purpose of this data was to find the cross sections of each material, however, this data is very effective at showing that current building materials, like Aluminum and Iron are not very good at shielding Neutrons like Water and Lucite. Unfortunately, due to the properties of water and Lucite, they would not meet the requirements to be neutron shielding even though Lucite is used as additional shielding in the MNR currently.

B. Current Radiation Shielding

The standard to today is to track the exposure of individuals workers to radiation. The Canadian Nuclear Safety Commission (CNSC) sets limits on the amount of radiation exposure acceptable for NEWs. The upper limits that a worker can be exposed to is 50 mSv/year or 100 mSv over five years. Additionally, there are equivalent does limits for different body parts of the body. The main goal is to keep this does as low as reasonabley possible. This involves decreasing the size of the source, decreasing the amount of time near the source, increasing the distance from the source and shielding the source. Shielding the source is the main focus to improve radiation safety as often the other options to decrease radiation is not possible.

Currently, in Candu reactors, shielding is obtained by placing the fuel pellets in a metal sheath of a fuel bundle which will stop Alpha and Beta radiation. The fuel bundles are then placed in a Zirconium tube and placed in the reactors stainless steel vessel. The reactor vessel is located within a concrete vault and the vault is enclosed in the concrete reactor building. The reactor is then remotely controlled and refueled. This is a system that keeps workers in a Candu plant safe from any radiation from the rods, however the main issue in this case is dealing with the large volume of material. Also, while the main rods themselves are shielded, areas such as plumbing into and out of the core may allow for neutron radiation to escape. In reactors like the MNR, which main purpose is producing neutrons for research, imaging and medical isotopes, the neutron beams are shielded by mainly concrete. This can cause limited workspace around the beamports that could be enhanced by more efficient shielding.

III. DEVELOPMENT OF SHIELDING WITH BORON

There have been several new neutron materials made in recent years by adding Boron or Boron compounds to different materials. Each new material has been designed to improve the ability to attenuate neutrons while

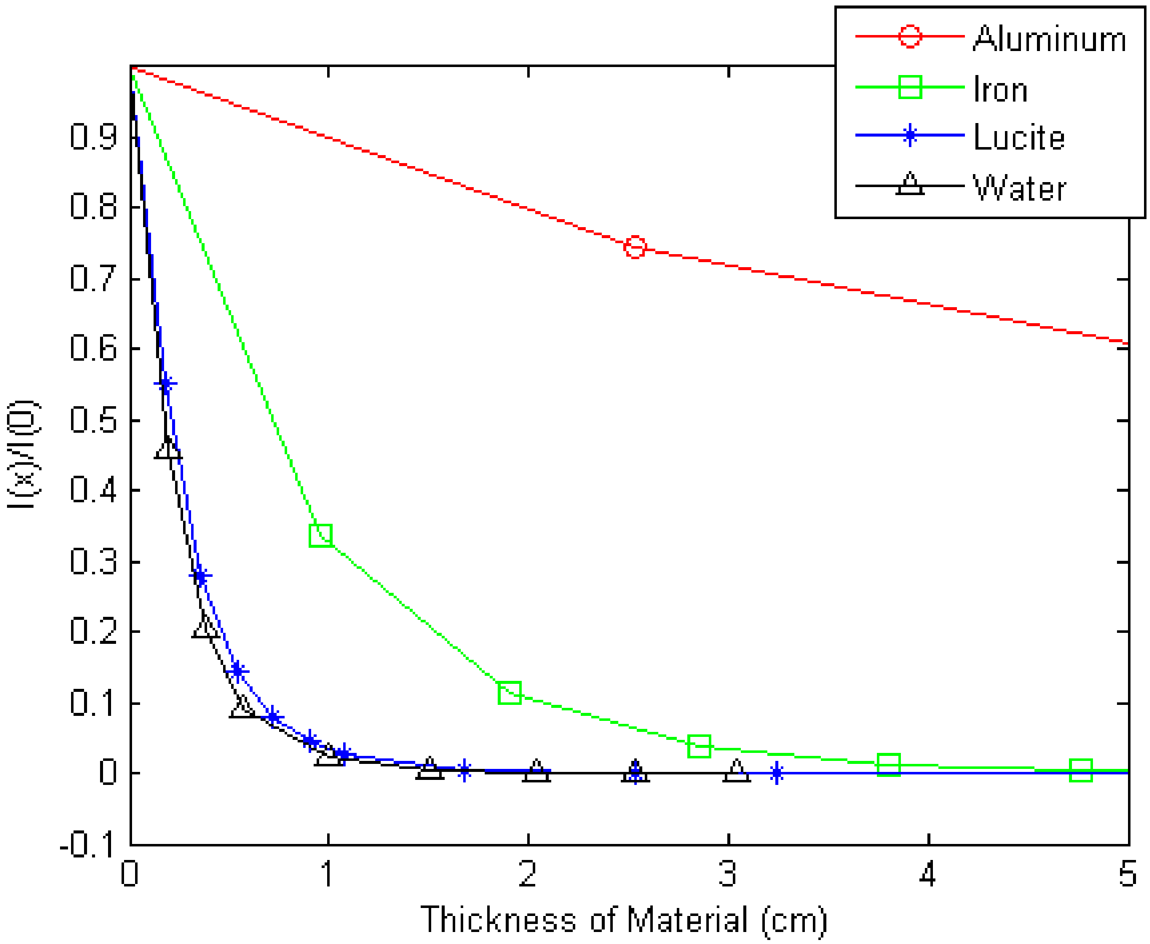

FIG. 1. This figure shows sample materials and the neutron beam is attenuated as a function of thickness of the shielding material.

being structurally strong and heat resistant materials. The materials below may also be made through different processes.

A. Boron Resin

In multiple types of reactors, an area that neutron radiation leaks from a reactor is from plumbing leading to and from the core. The shielding also needs to be heat resistant as using just polyethylene will start to deform at 120^0C. Another drawback of just using polyethylene is that the neutrons interact with the hydrogen and produce gamma radiation. Adding concrete around the piping is not an option, as it is not as good of a neutron attenuator as polyethylene. One of these types of resins is KRAFTON-HB4. This is an epoxy based resin with boron added. It is designed to reduce the amount of gamma radiation produced by the shielding. Another resin developed by scientist at the Japan Atomic Energy Agency starts to harden between 5 and 35^0C. This means is can easily be shaped and applied where necessary on site. The resin is also heat resistant up to 200^0C. The resin contains around 3.4% of boron and outperforms polyethylene in neutron attenuation.

B. Boron Rubber

Ethylene Propylene Diene Termonomer (EPDM) is a rubber that is already used in the Nuclear industry because of it's high hydrogen content. A material was developed in Turkey as neutron shielding by combining Boric Acid and EPDM. Boric Acid was chosen as it is considered to be a non-toxic substance and environmentally friendly. Varying amounts of boric acid was added to the EPBM rubber. Adding wt. 20% Boric acid created a material that could reduce the neutron beam to under 20% of the initial beam intensity. The mixture maintains structural properties well at low temperatures, however at a concentration of 20% Boric acid, the structural integrity of the material starts to fail at high temperatures as compared to 0% Boric acid.

C. Boron Alloyed Stainless Steel

Stainless steel with boron alloys has applications in the transportation and storage of nuclear waste. In order to transport spent fuel rods safely, the shielding material needs to be non-corrosive as well as when in storage, the container must be able to withstand corrosion indefinitely. One issue that occurs when constructing boron alloyed steel is that often the born will not be evenly distributed within the steel. This will cause issues with some areas of the shielding having a greater resultant neutron beam than other areas of the shielding. By developing a microstucture that better distributes the boron, boron alloyed stainless steel would be a favourable shielding material due to it's non corrosive properties.

D. Boron Sandwiched Between Aluminum Plates

Mixing a boron compound into another substance often sacrifices some of the material properties like flexibility or strength of the materials. One possible solution is to sandwich Boron in between two layers of a material. An example of this is Boron Carbide (B_4C) is mixed Aluminum and then the mixture is placed in between two Aluminum plates. This allows the strength of the Aluminum to be maintained while maintain the strength of the Aluminum. This material was made by scientist in Korea by first creating the inner core of Al and 10-40 wt.%B_4C. The core is pressed in a hot isostatic press and then the inner core is placed in between two Al plates. The resultant material with a B_4C concentration of 40% wt. was able to reduce the neutron beam to under 20% of the initial beam intensity in 2 mm of material. Within 3mm a minimal amount of the neutron beam was detectable. As neutron attenuator, this material could save a large amount of space and improve safety of workers at the same time as this material outperforms other materials. This can be seen by comparing it to Lucite in figure 1. Over 1.5 cm of material is needed for the same effect.

IV. CONCLUSION

From looking at current research in the area, it can be concluded that adding Boron and Boron compounds to current materials a beneficial way to improve neutron shielding materials. By including boron into a material, it increases the overall macroscopic cross section of the material and neutrons are attenuated by the material more efficiently. The structure properties such as resistance to high temperatures, strength and flexibility can be taken advantage of when selecting the materials to mix the Boron with creating a new and more desirable building or shielding material to use in the Nuclear industry to improve safety and to potentially make better use of space in the Nuclear Facility or labs that have neutron sources.

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