Development of novel jute based composite material for radiation shielding applications

Md. Farhan Hasan, Nazmul Ahasan, Achiya Khanam, Md Akhlak Bin Aziz
Department of Nuclear Science and Engineering,Military Institute of Science and Technology.
Mirpur Cantonment, Dhaka,Bangladesh.

Abstract—Polymer composites have become attractive candidates for developing materials that can be designed to effectively attenuate photon or particle radiation. In this work, polymer composites reinforced with easily available materials have been developed for their use in radiation shielding applications. Sample 1 has a density of 13.412 g/cm^3 with 2.605 mm thickness containing polyethylene, boric acid, lead and jute. Sample 2 with a density of 2.997 g/cm^3 and 3.875 mm thickness was developed adding silica with sample 1. For the first sample, boric acid and polyethylene was mixed together. Lead sheets were used as outer layers with jute slice in the middle. For the second sample, silica was added with the boundary material of previous sample.Heat press was employed for developing the composite as it provides great control and consistency of temperature, pressure and timing. Finally, Monte Carlo Particle code was utilized for testing the shielding materials.

Index Terms—Compositematerial, Jute,Low cost , Low weight,Polymer, MCNP simulation, Radiation shielding

◆

1 INTRODUCTION

Hydrogen is the most effective material for slowing down neutrons. Slow neutrons can then be absorbed by an isotope exhibiting high affinity for adsorbing moderated neutrons such as boron [1]. As a result, Polymer-based lightweight composite materials are now widely used by the radiation protection industry to prevent human being from harmful radiation.Hydrogen-rich materials like jute are also used to shield against neutrons.

Effective shielding material to reduce the external radiation hazard implements when reducing the time of exposure or increasing the distance from source may not be possible. The proper material dependson the type of radiation and its overall energy. Most radiation shielding refers to the protection of human beings alone, that involves ionizing radiation refers to human contact. [2] It is extremely important to use specific types of shielding materials against the different types of radiation. [3]Exposure to radiation doses within the occupational limits produce no apparent indications of exposure. As a result, we must employ shielding materials to protect radiation. [4] Using epoxy is advantageous as the base material in composite fabrication. [5] The aim of this study is to design a shielding system that will reduce the nominal radiation dose received from the radioactive source to human body and radiation-sensitive instrumentation to as reasonably low a level as possible.[6] To protect the reactor against transients from incoming radiation, from natural forces (i.e. temperature swings and dust storms) and from corrosion due to energetic particle bombardment. [7]

2 METHODOLOGY

In this work we two samples were prepared for making composite materials. First sample consisted of polyethylene, boric acid, lead and jute.Firstly, jute was covered by the lead sheets and then boric acid and polythene was used by layer. Second Sample consists of polyethylene, boric acid, lead, jute and silica which arrangement is same as previous sample. In addition, silica was mixed with polythene and creating a layer by heat press machine. A heat press machine combines heat with pressure and is specially designed to imprint a design or graphic to a substrate. We also chose two “clamshell version” heat press machine for making the shielding materials. Multi-function heat pumps both heating and cooling offer many potential advantages over conventional residential mechanical design strategies. The materials were then tested using Monte Carlo n-particle code.

3 REVIEW OF NEUTRON SHIELDING MATERIALS

Neutrons can pass through an electron cloud to interact directly with the atomic nucleus and transfer most of itsenergy. As the human body has a high water content, there is a high density of hydrogen atoms present. The mass of the hydrogen nucleus is close to that of the neutron. Therefore, exposure to free neutrons can be hazardous, since the interaction of neutrons with molecules in the body can cause disruption to molecules and atoms as well as cause reactions which give rise to other forms of secondary radiation [8],[9].

Neutron shielding requires materials with an atomic mass close to that of the neutron. Considering the properties of neutrons the best shielding materials are uncharged with an atomic mass close to that neutron.The energy of scattered neutrons is given by the following equation:

$$E_s = \left(\frac{M-m_n}{M+m_n}\right)^2 E_i \qquad (1)$$

$$E_s = \left(\frac{A-1}{A+1}\right)^2 E_i \qquad (2)$$

Where A is the atomic mass number,$E_s$is the energy of scattered neutron and Ei is the energy of incident neutron[10].

Materials made of polyethylene or epoxy resin mixed with boron compound are widely used as neutron shielding materials, but they usually exhibit sizable weight and volume, which results in low-flexibility performances [11]. The most effective neutron shielding material can be obtained by appropriately mixing high hydrogen-content materials, heavy element and thermal neutron absorbers. High hydrogen-content materials can undergo elasticscattering with fast and intermediate-energy neutrons. Heavy elements can undergo inelastic scattering with fast neutrons and can attenuate the secondary gamma ray emission. Finally, neutron absorbers function to greatly reduce the number of thermal neutrons.

3.1.1 Polyethylene Based Shielding

Polyethylene is relatively high hydrogen content material which has been used to provide a neutron shield around radioactive areas. Also, in some instances boron or compounds incorporated in the polyethylene. Polyethylene, with or without boron has been used only in sheet or slab form. Such sheets or slabs are not completely suitable for use when it is necessary to shield reactor parts.[12]Borated polyethylene is one of the most convenient shielding materials. It is easy to work with, fabricate, and install, wide range of shielding applications making it ideal for a wide range of shielding application.

4 REVIEW OF GAMMA SHIELDING MATERIALS

Shielding is a process to reduce the intensity of gamma radiation.The effectiveness of shield depends upon the energy of the radiation, thickness and type of the shielding material. Most materials absorb the energy of gamma rays to some extent. The extent of attenuation which means the reduction of power or intensity depends on the density and thickness of the shielding material.
The attenuation of gamma radiation can be then described by the following equation.

$I=I_0.e\text{-}\mu x$ (3)

Where, I is intensity after attenuation, Io is incident intensity, μ is the linear attenuation coefficient (cm^{-1}) and physical thickness of absorber (cm).

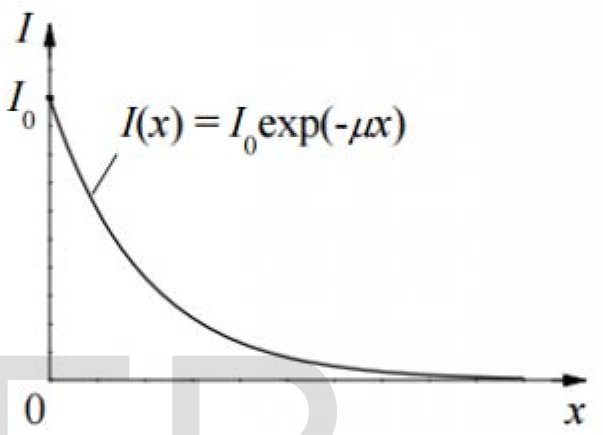

Figure 1: Dependence of gamma radiation intensity on absorber thickness. [13]

4.1 Lead as gamma shielding:

Lead is widely used as a gamma shield. Major advantage of lead shield is in its compactness due to its higher density. High energy gamma radiation will not be wholly blocked by a foot of lead, while lower energy levels can be safely blocked by 3/16 inch or less of lead. [14] The currently used portable shield materials containing lead are: Lead Bricks, Leaded Glass, Sheet and Bricks, Leaded Plastics Lead Clad Building Material, Lead Laminated Panels, Lead Shot,Lead Sheet and Foil.[15] Lead shields are frequently used where space is limited or where only a small area of absorber is required.[16] Because of its high ductility, lead cannot be machined easily or hold a given shape unless supported by a rigid material.

5 SELECTION OF MATERIALS FOR BOTH NEUTRON AND GAMMA RADIATION SHIELDING

In this experiment we have developed two samples of composite materials for radiation shielding.

Sample 1 consists of polyethylene, boric acid, lead and jute. Sample 2 consists of polyethylene, boric acid, lead, jute and silica.

Some highlights of the chosen materials are listed below:

●Polyethylene, $(CH_2)n$, is a very effective neutron shield because of its hydrogen content (14% by weight) and its density (≈ 0.92 g cm-3). It can thus attenuate so-called "fast" neutrons. In many circumstances, it provides very adequate shielding and is highly efficient due to the high hydrogen content.[17]
●Boron is used for both thermal neutron capture and capture-gamma suppression.[18]
●Lead is very effective at stopping gamma rays because of its high molecular density.
●Jute is a high-density composite material of carbon and hydrogen. Carbon is an excellent neutron absorber. [19]

5.1 Choice of Machine

The heat press machine was used to construct our shielding material.As the name implies, a heat press machine combines heat with pressure and is specially designed to imprint a design or graphic to a substrate. Heat presses can be used to imprint onto a wide range of substrates such as mugs, plates, caps, and other promotional or personal items.

The clamshell heat press machine has an upper heat platen that opens like a clamshell. [20]A heat press is the machine that presses aonto an imprint able substrate. Using high temperatures and heavy pressures for a certain amount of time, the transfer is permanently embedded into the product.
Standard transfers require from 375° to 425° F demand serious force in pressing often from 40-80 psi. These temperatures and pressures are simply not possible with other heated devices. [21]

5.2 Procedure of preparing shielding material

Table 1: Sample configuration

Sample	Sample Density	Thickness	Composition	Composite Density
1	3.412 g/cc	2.605mm	Polyethylene (C_2H_4) = 20g Boric Acid (H_3BO_3)= 4g Lead(Pb) = 212.36g Jute= 2.54g Total = 238.9g	C=2.258 g/cc H=8.85 g/cc O=1.429 g/cc B=2.46031 g/cc Pb=11.339 g/cc
2	2.997 g/cc	3.875mm	Polyethylene (C_2H_4)=40g Boric Acid (H_3BO_3) = 8g Lead(Pb) = 196.25g Jute = 2.5g Total = 254.75g	C=2.259 g/cc H=8.92*10^-5 g/cc O=1.429*10^-3 g/cc B=2.466 g/cc Si=2.32 g/cc Pb=11.34 g/cc

We have implemented two machines, one is hydraulic heat press machine and another is multiple operating (both heat and cooling) machine.

A heat press machine combines heat with pressure and is specially designed to build composite shielding materials.

At first, the weight of all materials used in the composition was taken carefully. Then the materials were uniformly mixed. Silicon paper and metal sheet was applied in both top and bottom side of the composite material. After that the mixture put through hydraulic heat press with temperature 320^0 F along with 4Pa atmospheric pressure. Then after waiting five minutes the composite material that was formed was not uniform. To make it uniform, the process mentioned was repeated again three times. Then a multiple operation machine cooled the composite material for about 10 minutes. Finally the composite shielding material was ready.

While building the composite shielding material, the hydraulic heat press machine was supposed to give uniform heat and pressure. But in reality it is difficult to maintain such conditions. As a result void was created within the composite material. To avoid this proper heat and pressure was maintained and inspected carefully.

5.2 Choice of testing method

We use MCNP code for testing of our shielding materials. Because MCNP is a very general Monte Carlo neutron-photon transport code with approximately 250 person years of Group X-6 code development invested. It is highly portable, user-oriented, and a true production code as it is used about 60 Cray hours per month. It has adatabase with the best cross-section evaluations available. MCNP contains state-of-the-art traditional and adaptive Monte Carlo techniques to be applied to the solution of an ever-increasing number of problems. Excellent user-oriented documentation is available for all facets of the MCNP code. Many useful and important variants of MCNP exist for special applications. The Radiation Shielding Information Center (RSIC) in Oak Ridge, Tennessee is the contact point for worldwide MCNP code and documentation distribution. [22]

(a) (b)

Fig.(a): Developed sample 1
Fig.(b):Developed sample 2

6 RESULT AND DISCUSSION

A Monte Carlo-based radiation transport calculation method to treat media containing randomly and uniformly dispersed spherical particles was developed. If the absorber particles are not small enough, the heterogeneity effect needs to be treated for accurate dose or activation estimations. The directheterogeneous representation of the small particles requires long computing time. The use of the MCNP method could considerably reduce the computational burdens without reducing its accuracy.

6.1 Monte Carlo N-Particle (MCNP) Simulation for Radiation Shielding

Source Name: Co-60

Source Strength Q=1 for γ-Ray

Dose Equivalent Rate DE (rem)=1 $rad \times Q$

Since 1R=0.876 rad in air

$$1mR = 10^{-3} \times 0.876\, rad = 8.76 \times 10^{-4} rad$$

$$1\frac{mR}{hr} = 8.76 \times 10^{-4}\frac{rad}{hr} = 0.876\frac{mrem}{hr}$$

$$1\frac{R}{hr} = 876\frac{mrem}{hr}$$

Source Name: Cf-252

Source Strength Q=$2.4 \times 10^{8}\frac{n}{s}$

TallyF5: n and F15: p (x=100,y=z=0)

DE15/DE15 card convert the photon fluence to air dose

<u>Tally Normalization</u>

FM5 normalizes the neutron tally to $\frac{mrem}{hr}$ for Q=$2.4 \times 10^{8}\frac{n}{s}$

FM15 normalizes the photon tally to $\frac{mR}{hr}$ for Q=$9.863 \times 10^{14}\frac{mR}{hr}$

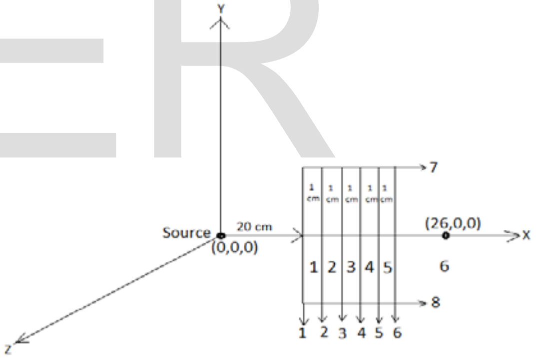

Fig.2:

Figure 2: Experimental setup for Monte Carlo N-Particle (MCNP) Simulation

Table 2: Tally normalizing

Particle Type	Location of Tally
Mode	n p
f5:n	26 0 0
fm5	8.64×10^{4}
fC5	Neutron DE Rate (mrem/hr)
f15:p	26 0 0
fm15	9.863×10^{14}
fc15	Secondary Gamma DER($\frac{mR}{hr}$)
Sdef	Par=1 pos=0 0 0 erg=d1
sp1	-2 1.42 $Maxwell fission spectrum

Table 3: Boundary conditions

Cell No	Mater ID	Density	Cell Bounded by surface
1	1	-2.9973	1 -2 8 -7 10 -9 imp:n,p=1
2	1	-2.9973	2 -3 8 -7 10 -9 imp:n,p=2
3	1	-2.9973	3 -4 8 -7 10 -9 imp:n,p=4
4	1	-2.9973	4 -5 8 -7 10 -9 imp:n,p=8
5	1	-2.9973	5 -6 8 -7 10 -9 imp:n,p=16
6	0	-11	8 -7 1 -6 10 -9 Imp:n,p=1
7	0	12	Imp:n,p=0

Table 4: Surface geometry

Surface Cards		
Surface No	Surface ID	Surface Location Distance
1.	Px	20
2.	Px	21
3.	Px	22
4.	Px	23
5.	Px	24
6.	Px	25
7.	Py	20
8.	Py	-20
9.	Pz	20
10.	Pz	-20
11.	SO	50

Table 5: Coordinate geometry

de5	**df5**
2.5×10^{-8}	10.21
10^{-7}	10.21
10^{-6}	12.4
10^{-5}	12.4
10^{-4}	11.97
10^{-3}	10.21
10^{-2}	9.921
10^{-1}	60.39
0.5	257.2
1	365.5
2.5	347.2
5	434
7	408.5
10	408.5
14	578.7
20	631.3

6.2 Results for neutron Radiation

Effects on neutron and secondary gamma shielding due to 5cm thickness shielding materials has been shown in table 6 and figure 3. The results have been discussed in the discussion section.

Table 6: Variation of neutron dose rate and secondary gamma dose rate with 5cm shielding of various materials tested.

Source Strength Q=$2.4 \times 10^{8} \frac{n}{s}$

Thickness	NDR($\frac{mrem}{hr}$)	SGDR($\frac{mR}{hr}$)	Sample 1
5cm	1.7420×10^{4}	1.3470×10^{1}	3.4120 g/cc

Thickness	NDR($\frac{mrem}{hr}$)	SGDR($\frac{mR}{hr}$)	Sample 2
5cm	1.4926×10^{4}	1.4926×10^{1}	3.4120 g/cc

Thickness	NDR($\frac{mrem}{hr}$)	SGDR($\frac{mR}{hr}$)	ORC
5cm	1.9012×10^{4}	1.298×10^{1}	2.3042 g/cc

Thickness	NDR($\frac{mrem}{hr}$)	SGDR($\frac{mR}{hr}$)	IMC
5cm	1.8576×10^{4}	2.2741×10^{1}	2.7602 g/cc

Thickness	NDR($\frac{mrem}{hr}$)	SGDR($\frac{mR}{hr}$)	Polyboron
5cm	1.1911×10^{4}	3.3496×10^{1}	0.9715 g/cc
Thickness	NDR($\frac{mrem}{hr}$)	SGDR($\frac{mR}{hr}$)	Lead
5cm	2.0533×10^{4}	1.6782×10^{1}	11.35 g/cc

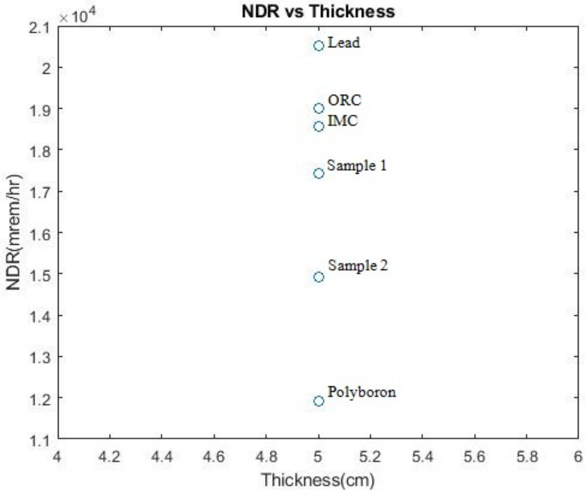

Figure 3: Variation of neutron dose versus thickness for various tested materials.

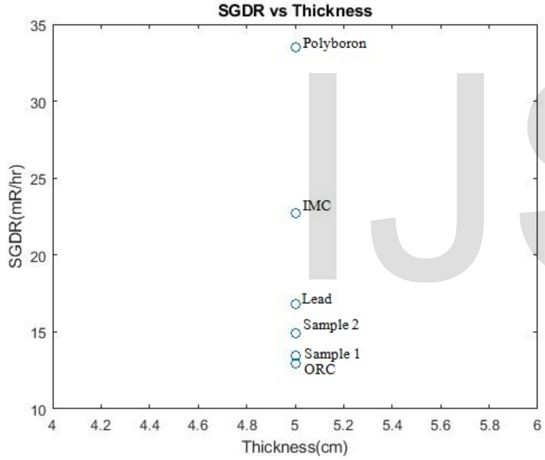

Figure 4: Variation of secondary gamma dose rate versus thickness for various tested materials.

6.3 Results for Gamma Radiation

Effects on primary gamma shielding due to 5cm thickness shielding materials have been shown in table 7 and figure 4. The results have been discussed in the discussion section.

Table 7: Variation of primary gamma dose rate with 5cm shielding of various materials tested

Source Strength: $3.04 \times 10^{14}\,\frac{Rad}{hr}$=$2.66 \times 10^{14}\,\frac{rem}{hr}$

Thickness(cm)	**Sample Name**	**PGDR($\frac{rem}{hr}$)**
5	Sample 1	52.64
5	Sample 2	58.28
5	ORC	75.03
5	IMC	71.27
5	Polyboron	89.93
5	Lead	8.30

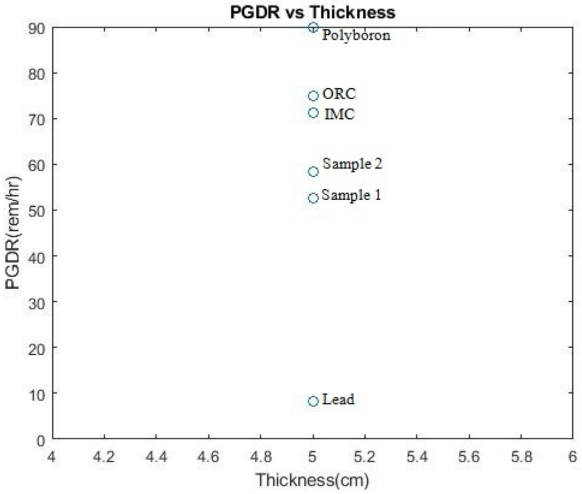

Figure 4: Variation of primary gamma dose versus thickness for various tested materials.

6.4 Discussion

In this experiment we have worked with two developed samples of composite materials for neutron and gamma shielding. For checking neutron shielding we have used Co-60 as its source material. Neutron dose rate (NDR) is 1.7420×10^4mrem/hr for sample 1 and 1.4926×10^4 for sample 2 and secondary gamma dose rate is 1.347×10mr/hr for sample 1 and 1.4926×10 for sample 2, which is quite less than the NDR and SGDR values we get by using ordinary concrete (ORC) and illuminate, magnetite, concrete (IMC).For checking gamma radiation shielding we used Cf-252 as source material. Here prompt gamma dose rate (PGDR) for sample 1 and 2 is 52.64 rem/hr and 58.28 rem/hr which is almost 5.7×10^{12} times less dose rate than the initial source emission.This composite material shields gamma radiation far better than ordinary concrete (ORC), illuminite magnetite concrete (IMC) and polyboron but not more than single lead as lead shields gamma more than any composite material.

7 CONCLUSION

Alongside many advantages of nuclear power there are some drawbacks of ensuring safety while working with radiation. In order to use nuclear power and the power of radioactivity shielding safety is of utmost importance not only for the people but also for the environment. The shielding material that we have used was made from lead, jute, polymer mixed with boric acid and silica which has produced locally and had effective neutron and gamma shielding with reasonable half value layer.Absorbed doses as shielding parameters were obtained by Monte Carlo N-Particle (MCNP) Simulation. Shielding materials that we have designed is lightweight and have good stopping power which can change the nuclear industry and increase the safety of working with radiation.Stopping power is defined as the retarding force acting on charged particles, typically alpha and beta particles, due to interaction with matter, resulting in loss of particle energy. Discussed materials are readily available and can be easily manufactured at low cost.

References:

1. Average Logarithmic Energy Decrement. https://www.nuclear-power.net/glossary/neutron-moderatoraverage-logarithmic-energy-decrement/ (accessed 11 August, 2018).
2. John R Haygood. Radiation Safety Procedures And Training For The Radiation Safety Officer: Guidance For Preparing A Radiation Safety Program , 1 ed. USA: iUniverse; 2013.
3. Debra Ronca. How Radiation Works. https://science.howstuffworks.com/radiation3.htm (accessed 11 August,2018).
4. FlorianaConstantin ,Sorina Alexandra Gârea , TeodorSandu , HoriaIovu. Characterization of Novel Epoxy Composites Based on Hybrid Inorganic/Organic Polyhedral OligomericSilsesquioxane. International Journal of Polymer Analysis and Characterization 2010; 15(2):
5. Tomomi Oguria, Shogo Takaharab,MasanoriKimuraband, Toshimitsu Homma. Study for shielding efficiency of evacuation facilities in nuclear emergency . Progress in Nuclear Science and Technology 2014; 4(1)
6. 7.MSR-Shielding,available on http://web.mit.edu/22.33/Chapters/Shielding/shielding-original.doc [Accessed 13 June 2018]
7. Kenneth S J and Faw R 2000 Radiation Shielding (Illinois: American Nuclear Society
8. J. Kenneth Shultis , Richard E. Faw. Radiation shielding, 1 ed. Illinois: American Nuclear Society; 1996.
9. Glenn F. Knoll. Radiation Detection and Measurement, 4 ed. USA: John Wiley & Sons; 2010.
10. http://www.nuclear-power.net/glossary/neutron-moderatoraverage-logarithmic-energy-decrement
11. Johann van Rooyen
Scientist: Radiation Shielding & Nuclear Criticality Safety at NECSA
12. www.linkedin.com/pulse/principles-neutron-shielding-johann-van-rooyen [1] [5 Kenneth S J and Faw R 2000 Radiation Shielding (Illinois: American Nuclear Society) [2] Knoll G 1979
13. Nuclear Power.Shielding of Gamma Radiation.Available from: https://www.nuclear-power.net/nuclear-power/reactor-physics/atomic-nuclear-physics/radiation/shielding-of-ionizing-radiation/shielding-gamma-radiation/[Accessed 26 February 2018]
14. William Schimpf et al.A guide to the use of lead for radiation shielding.*Canada metal north America*[Preprint],2016.Available from:http://www.canadametal.com/wpcontent/uploads/2016/08/radiation-shielding.pdf [Accessed 10 March2018]
15. J.C. *Domanus.Collimators for thermal neutron radiography an* overview.In:J.F.WMarkgraff .(ed.)Dordrecht:D.reidel publishing company;1987.p.7-8
16. SiqiXu, Mohamed A. Bourham, AfsanehRabiei. A Novel Ultra-light Structure for Radiation Shielding, 2008Shieldwerx.Polythylene based shielding.Availablefrom:http://www.shieldwerx.com/poly-based-shielding.html [Accessed in 7 april 2018]
17. Shieldwerx.Polythylene based shielding.Availablefrom:http://www.shieldwerx.com/poly-based-shielding.html [Accessed in 7 april 2018]
18. Marc M. Cohen. Carbon Radiation Shielding for the Habot Mobile Lunar Base. ,NASA-Ames Research Cente, 2004-01-2323.
19. Pro print gear.Heat press process. Available from: www.proprintsgear.com/heat-press [Accessed in 9 april 2018]
20. Geo knight & co inc.Heat transfer technology.Available from: http://www.heatpress.com/learn.php?gclid=CjwKCAjw6ZLOBRALEiwAxzyCW9B14Rnk0PaMXbdeibdEH3zTzK0cGZ [Accessed in 9 april 2018]

21. R. A. Forster ,T. N. K. Godfrey. “MCNP - a general Monte Carlo code for neutron and photon transport”,Monte-Carlo Methods and Applications in Neutronics, Photonics and Statistical Physics , vol.240.2006.p.33-55.
22. Markmodera et al. One Machine for Heating Cooling & Domestic Hot Water: Multi-Function Heat Pumps to Enable Zero Net Energy Homes.Available from: https://wcec.ucdavis.edu/wp-content/uploads/2014/11/Multi_Function_Heat_Pumps_ZNE_Homes.pdf [Accessed in 20 may 2018]