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Changing the World's Energy Future

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Streaming in a Nuclear-grade Sandwich Composite for Microreactor Shielding

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INTRODUCTION

Microreactors are envisioned to serve as reliable sources of clean energy and process heat, but at a smaller scale in comparison to traditional reactor concepts. The ability to supply remote locations, disaster relief areas, or micro-grids with nuclear energy has motivated nuclear design vendors to seek out a microreactor concept that can be deployed sometime within the next decade. For easy deployment, microreactors will need to be transported via traditional means (i.e., road, rail, air, or shipping vessels). Thus, microreactors (and their supporting shielding and reactor vessel) must fit inside International Organization for Standardization (ISO) intermodal containers and adhere to current transportation requirements pertaining to weight, volume, and radiation dose limits [1].

To better enable microreactor shielding, nuclear-grade sandwich composites (NGSCs) have been proposed [2, 3]. In NGSCs, the reactor pressure vessel and biological shielding are combined to create stainless steel (SS) layers (called skins) filled with neutron and gamma ray attenuating pellets (called cores). The resulting single composite material provides greater strength and radiation attenuation (for less weight) than what can be achieved by implementing a pressure vessel with a separate shield. Previous work has examined the feasibility of NGSCs by optimizing the materials in each layer to minimize the neutron dose, gamma dose, and rough cost yet still maintain an appropriate weight [2, 3].

It is currently envisioned that the NGSC will be able to take advantage of additive manufacturing to create each layer and skin. Layers can be added individually, where either ceramic compacts or powders can be placed in the cores to create a continuous shielding material. The use of compacts or powders will likely have a large impact on both radiation shielding and the structure mechanics of the NGSC; this work is ongoing.

Previous NGSC assessments utilized a 1-D model with alternating layers of SS skins and shielding-material cores. However, in reality, the core regions would contain SS ribs for structural support, introducing a potential streaming path for radiation. The present work examines the streaming of neutrons and photons through a NGSC when ribs are actually included in the model.

The examined representative core materials varied in terms of the amount of tungsten tetraboride (WB_4) and boron carbide (B_4C) found in the given NGSC [2, 3]. The present work examines two designs: one with six layers of B_4C and one with six layers of WB_4. B_4C is used to provide a low-density neutron shield, whereas WB_4 provides a high-density gamma shield. Examining NGSCs filled solely with each material is expected to lead to a bounding case and to foster a general understanding of how structural ribs affect radiation streaming.

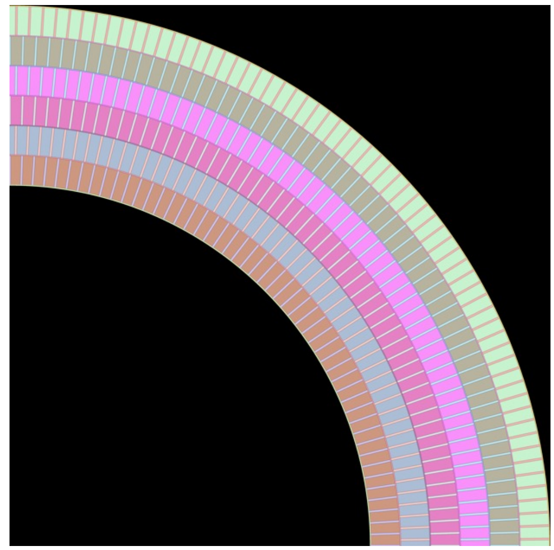


Fig. 1: Quarter section of the 2-D NGSC.

METHODOLOGY

For the present work, a 10-MW_{th} high-temperature gas-cooled reactor served as the test case [2]. The neutron and photon spectra at microreactor end of life were captured from previous work and utilized here as a surface current. The surface currents of neutrons and photons leaving the reflector were deemed to be 1.0×10^{12} $(\frac{n}{cm^2 s})$ and 6.7×10^{11} $(\frac{p}{cm^2 s})$, respectively.

NGSCs leverage the strength afforded by sandwich composite materials, while simultaneously minimizing the space needed for radiation shielding. Current iterations of NGSCs utilize six different layers of composite materials. The inner edge begins at a radius of 80 cm, representing the edge of the microreactor reflector. The outer edge extends to 120 cm, thus enabling the microreactor and NGSC to fit inside an ISO intermodal container.

For the present study, each layer contained a 0.22 cm SS-316 skin atop 6.41 cm of core material. The skins were interconnected via a series of 0.22-cm-thick ribs that lent the NSGC its structural integrity. The first layer contained 200 ribs. To maintain consistency in the core width, an additional 10 ribs were included in each subsequent layer . Figure 1 shows a six-layer NGSC surrounded by a ring of air.

WB_4 was originally proposed as a core material; however, manufacturing of WB_4 proved to be difficult and WB_4-cermet was used instead [3]. WB_4-cermet, which is composed of 85% WB_4 and 15% SS-316, was used because it is more malleable than pure WB_4. That work only examined a simplified 1-D problem, in which the ribs were ignored in favor of simplified modeling. The concern is that including the ribs could open up an avenue for radiation streaming (particularly in photon transport).

The present work introduces a 2-D NGSC model in which the structural ribs are included. To examine the effect of these ribs, an end-of-life neutron/photon transport problem was explored. Two variations were examined: one with the structural ribs and one without. In both versions of the problem, all six layers were filled with either WB_4-cermet or B_4C so as to elucidate the effects of adding ribs to each material.

To assess the inclusion of SS-316 ribs, the Monte Carlo code Serpent was used [4] in conjunction with the ENDF/B-VII.1 cross-section library [5]. Serpent was used the external source problem, where the neutron and photon surface current initialized incident to the inner-most skin layer. Resulting uncertainties for the current and dose leaving the core were below 1% for both neutrons and photons.

RESULTS

The results have been divided up to enable separate examination of the neutron current (Figure 2) and the photon current (Figure 3). Both figures shows the current through the NGSC as a function of radius.

For the neutron current, including the SS-316 ribs degraded the shield efficiency. The rib-containing B_4C shield is only approximately 61% as efficient as the 1-D simplified one. This is because replacing B_4C with SS-316 decreases the effective absorption cross section as boron is replaced with isotopes in SS-316. WB_4-cermet undergoes a similar trend, with the inclusion of SS-316 ribs leading to a shield that is only 43% as effective as the simplified version.

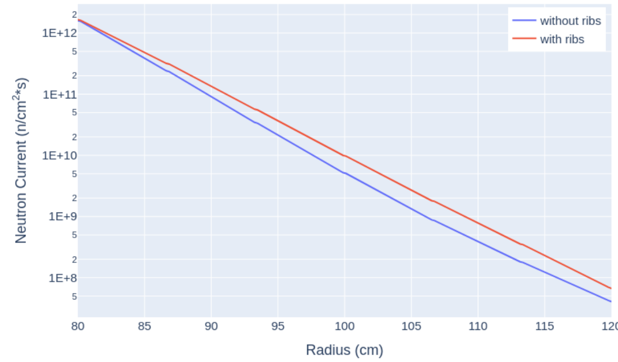
The attenuation loss for B_4C is likely less than that for WB_4, due to the change in density. (SS-316 has a density of about 8.0 g/cm^3; B_4C has a density of 2.42 g/cm^3.) Replacing B_4C with SS-316 results in a loss of boron but a subsequent increase in mass density, leading to additional neutron attenuation.

WB_4-cermet and SS-316 both possess nearly the same density (8.4 and 8.0 g/cm^3, respectively). When WB_4-cermet is replaced, no corresponding density increase occurs to offset the decrease in boron. This makes the design with WB_4 less effective when the ribs are added, as compared to B_4C.

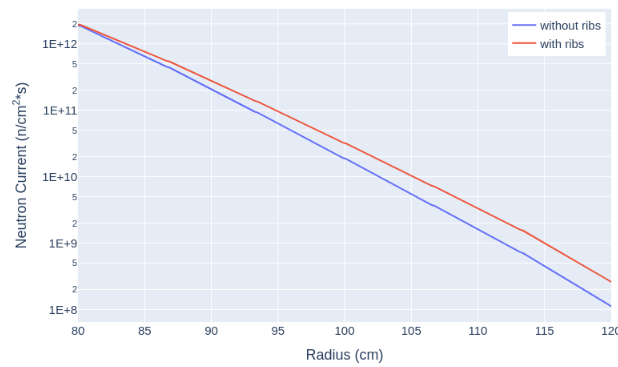
In regard to photon shielding, inclusion of SS-316 has a significant impact on the B_4C layers. B_4C's low material density makes it nearly transparent to photons. Figure 3a shows a near step function for the simplified version. In including the ribs, the addition of the more dense material produces regions in the core where photons are more likely to interact. This makes the ribbed version nearly three times more effective than the simplified one. For B_4C, there is an in the increase number of photons in the first layer due to the neutron interaction $^{10}B(n,\alpha)^7Li$, which releases a 478 keV photon [6].

For WB_4-cermet, the difference in photon shielding reflects a trend similar to that for neutron shielding, with the ribbed version being only half as effective as the simplified one. Though the densities of the two materials are similar, tungsten has a higher affinity for both scattering and absorbing photons.

The current through the NGSC helps explain how neutrons and photons are transported through the NGSC. More importantly, the dose level outside the core serves as an importance factor for the radiation escaping the NGSC.



(a) B_4C



(b) WB_4-cermet

Fig. 2: Neutron current through the NGSC with WB_4-cermet or B_4C layers.

TABLE I: Neutron dose (mrem/hr) outside the NGSC.

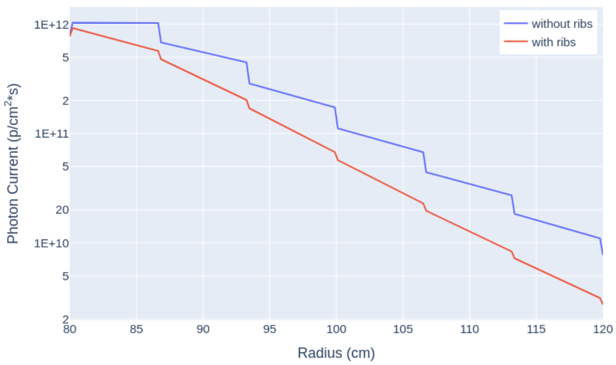
	1D	2D	1-D/2-D Ratio
B_4C	4,434	5,612	0.79
WB_4-cermet	5,688	11,376	0.50

Tables I and II show the expected neutron and photon doses outside the NGSC. The dose-related trends are similar to those pertaining to the neutron and photon currents. On average, inclusion of the ribs reduces the shielding effectiveness by 25%–50%—the one exception being in regard to the photon dose in the B_4C, where including the ribs actually triples the shielding effectiveness.

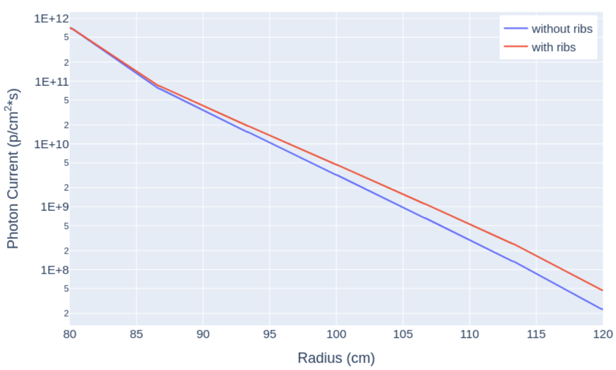
TABLE II: Photon dose (mrem/hr) outside the NGSC.

	1D	2D	1-D/2-D Ratio
B_4C	2,494	806	3.09
WB_4-cermet	0.05	0.07	0.75

Overall, inclusion of the ribs has a larger impact on the WB_4-cermet layers. Table III shows the total dose (i.e., the



(a) B_4C



(b) WB_4-cermet

Fig. 3: Photon current through the NGSC with WB_4-cermet or B_4C.

combined neutron and photon doses) outside the NGSC. The ribs reduce the total amount of neutron-absorbing material, significantly affecting its neutron-removal capability. For the B_4C layers, inclusion of the ribs reduces the neutron absorption effectiveness, but creates a much more effective photon shield. This results in similar total doses when comparing both the simplified and the ribbed cases.

TABLE III: Total dose (mrem/hr) outside the NGSC.

	1D	2D	1-D/2-D Ratio
B_4C	6,928	6,417	0.92
WB_4-cermet	5,687	11,376	2.00

CONCLUSIONS

NGSCs represent a new microreactor shield structure development method that combines biological shielding with the reactor pressure vessel. NGSCs are comprised of six layers, each containing a SS-316 skin in addition to a core material that reduces the neutron and gamma dose. Previous work has examined how a simplified NGSC can be optimized in terms of cost, dose, and weight.

The present work explored the inclusion of SS-316 ribs, which help maintain NGSC structural integrity and affect the transportation of radiation through the NGSC. For B_4C layers, inclusion of the ribs reduces neutron absorption but increases photon absorption. For WB_4-cermet layers, inclusion of the ribs reduces both neutron and photon absorption.

Inclusion of ribs reduces the NGSC's overall effectiveness for both neutron and photon shielding. No straightforward relationship has yet been discovered for determining how a single layer would be affected by adding ribs. When multiple layers of WB_4-cermet and B_4C are included in the NGSC, it becomes important to capture the effects of the ribs. Future research regarding how individual layers of materials interact with each other may serve to unlock a deeper understanding of how radiation transport through NGSCs occurs.

For normal operation scenarios, the reactor is likely to be enclosed in some type of concrete bunker. Such an enclosure would likely place strong importance on neutron and photon doses. Future work could examine whether the ribs significantly impact the dose outside the concrete shielding. And similar research could examine how ribs affect photon streaming out of the NGSC during transportation.

This work uses the two extreme examples with six layers of B_4C or WB_4 to examine how the inclusion of SS-316 ribs effects radiation transport through the NGSC. While this is important for determining dose and environmental activation, there are other areas of research needed to ensure the NGSC is feasible. The inclusion of large amounts of boron in the shielding structure implies a high degree of alpha heating, especially in the first couple of layers. Additional heat generation in the shielding material may have impacts on the structural integrity of the shield and decay heat removal. Future work is currently underway to understand how the use of B_4C and WB_4-cermet will effect these parameters and the operation of the microreactor.

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