INL/EXT-06-01152

GFR Subassembly Shielding Design Studies

James R. Parry

January 2006

Idaho National Laboratory

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

INL/EXT-06-01152

GFR Subassembly Shielding Design Studies

James R. Parry

January 2006

Idaho National Laboratory
Irradiation Test Programs
Idaho Falls, Idaho 83415

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

Abstract

This report presents the methodology and results for a preliminary study for Gas-Cooled Fast Reactor (GFR) subassembly fast neutron shielding configurations. The purpose of the shielding in the subassembly is to protect reactor components from fast (E>0.1 MeV) neutrons. The subassembly is modeled in MCNP version 5 release 1.30. Parametric studies were performed varying the thickness of the shielding and calculating the fast neutron flux at the vessel head and the core grid plate. This data was used to determine the minimum thickness needed to protect the vessel head and the core grid plate. These thicknesses were used to analyze different shielding configurations incorporating coolant passages and also to estimate the neutron and photon energy deposition in the shielding material.

Contents

GFR Subassembly Shielding Design Studies

Introduction

Neutron shielding is incorporated in the GFR design to protect important structural material from fast neutrons (E>1.0 MeV). In an attempt to move the shielding from the individual fuel pins to the subassembly, parametric studies have been performed to determine the thickness of shielding needed to stay below the fluence limits on the grid plate and the vessel head. The shielding material considered in these studies is a mixture of 50% B_4C and 50% 316 stainless steel. The maximum fast fluence limit is currently set at 3×10^{19} n/cm^2 for the expected 40 year life of the reactor. Shielding thicknesses from 0 cm (no shielding) to 100 cm were evaluated indicating that approximately 80 cm of shielding material is needed to protect the grid plate while approximately 70 cm of shielding is adequate for the vessel head. Two very preliminary designs incorporating helium flow passages were analyzed to start looking at the effect of flow passages on the fluence seen at the grid plate and the vessel head.

Analysis Method

MCNP5 Version 1.30 [1] was used to model a single GFR subassembly and predict the neutron flux at the core grid plate and the vessel head. MCNP is a general purpose Monte Carlo N-Particle code written by the Los Alamos National Laboratory. The code was also used to predict the neutron and photon energy deposition (heating) in the shielding material. The built-in cross section data set in MCNP was used for all material definitions.

The Single Subassembly Model

The subassembly model uses reflected surfaces as the radial boundaries to represent an infinite core in the radial direction. The reflected surfaces are the outside surfaces of the helium gap between subassemblies. Axially, the model ends at the top surface of the vessel head and the bottom surface of the core grid plate. The vessel head is modeled as a solid structure inside the reflected boundaries. The core grid plate is a smeared region to account for the helium coolant flow passages. It extends to the reflected boundaries below the subassembly. Other smeared regions include the fuel region, the reflector region, and the plenum region of the fuel rods inside the hexagonal duct. The hexagonal duct is explicitly modeled along with the helium outside the duct. The model dimensions are based on the dimensions in Rouault [2]. In all cases, the smeared region maintains the proper material mass of the included components but does not maintain geometric relationships of the components smeared together. The B_4C/SS shielding is modeled explicitly inside the hexagonal duct. The materials used in the model for the regions described above are listed in Table 1.

Table 1. Materials list for the major components.

Component	Material
Fuel	Plutonium/Uranium Carbide
Cladding	SiC
Reeflector	Zr_3Si_2
Hexagonal Duct	SiC
Coolant	Helium
Vessel Head	2.25 Cr 1 Mo Steel
Core Grid Plate	316 SS
Shielding	50% B_4C 50% 316 SS

Assumptions

1. The power of the single assembly is equal to the power in the peak assembly based on a 2400 MWt reactor, 111,021 fuel pins, 271 fuel pins per non-control assembly, and a peak to average power ratio of 1.25.

$$\frac{2400\ MWt}{111{,}021\ fuel\ pins} \times \frac{271\ fuelpins}{subassembly} \times 1.25 = \frac{7.323 MWt}{peak\ power\ subassembly} \qquad (1)$$

2. The number of neutrons released per fission in the GFR is 2.917 as calculated in the MCNP runs.

3. The B_4C/SS shielding material can be represented by a smeared mixture of 50% B4C and 50% 316 SS by volume.

4. The fast (E>0.1 MeV) neutron fluence limit for the 40 year life of the vessel is 3.0 x 10^{19} n/cm^2. This results in a maximum fast flux limit of 2.38 x 10^{10} n/cm^2-s.

$$3 \times 10^{19}\ {}^{n}\!/_{cm^2} \div 40\ years \times \frac{1\ year}{31557600\ s} = 2.38 \times 10^{10}\ {}^{n}\!/_{cm^2 \cdot s} \qquad (2)$$

Parametric Study

Parametric studies were performed to determine the necessary thickness of shielding required to stay below the maximum fluence limit of 3.0 x 10^{19} n/cm^2. The single subassembly model described above was modeled with a solid B_4C/SS shielding block above and below the plenum region and inside the hexagonal duct. 11 separate models were created with the shielding block thickness varying from 0 cm to 100 cm in 10 cm increments. Flux tallies were created for the vessel head and the core grid plate. Graphical representations of the model with no shielding and the model with 100 cm of shielding are presented in Figures 1 and 2 respectively.

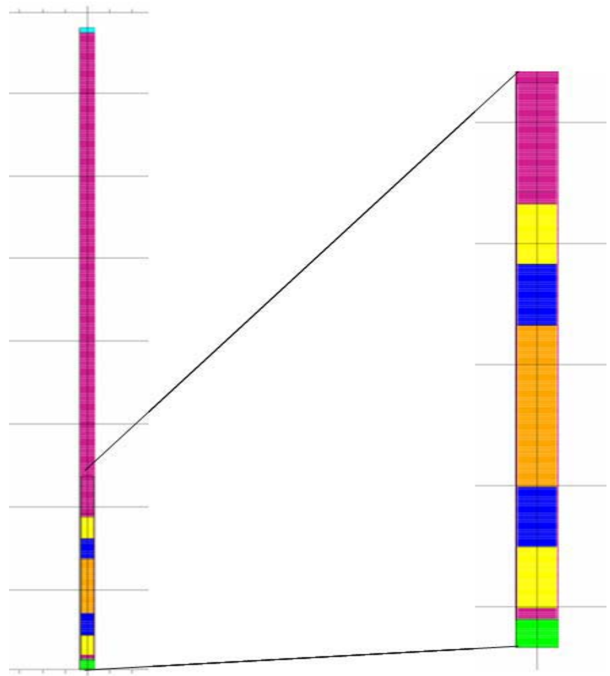

Figure 1. Parametric model representation showing no shielding. Light blue is the vessel head, light green is the core grid plate, red is helium, yellow is the plenum zone, blue is the reflector zone, and orange is the fuel zone.

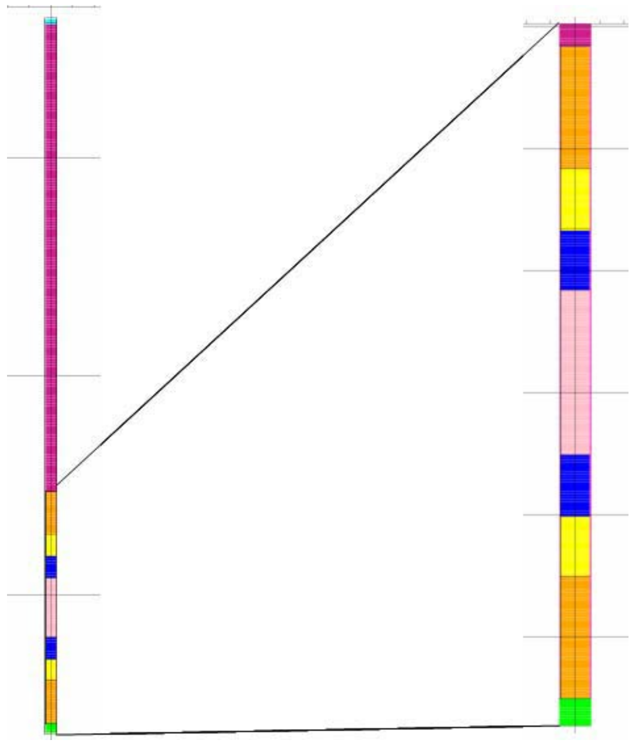

Figure 2. Parametric model representation showing 100 cm of shielding. In this figure, the fuel zone is pink and the shielding is orange.

Parametric Study Results

The results indicate that a shielding thickness of 70 cm at the top of the hexagonal duct will prevent the vessel head from receiving a fast neutron fluence greater than 3.0 x 10^{19} n/cm2 over the anticipated 40 year life. 80 cm of shielding is required to prevent the core grid plate from exceeding the 40 year fluence limit. The results are shown in Table 2. Visual representations are shown for the vessel head results in Figure 3 and the core grid plate results in Figure 4.

Table 2. Parametric studies results for shielding thickness variations from 0 cm to 100 cm.

Shielding Thickness	Vessel Head		Core Grid Plate	
	Flux (n/cm^2-s)	Fluence (n/cm^2)	Flux (n/cm^2-s)	Fluence (n/cm^2)
No Shielding	2.92E+11	3.68E+20	6.77E+11	8.55E+20
10 cm	1.07E+11	1.35E+20	2.23E+11	2.81E+20
20 cm	5.80E+10	7.32E+19	1.03E+11	1.30E+20
30 cm	3.89E+10	4.91E+19	6.37E+10	8.04E+19
40 cm	3.28E+10	4.14E+19	4.19E+10	5.29E+19
50 cm	2.50E+10	3.16E+19	3.70E+10	4.67E+19
60 cm	2.34E+10	2.96E+19	2.71E+10	3.42E+19
70 cm	2.16E+10	2.73E+19	2.48E+10	3.13E+19
80 cm	1.94E+10	2.45E+19	1.89E+10	2.39E+19
90 cm	1.56E+10	1.98E+19	1.74E+10	2.20E+19
100 cm	1.61E+10	2.03E+19	1.42E+10	1.79E+19

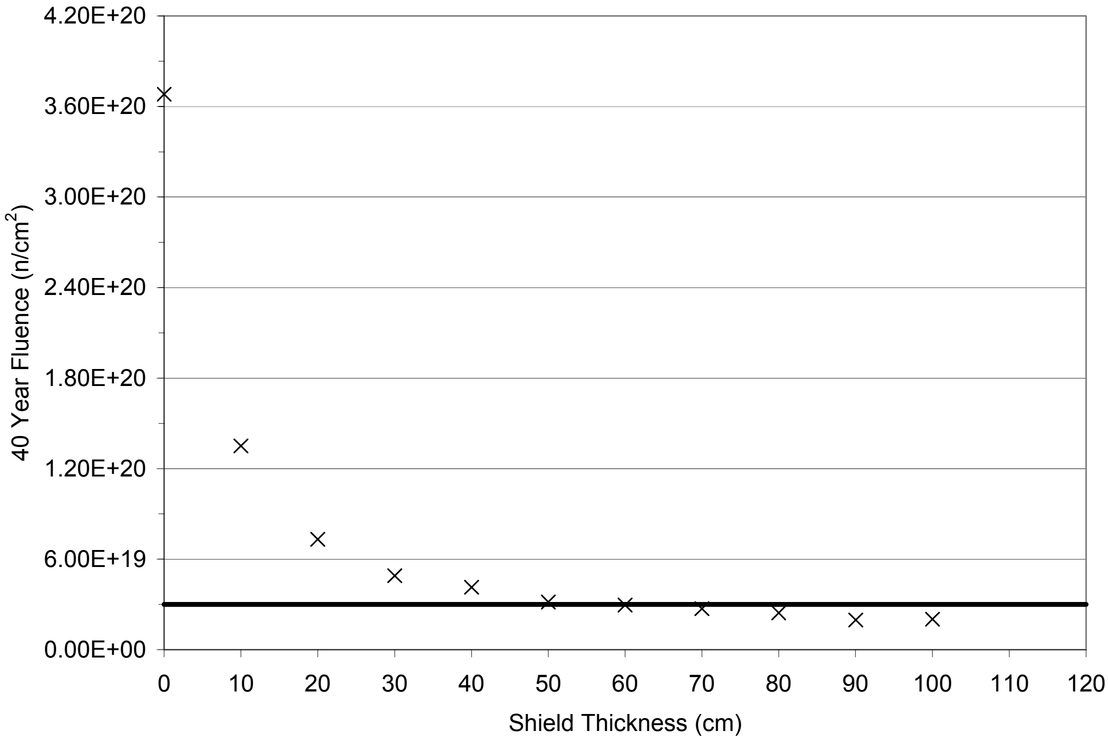

Figure 3. Vessel head parametric studies results.

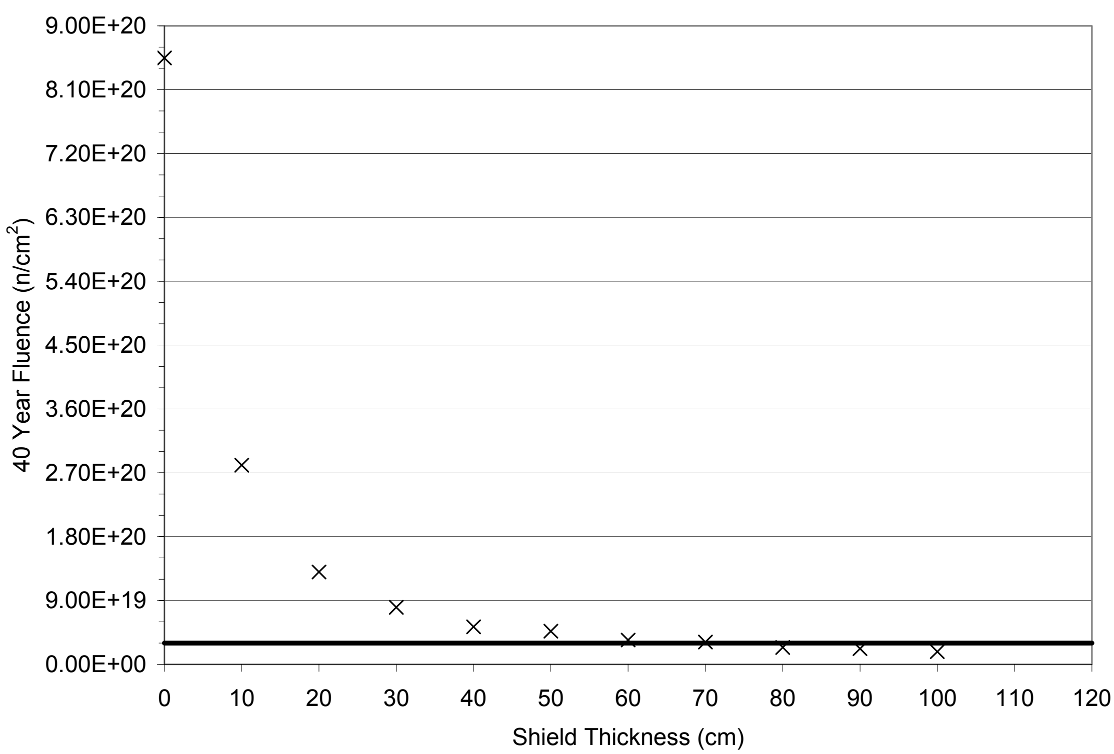

Figure 4. Core grid plate parametric studies results.

Preliminary Shield Designs

Since helium coolant needs to flow through the subassemblies, a solid shielding block is not a realistic option. Incorporating helium flow passages in the shielding will tend to increase the overall axial dimension of the shielding. The flow passages must be designed in a manner which prevents neutron streaming paths allowing the neutrons to escape the subassembly without passing through the shielding material. The passages must also be designed to allow for cooling of the reactor through natural convection under certain circumstances. Two very preliminary shielding designs have been implemented into the MCNP model to look at the effects of cooling passages on the neutron fluence at the vessel head and the core grid plate. Also integrated in these models are tallies to estimate the neutron and gamma energy deposition (heating) in the shielding.

These preliminary designs start with the previously described model. One design incorporates a conical flow channel for both the top and bottom of the assembly. Care was taken to maintain 70 cm of effective shielding thickness above the fuel pins and 80 cm of effective shielding below the fuel pins. The shielding was modeled explicitly and is shown in Figure 5. The second preliminary design incorporates an angled channel as shown in Figures 6. This design again maintains the 70 cm and 80 cm above and below the fuel pins respectively.

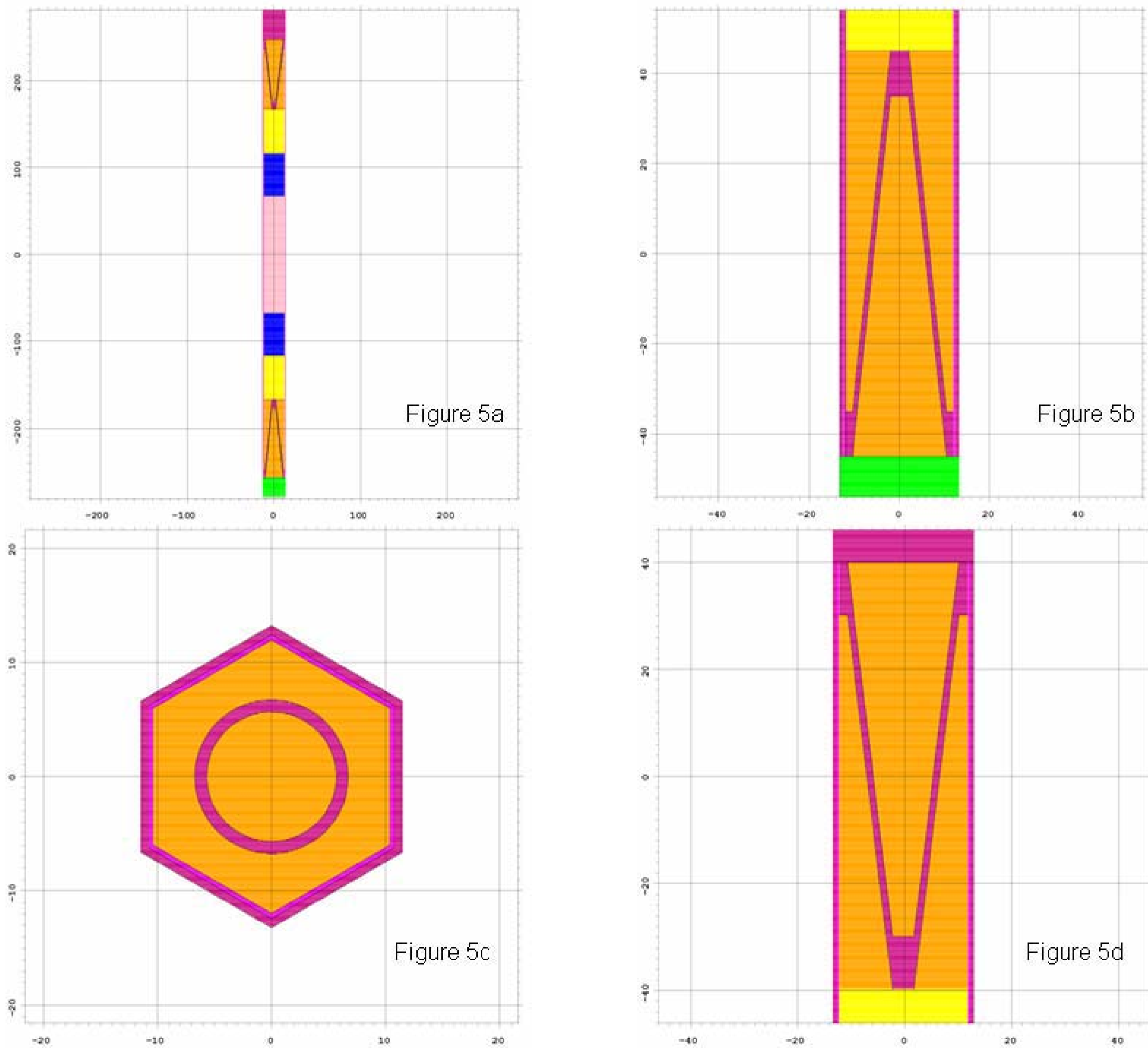

Figure 5. Conical type flow passage. Figure 5a is an axial representation from the core grid plate to the upper shielding. The colors are the same as defined for Figure 2 (the pink color is the hexagonal duct). Figure 5b is an axial cross section at the lower shielding. Figure 5c is a radial cross section at the lower shielding. It would be the same for the upper shielding. Figure 5d is an axial cross section of the upper shielding.

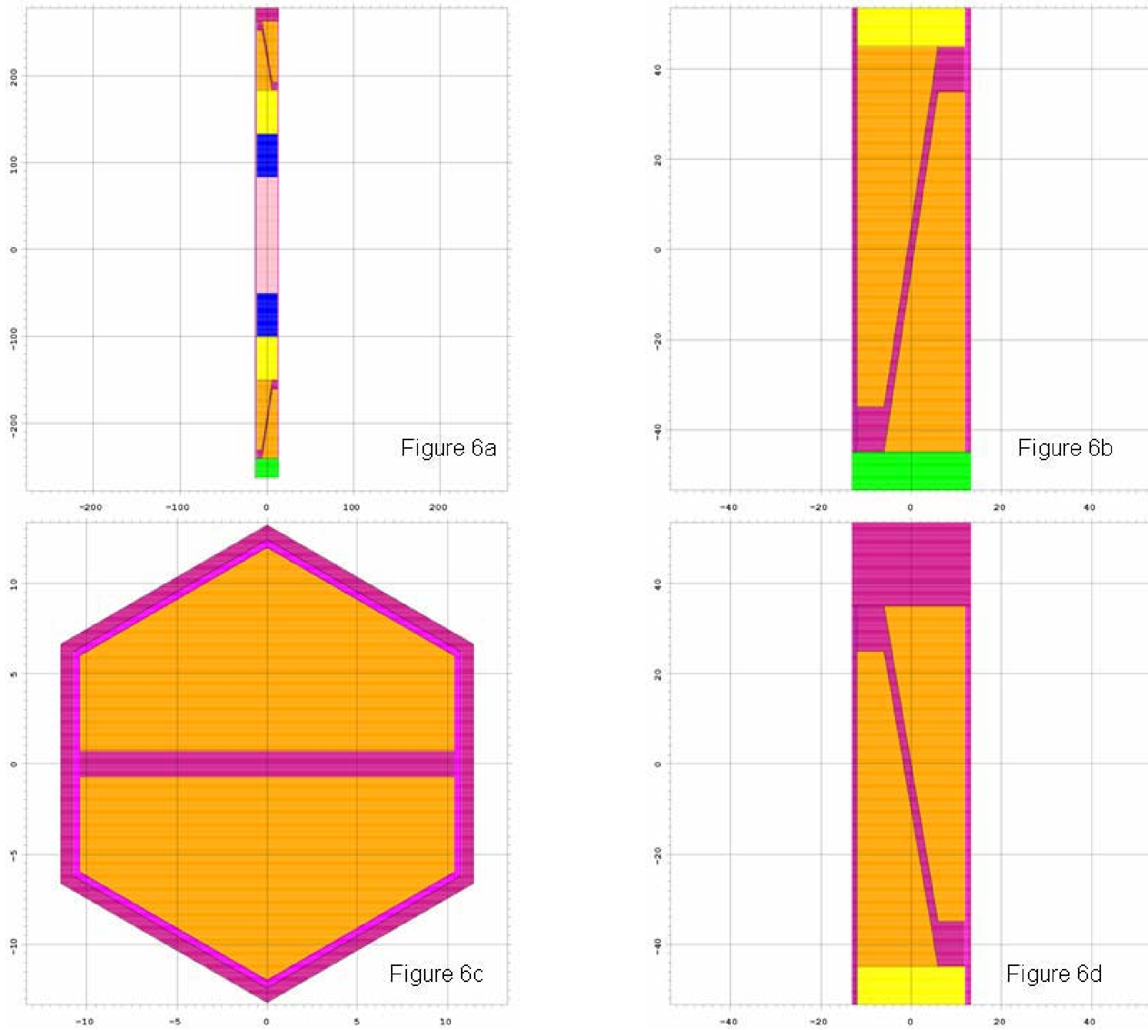

Figure 6. Channel type flow passage. Figure 6a is an axial representation from the core grid plate to the upper shielding. The colors are the same as defined for Figure 2. Figure 5b is an axial cross section at the lower shielding. Figure 5c is a radial cross section at the lower shielding. It would be the same for the upper shielding. Figure 5d is an axial cross section of the upper shielding.

Preliminary Shield Design Results

The two preliminary designs provided fluence results in line with what the parametric studies indicated they should be as shown in Table 3. Maintaining the effective thickness of the shielding gives assurance that the fluence limits will not be compromised. Maintaining the effective thickness does lengthen the overall shielding height and thus the subassembly height, but the extra shielding length may provide slightly enhanced capabilities by providing more effective shielding thickness for the neutrons leaving the origination subassembly and entering an adjacent subassembly shielding zone. These designs have not had any optimization (as is evident in the figures) performed for thermal hydraulic flow either under forced convection or natural convection. As more configurations are analyzed, the optimization of helium flow needs to be addressed.

Table 3. Flux and fluence results for conical shape and channel shape flow passage shielding designs.

Flow Passage Description	Vessel Head		Core Grid Plate	
	Flux (n/cm^2-s)	Fluence (n/cm^2)	Flux (n/cm^2-s)	Fluence (n/cm^2)
Cone Shape	2.10E+10	2.65E+19	1.74E+10	2.20E+19
Slab Shape	2.18E+10	2.75E+19	1.80E+10	2.28E+19

The heating results for the shielding suggest the additional heat generated in the shielding is insignificant when compared to the overall subassembly heat generation rate. The heating results are shown in Table 4. It is large enough that it likely cannot be ignored for the thermal hydraulic calculations but should not pose any problems. Decay heat from the various activation products in the shielding has not been considered at this point. However, the decay heat is typically much lower than the heat generated through the neutron and photon energy deposition.

Table 4. Heating rates for the conical shape and channel shpe flow passage shielding designs.

Flow Passage Description	Shielding Material Heating			
	Vessel Head		Core Grid Plate	
	W/gm	Total Watts	W/gm	Total Watts
Cone Shape	4.61E-03	635	4.04E-03	635
Slab Shape	4.62E-03	636	4.04E-03	635

Future work

More flow passage configurations need to be analyzed and all of the configurations need to be optimized for helium flow. Eventually a more accurate multi-subassembly model (possibly as large as a full core) would be beneficial to evaluate to confirm the results of the single subassembly model. Feedback and suggestions from thermal hydraulic experts on optimal flow passage configurations would be useful for incorporation into the models to prevent wasting time on configurations which have no chance of meeting cooling requirements. Activation cross sections will be generated using MCNP for the shielding materials and used with the ORIGEN2 [3] computer code to estimate the decay heat rates in the shielding.

References

[1] Tim Goorley, Jeff Bull, Forrest Brown, et. al., "Release of MCNP5_RSICC_1.30," MCNP Monte Carlo Team X-5, LA-UR-04-4519, Los Alamos National Laboratory, November 2004

[2] J. Rouault, T. Y. C. Wei, "Development of Gen IV Advanced Gas-Cooled Reactor with Hardened/Fast Neutron Spectrum", International Nuclear Energy Research Initiative #2001-002-f, May 2004.

[3] A. G. Croff, .A User.s Manual for ORIGEN2 Computer Code,. Oak Ridge National Laboratory report ORNL/TM-7175 (July 1980).