INL/CON-23-75366-Revision-0

Preliminary Analysis of a Nuclear Grade Sandwich Composite for Transportable Micro-Reactor Shielding

April 2024

Changing the World's Energy Future

Ryan Hunter Stewart, Samuel E Bays, Adam X Zabriskie, Joshua Nicholas Zelina, Abderrafi Mohammed-El-Amine Ougouag, Robert C O'Brien

Idaho National Laboratory

INL/CON-23-75366-Revision-0

Preliminary Analysis of a Nuclear Grade Sandwich Composite for Transportable Micro-Reactor Shielding

Ryan Hunter Stewart, Samuel E Bays, Adam X Zabriskie, Joshua Nicholas Zelina, Abderrafi Mohammed-El-Amine Ougouag, Robert C O'Brien

April 2024

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Preliminary Analysis of a Nuclear-Grade Sandwich Composite for Transportable Microreactor Shielding

Ryan H. Stewart[1], Samuel E. Bays [1,*], Adam X. Zabriskie[1], Joshua N. Zelina[1], Abderrafi M. Ougouag[1], Robert C. O'Brien[1]

[1]Idaho National Laboratory, Idaho Falls, ID

[leave space for DOI, which will be inserted by ANS]

ABSTRACT

Transportable microreactors pose a unique shielding challenge compared with conventional reactors. Many vendors are seeking to transport a microreactor to a site, operate it for a number of months or years, and then transport it to another site. This involves providing the reactor with sufficient shielding during operations and post-irradiation transportation to ensure the safety of the public, all while making it transportable via traditional means. This work examines the use of a nuclear-grade sandwich composite (NGSC) that seeks to combine the reactor pressure vessel and the biological shielding functions into a single unit. This work determined that the NGSC was sufficient to adequately reduce neutron and gamma current exiting the structure. The results attained show that the concept warrants further investigation as a potential combined vessel and shield option for microreactors.

Keywords: microreactor, shielding, sandwich composite, multi-objective optimization

1. INTRODUCTION

The concept of a fission battery, or transportable microreactor, has gained significant attention for its potential to drastically improve access to high reliability nuclear electricity and process heat in remote locations. To provide power to remote locations, the fission battery and its radiation shield must be sufficiently light to allow overland transportation. The requirement for overland transportation can be broken down into weight, volume, and radiation dose rate limits [1]. To accommodate these transportation constraints, the entirety of a microreactor should fit into an International Organization for Standardization (ISO) intermodal container. The ISO container places limits on the outer diameter of the microreactor, where the method of transportation places limits on the weight. The radiation dose outside the reactor results from both the neutron and gamma-ray currents escaping the shielding structure.

The volume of a road transportable microreactor is fixed by its vessel outer diameter that must fit within the transportation container; however, the weight, neutron current, and gamma current are three additional parameters to be minimized when designing a microreactor shield. These three constraints frame the optimization problem that is typically examined for shielding a microreactor.

*samuel.bays@inl.gov

For a traditional reactor concrete is commonly used. Concrete is essentially a low-cost mixture of strongly moderating and other lesser attenuators that can serve the dual objectives of shielding gamma-rays and neutrons. The ubiquitous use of concrete as a shield results from its being inexpensive and a high-strength composite when reinforced with steel rebar. With steel rebar, concrete can be both a structural ”building” material and a shield. Compared to lead, tungsten, and iron, concrete lacks the strong attenuation coefficient to be made into a viable light shield such as those used in transport casks. For casks, the shield is the only heavy component other than the fuel itself. In a reactor, the steel vessel is also a substantial contributor to the overall weight.

To simultaneously implement neutron and gamma-ray attenuation along with mass minimization, we hypothesize that combining the reactor shield and reactor vessel into a single composite material system will have more strength and more attenuation for less weight than the combination of a steel reactor vessel and a separate shield. To accomplish this, we propose a laminated sandwich composite with layers of reactor vessel steels and steel honeycombs filled with neutron and gamma-ray attenuating hexagonal pellets. The amalgamation of these various skins and intervening honeycomb grids is denoted as a nuclear-grade sandwich composite (NGSC). Sandwich composites of graphite fiber and aluminum honeycombs have been used in commercial turbojet engine nacelles for decades. A nuclear grade version of this sandwich material system is likely possible using modern manufacturing methods.

The goal of the NGSC is to combine the reactor shield and vessel into a single vessel which can be used during operations and transportation. During operations, it is envisioned that the NGSC will help reduce the neutron and gamma-ray fields immediately surrounding the reactor. This would in turn help reduce activation of surrounding materials. For transportation, the NGSC would provide a manner for complying with transportation dose requirements. This work focuses on examining post-irradiation transportation, specifically examining the neutron current, gamma-ray current, and weight of the NGSC.

2. REACTOR DESIGN

To provide a reasonable test case, a generic high temperature gas-cooled microreactor created in previous work is used. The reactor was not modeled explicitly, but to provide a reasonable test case, a generic high-temperature gas-cooled microreactor created in previous work was modelled. Instead, the neutron and gamma current from the reflector of the reactor were used a source into the NGSC. The general reactor geometry, material, and operating parameters are summarized in Table I.

Table I. Summary of reactor model parameters.

Parameter	Value	Parameter	Value
Core Power	10 MW_{th}	Fuel Element Height	79 cm
Core Life	4-year	Number of Fuel Channels	216
Core Diameter	112 cm	Number of Coolant Channels	108
Core Height	238 cm	Fuel and Coolant Channel Diameter	1.27 cm
Radial Reflector Diameter	160 cm	^{235}U Enrichment	19.75%
Axial Reflector Thickness	79 cm	UO_2 Kernel Diameter	0.0425 cm
Fuel Elements	21 full / 18 partial	TRISO[1] Outer Diameter	0.0855 cm
Fuel Element Flat-to-Flat	36 cm	TRISO[1] Packing Fraction	30%

The core comprises seven full fuel elements radially, with three axial layers, resulting in 21 total fuel elements. Eighteen partial fuel elements (six partial elements repeated over three axial layers) are used to

[1]TRi-structural ISOtropic (TRISO)

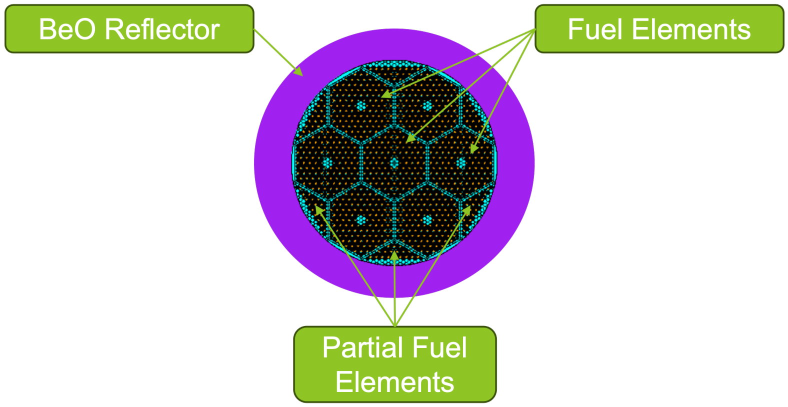


Figure 1. Axial cut of HTGR core used for preliminary shielding analysis.

fill the gap between the full fuel elements and the reflector region. The resulting core has an active core diameter of 112 cm and a height of 238 cm. A cross-section through the mid-plane of the reactor is provided in Figure 1. Surrounding the core is a 24-cm-thick beryllium oxide (BeO) reflector. Immediately outside the reflector is where the NGSC will be positioned to act as both the reactor pressure vessel (RPV) and reactor shield. The axial BeO reflector above and below the active core is 45-cm thick. For this work, a two-dimensional representation of the core is assumed and, as such, the axial reflectors are ignored.

3. SHIELD STRUCTURE DESIGN

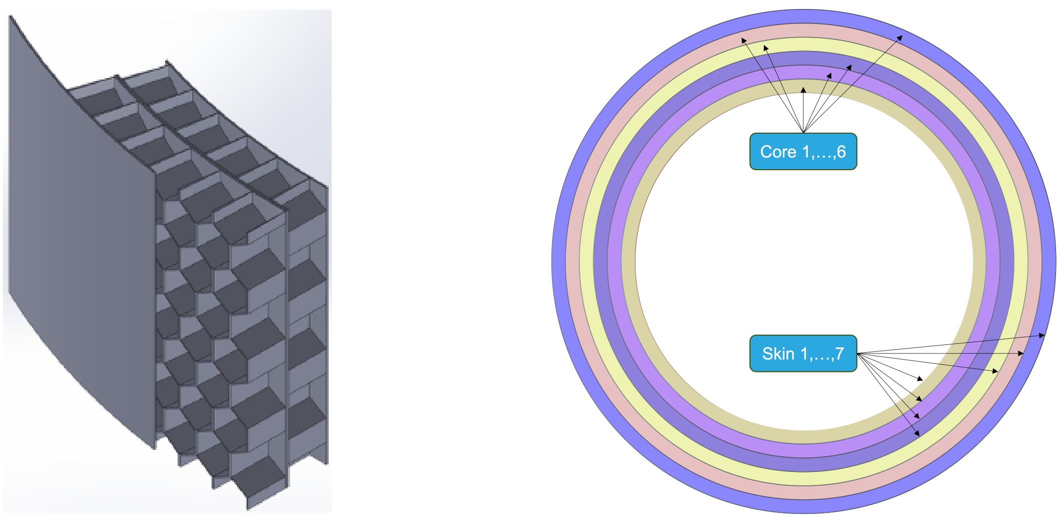
The NGSC can serve multiple purposes. It can function as structural material, a pressure vessel, and a nuclear shield. A sandwich composite is a laminate material system having one or more outer layers of high-strength materials (skin) and one or more low-density inner layers (core). Since initial inception in the 1940s, a great many material combinations have been explored [2]. Laminate composites are most common in aeronautic applications where the skin is made of glass, carbon, or Kevlar fibers and the core is made of aluminum alloys or special foams. Typically, the core materials have the shape of an air-filled hexagonal “honeycomb” lattice. We propose to use the same geometry system but with reactor grade steels for the skin and honeycomb core. The honeycomb core will be filled with ceramic shielding materials containing tungsten and boron. An example of this can be seen in Figure 2a, where two layers of the NGSC are shown.

For this work, three major materials are of interest: stainless steel 316 (SS316), boron carbide B_4C, and tungsten tetraboride (WB_4). SS316 makes up the constituent structural skins and honeycomb structures which will contain the core materials. B_4C is one of the core materials, constituted of relatively low-Z neutron attenuating atoms/nuclei. WB_4 is one of the other core materials This one is constituted of both high-Z gamma-ray attenuating material (W) and a low-z neutron attenuating one (B). For this work, only a single low-Z and a single high-Z material are examined to reduce the design space for the optimization problem.

The combined vessel and shielding structure has an inner radius of 80 cm, and is allowed a maximum outer radius of 120 cm. The inner radius is the minimum radius to contain the core and reflector of the microreactor. The outer radius is the maximum dimension to allow the entire microreactor to fit within a standard ISO container for transportability. The design of the laminated sandwich composite assumes that the structure replaces the core former and the reactor vessel while also fulfilling a shielding function. These restrictions limit the number of composite core layers that can be allowed. This number was fixed at six, requiring a complement of seven skin layers; one outermost, one innermost and five intervening. It must be noted that the fill material bonded to the skins is referred to as “cores” in standard composite nomenclature. That should not confused with the reactor core. Each core layer had a thickness of 6.41 cm, while the skin layers have a thickness of 0.22 cm; resulting in a total thickness of 40 cm for the NGSC.

For this study, the stainless steel honeycomb structure in the composite layers is neglected. Instead, the core layers are modeled with only core material (WB_4 or B_4C) present. It is noted that stainless steel can significantly effect gamma-ray shielding. Neglecting the stainless steel at this stage allows for a simplified understanding of the system response.

This analysis assumed simplified R-Z symmetry and neglects the axial contribution. The axial components of the core will likely have additional shielding which is greater in thickness to the radial region resulting in a smaller source term. The NGSC evaluates the trade-space between, on one side, neutron and gamma-ray attenuation maximization, and on the other side, and weight minimization. Figure 2b shows the simplified NGSC. Future iterations will incorporate the the stainless steel honeycomb structure and the axial contributions to provide a more robust analysis.



(a) Two layers of the NGSC with honeycomb structure. **(b) Simplified NGSC for preliminary study.**

Figure 2. Proposed (a) and simplified (b) design for a NGSC.

4. OPTIMIZATION

4.1. Problem Description

The work presented here entails an application of the multi-agent blackboard system’s (MABS) multi-objective optimization approach and subsequent analysis to provide context for the current state of the NGSC [3]. The design variables consisted of the material and density for each of the six layers; thus, a total of 12 design variables are present. The materials present and the fraction of theoretical density allowed for the design variables are shown in Table II. Utilizing the density as a design variable allows for greater variability in the overall mass of the system. The objective functions are the neutron current, the gamma-ray current, and the linear mass of the system. All are to be minimized.

The Serpent reactor physics software is used to simulate both neutron and gamma-ray transport within the shield [4]. Serpent is also used to model the gamma-ray buildup due to secondary production from neutron adsorptions and inelastic scattering. The magnitude of the neutron and gamma-ray sources emanating from

Table II. Design parameters for each layer of the NGSC optimization problem.

Design Variable	Options / Range
Material	WB_4, B_4C
Density (fraction of theoretical)	0.74–0.94

the core were 1.13×10^5 $\frac{n}{cm^2 s}$ and 2.89×10^9 $\frac{gamma}{cm^2 s}$, respectively. The neutron and gamma-ray currents leaving the reflector were tallied as a function of energy and angle in a full-core simulation of the reactor defined by Table I. These currents were then defined as particle sources defined on the interior surface of Figure 2a. These neutron and gamma-ray sources represent the core 30 days after being shut down. For the neutron and gamma currents, the major goal of the NGSC is to drop the magnitude by roughly six orders of magnitude.

Serpent is used to model the transportation of radiation through the shielding structure; however, the mass of the system is calculated using a simplified approach at this stage. For this, the mass of the microreactor given in Section 2 is taken as approximately 116,390 kg. Given that the shield is two-dimensional, the linear mass provides an approximation for the total mass of the system. With the use of a super heavy tractor trailer combination, the allowable weight is approximately 192,490 kg [5, 6], which leaves a mass of 76,100 kg for the shield once the reactor weight is deducted. In this scoping study, other weights associated with transportation are assumed to be negligible. If we assume a length of 396 cm for the shield, this provides a total linear weight of approximately 190 kg/cm.

The combination of the neutron current, gamma-ray current, and linear mass provides a semi-realistic objective space to explore the optimization problem. The range for the objectives can be seen in Table III. Ranges here were selected arbitrarily based on initial findings of the NGSC. The neutron and gamma-ray currents are treated equally in this assessment as it is envisioned to explore at-power operations in the future.

Table III. Objective functions for the NGSC optimization problem.

Objective Function	Allowable Range	Goal
Neutron Current ($\frac{n}{cm^2}$)	0.0 - 1.0×10^3	Minimize
Gamma-ray Current ($\frac{\gamma}{cm^2}$)	0.0 - 5.0×10^6	Minimize
Linear Mass ($\frac{kg}{cm}$)	0.0 - 190.0	Minimize

To perform the optimization, the MABS approach was used because of the multitude of Serpent simulations required to be run on Idaho National Laboratory's High-Performance Computing (HPC) cluster [3]. The MABS was set up to examine 1,000 different designs, where five global agents were used to explore the design space and five local agents were used to examine optimal solutions. The relatively small number of designs explored allows for an initial exploration of the design and objective spaces. These are not meant to be all-encompassing as future work will examine optimization with feedback from multiphysics simulations.

4.2. Analysis of the Pareto Front

The Pareto front (PF) [7], i.e. the selection of optimal solutions, generated by the MABS consisted of 281 designs. These represent roughly 30 percent of the designs examined. Figure 3 shows the PF for all three of the objective functions. The PF highlights that, as the gamma-ray current is reduced, there tends to be an increase in the linear mass of the system.

Figure 4 expands the examination of our PF by looking at the total number of WB_4 layers present in the core. An increased number of WB_4 layers helps reduce the gamma-ray current. It can be seen that the two

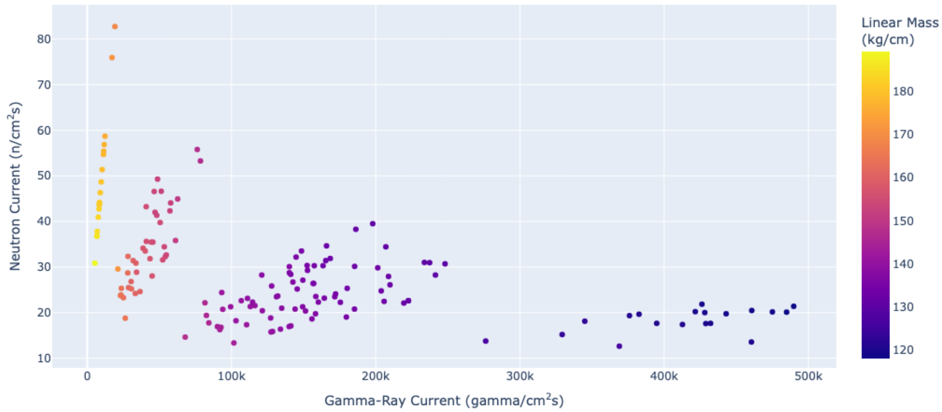


Figure 3. PF for the thee objectives in the NGSC design.

minimal gamma-ray current designs are achieved with five layers of WB_4. The variation around the three objectives for a single given number of WB_4 layers is due to the different positions the layers can be in and the density. The main finding illustrated in Figure 4 is that increasing the number of WB_4 layers decreases both the gamma-ray and neutron currents but causes a subsequent increase in the linear mass.

The figure also highlights the four regions of optimal solutions. Solutions that optimize the gamma-ray current tend to have five or six WB_4 layers. Solutions which optimize the neutron current and linear mass tend to have three or four WB_4 layers. This is less than ideal for an optimization problem as we would like to have solutions that optimize the objectives more concurrently. This may imply that additional constraints or a new set of objectives should be used to further explore the design space.

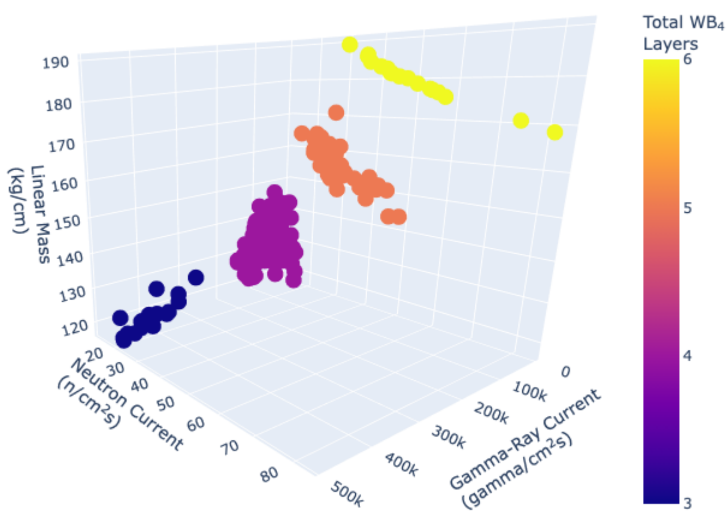


Figure 4. PF for the NGSC considering the total number of WB_4 layers.

The initial optimization of a transportable NGSC around a microreactor that has just been discussed, resulted in a Pareto front that demonstrates the tradeoff between weight, neutron current, and gamma current. Overall, it is found that replacing WB_4 with B_4C causes a reduction in the attenuation of gamma-rays resulting in higher gamma-ray currents. The benefit of this transition from one material to the other is to reduce the weight of the system. Future work will focus switching from the objective of minimizing the linear mass

Table IV. Statistical distribution of objective functions.

	Gamma-ray Current	Neutron Current	Linear Mass
Mean	$1.39\text{x}10^5$	$2.90\text{x}10^1$	148
Minimum	$5.30\text{x}10^3$	$1.26\text{x}10^1$	117
Maximum	$4.90\text{x}10^6$	$8.27\text{x}10^1$	189

to a constraint of a maximum allowed mass. This change would make possible the performance of a more detailed optimization analysis of the attenuation layers and their compositions.

4.3. Statistical Analysis

From the foregoing discussions, an understanding of where the optimal solutions lie on the PF has been established. Now a statistical analysis can be performed from which to glean information about the optimal designs. The statistical analysis is performed based only on the solutions present in the PF. Table IV shows the mean, minimum, and maximum values for each of the objectives. As expected for a shutdown reactor, as in the transportation case, the leakage of neutrons is of minimal consequence. This is of course different from the cases of an operating reactor at any significant fraction of the full power level The gamma-ray current leaving the reactor has the largest range of variation for allowable values among the objective functions, spanning from a low of $5.30\text{x}10^3$ $\frac{gamma}{cm^2}$ to a maximum of $4.90\text{x}10^6$ $\frac{gamma}{cm^2}$. This wide range will be instrumental to understand what design variables are most important in creating the range of values.

To explore the causes of the gamma-ray variability of the various optimized shielding designs, we examined the correlation matrix associated with our design variables and objective functions. A correlation matrix examines the relationship between two variables, where each coefficient can range between -1 and 1. A value of -1 indicates a strong negative relationship, a value of 1 indicates a strong positive relationship, and a value of 0 indicates no relationship. For the correlation matrix in Figure 5, the Spearmann rank correlation [8] is used because it more accurately describes if the relationship follows a monotonic function rather than a pure linear relationship. In the correlation matrix, the interaction between the objective functions and design parameters are examined. For the design parameters, the total number of B_4C and WB_4 layers and whether or not B_4C is being placed in the first or last layer of the design are examined.

Among the objectives in the problem, there is a strong negative correlation between the gamma-ray current and both the linear mass and total WB_4 layers. This relationship is due to the fact that decreasing the gamma-ray current requires the inclusion of WB_4 in additional layers which substantially drives up the linear mass due to WB_4 being about three times denser than B_4C. There is also a slight negative relationship between the neutron and gamma-ray currents indicating that the gamma current is reduced at the expense of the neutron current. The important aspect is that this relationship is weak, meaning the increase in neutron current likely occurs at a slower rate than the decrease the gamma-ray current. This relationship will be shown to be true when individual shielding configurations are examined.

The final aspect that examined is the distribution of WB_4 and B_4C across the six layers. Figure 6 is a bar chart presenting the number of designs for which each of the two materials is present in which of the six layers of the NGSC. That is to say, the figure shows the frequency with which a material is present in the six layers of the NGSC. For this optimization problem, nearly all of the designs place WB_4 in the first three layers.

From the PF, most solutions have between one and three B_4C layers. The B_4C layers appear to be relatively evenly distributed throughout layers three through six. This may indicate that there is little preference on what additional layers (after the first three) should contain B_4C to optimize the problem. This results in

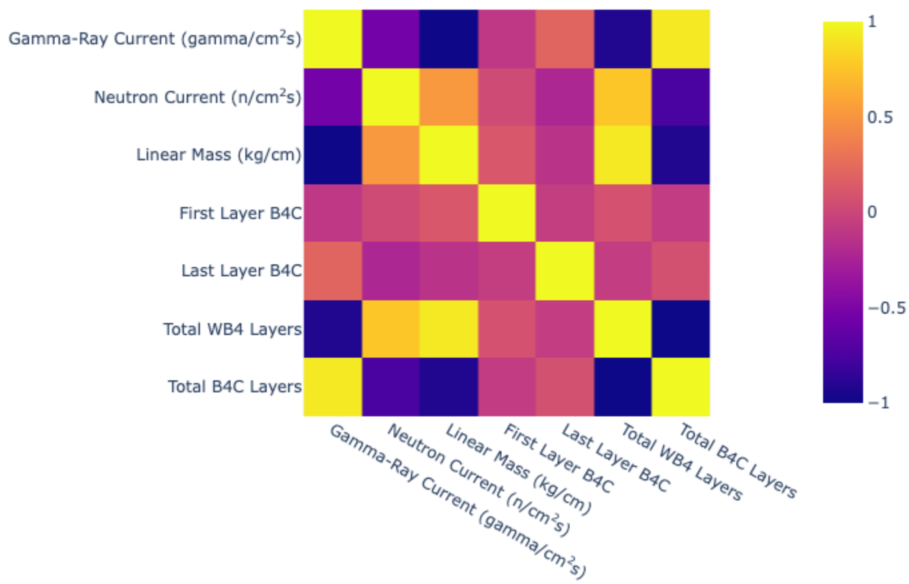


Figure 5. Correlation matrix for the objective functions and material layers.

weaker relationships between the B_4C layer placement and the objectives.

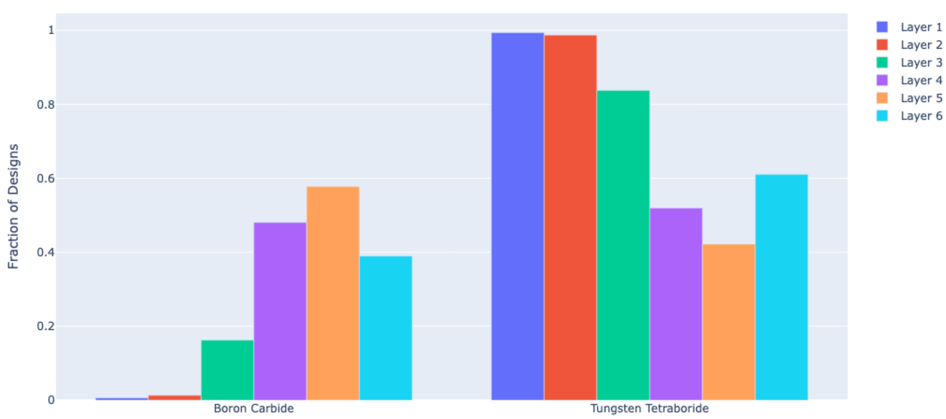


Figure 6. Distribution of materials across layers.

4.4. Examination of Three Optimal Designs

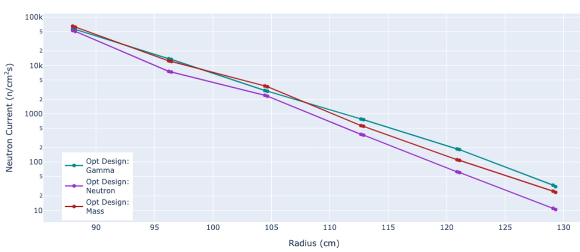
To provide more insight into the PF, three of the optimal designs are examined further. Each of the selected designs minimizes one of the three objectives. This further examination is intended to further the understanding of gamma and neutron. For the three optimal designs, we designate them as "Opt Design: Gamma," "Opt Design: Neutron," and "Opt Design: Mass" for being optimal in neutron attenuation, gamma-ray attenuation, and mass reduction, respectively. Table V shows the materials for each layer of the optimal designs.

For all three three optimal designs, layers one and three are comprised of WB_4. For the gamma-ray optimal design, all six layers are comprised of WB_4, which follows from the PF seen in Figure 4. For the neutron and

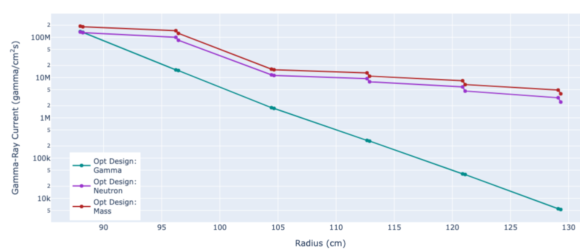
Table V. Optimal design layer configurations.

	Opt Design: Gamma-Ray	Opt Design: Neutron	Opt Design: Mass
Layer 1	WB_4	WB_4	WB_4
Layer 2	WB_4	B_4C	B_4C
Layer 3	WB_4	WB_4	WB_4
Layer 4	WB_4	B_4C	B_4C
Layer 5	WB_4	B_4C	B_4C
Layer 6	WB_4	B_4C	B_4C

mass optimal designs, both designs have the same layer compositions, however the density for the layers are slightly different which yields different designs. Figure 7a and Figure 7b show the neutron and gamma-ray current as a function of radius through the NGSC for each of the three optimal designs. Figure 7b shows that WB_4 is significantly better at reducing the gamma-ray current in comparison to B_4C due to the significantly higher density. We also find that the rate at which we can decrease gamma-rays with WB_4 is larger than the reduction in neutron attenuation. The neutron current leaving the shielding structure is only three times higher when comparing the neutron optimal and gamma optimal designs. For the gamma-ray current leaving the shielding structure the neutron optimal design is nearly three order of magnitude higher.



(a) Neutron current results.



(b) Gamma-ray current results.

Figure 7. Neutron (a) and gamma-ray (b) currents normal to each layer for the NGSC optimal designs.

5. CONCLUSIONS

This work examined the development of a NGSC as a means for shielding a microreactor during transportation following operation at full power. A series of optimization calculations were performed where we sought to minimize the neutron and gamma-ray current leaving the shielding while simultaneously trying to minimize the weight of the system. Of the 281 designs that were deemed optimal by the MABS, three optimal designs were selected. The resulting Pareto front showed that it was not possible to simultaneously optimize all three objectives. Despite this, a great deal of knowledge was gained. For the NGSC, nearly all of the optimal designs contained WB_4 as their first two to three layers (i.e. closest to reactor core) indicating a potential reduction in the initial design space for future examination. To reduce the objective space, the neutron and gamma-ray currents could be transformed a single objective looking solely at their dose equivalence.

Along with this, the linear mass ranged from 117 kg/cm to 189 kg/cm, which allows for two transportation options; a 19- or 24-axle truck [5, 6]. Ideally, the 19-axle truck would experience some, but minimal, interruption to transporting the core from its manufacturing facility to its operational location. In contrast, the 24-axle truck would require both lanes of an interstate highway, and would necessitate months of preparation and planning to transport it between locations. Depending on the availability, two separate constrained optimization problems could be devised and pursued; one that seeks a linear mass of 156 kg/cm or less (corresponding to a 19-axle limit) and one that allows for 310 kg/cm or less (corresponding to a 24-axle limit).

Two ways to reduce the objective space of the design have already been discussed; however, future iterations could examine a slightly different set of objective functions to incorporate full-power operations and cost. To incorporate full-power operations, one can examine both the neutron current and the gamma-ray current near the core end of life (when neutron and gamma currents are expected to be highest). The neutron current could be examined in terms of its ability to activate the surrounding material (such as soil) to prevent unwarranted activation. Another method of examination is to convert the neutron current and gamma current to a dose rate equivalent. This would allow one to determine the implication of the NGSC on dose equivalent to workers, an important measure, especially if maintenance is required shortly after shutdown. An economic study could be a relative cost estimate to examine the price per kg of material for the B4C and WB4, along with associated manufacturing costs, to get an understanding of the implications on the price of building an NGSC and implications for the price of generated energy (e.g., electricity). In summary, it is recognized that multiple areas of future research could be considered in the development and optimization of a NGSC for shielding a transportable microreactor.

ACKNOWLEDGEMENTS

This work is supported by DOE, under DOE Idaho Operations Office Contract DE-AC07-05ID14517. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes. This research made use of the resources of the High Performance Computing Center at INL, which is supported by the DOE Office of Nuclear Energy and by the Nuclear Science User Facilities under contract no. DE-AC07-05ID14517.

REFERENCES

[1] E. Kitcher. "Microreactor Spent Nuclear Fuel Transportation, Management, and Disposition Options." Technical Report INL/EXT-20-59779, Idaho National Laboratory (2020).

[2] N. Hoff et al. "Sandwich construction." *Technomic Publishing Co, Inc, Monocoque, Sandwich, and Composite Aerospace Structures: Selected Papers of Nicholas J Hoff,*, pp. 463–469 (1986).

[3] R. Stewart et al. "An agent-based blackboard system for multi-objective optimization." *Journal of Computational Design and Engineering*, **volume 9**(2), pp. 480–506 (2022).

[4] J. Leppänen et al. "The Serpent Monte Carlo code: Status, development and applications in 2013." *Annals of Nuclear Energy*, **volume 82**, pp. 142–150 (2015).

[5] K. Jensen. "Heavy haul trucking: How does freight weight impact trailer type?" (2022). URL https://www.atsinc.com/blog/how-does-heavy-haul-freight-weight-impact-trailer-type.

[6] "Oversize/Overweight Load Permits - FHWA Freight Management and Operations." URL https://ops.fhwa.dot.gov/freight/sw/permit_report/index.htm.

[7] R. Stewart et al. "A survey of multi-objective optimization methods and their applications for nuclear scientists and engineers." *Progress in Nuclear Energy*, **volume 138**, p. 103830 (2021).

[8] J. Myers et al. *Research Design and Statistical Analysis*. Routledge, 3rd ed. edition (2010).