Effects of Neutron Radiation and Shielding Recommendations for the PFRC4

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Abstract

Shielding is required in a fusion reactor to protect both the sensitive parts of the reactor and operators from energetic neutrons produced by the reaction being burned. To determine how much shielding is necessary to maintain superconductivity at liquid nitrogen temperatures, a variety of shielding materials and configurations were tested and the fluence delivered to the conductors was recorded. Alternate configurations included varying the thickness of shielding between and beneath the conductors. Alternate materials included isotopically enriched varieties of B4C, and the presence or absence of a tungsten layer between the B4C shielding and the plasma. Also considered were the possible effects of the radiation on humans in close proximity to the reactor. In addition to determining how these design changes affect the neutron fluence to the superconductors, we also investigated the effects of these changes on the helium production, nuclear heating, and displacements per atom (DPA) in the inner vacuum vessel wall, the B4C shielding, and the RF antenna. Conductor fluence was the most significant determinant for the minimum amount of shielding needed. Heating due to the neutron radiation was not a major factor in reactor design because a very small amount of energy of the reactor comes out in neutrons. Heating due to bremsstrahlung and synchrotron radiation is much more significant than heating from neutron radiation, and thus would dominate design choices based on cooling requirements. Displacements per atom could have a significant effect on reactor materials, but further studies on the rate of DPA caused by the reactor neutron flux would be required to determine these effects precisely. Additional shielding could even keep human operators near the reactor safe during testing, but would not be recommended for a space-travelling reactor due to the additional mass. 32.85 cm of shielding was sufficient to ensure a lifetime of at least 30 years for the superconductors. A detailed study on the precise effects of neutron irradiation on high-temperature superconductor materials would be desirable, since it is currently unknown exactly how the materials respond to such irradiation. Data on fluence levels for changes in critical current and temperature exist, but understanding the microscopic effects on the materials would yield a better understanding of the mechanisms that cause these effects. It is also of interest to study the effects of the small number of 14.1 MeV neutrons produced by secondary deuterium-tritium reactions. As the reactor design is further developed, a study of different shielding designs would be helpful in determining the optimal configuration for the final reactor.

Introduction

The field-reversed configuration (FRC) reactor is a fusion reactor that burns deuterium and Helium-3

$$^2D + ^3He \rightarrow ^4He + ^1p + 18.3 \text{ MeV}$$

This reaction is aneutronic, which has several advantages in reactor design. Neutron bombardment causes many harmful effects on materials. Energetic neutrons can collide with atoms in materials, knocking them out of their lattice sites, inducing radioactivity, and causing heating. This damage can cause embrittlement, swelling, and helium production on a macroscopic scale [1]. Additionally, neutron radiation is considered the most dangerous form of radiation to humans due to the high kinetic energy of neutrons and the secondary beta and gamma radiation they can cause [2]. Because they have no charge, neutrons cannot be contained in a magnetic field, requiring shielding to protect against these effects. An aneutronic fusion reactor thus will require less shielding than one that burns D-T.

A reactor burning D^{-3}He will produce some neutrons through the small number of D-D and secondary D-T reactions that will occur. These reactions and the resulting wall load of neutrons from these reactions can be reduced in a number of ways, including making the reactor smaller, removing the produced tritons, using a 3He-rich fuel mixture, and operating at a non-optimal temperature for D-T and D-D fusion, and it is theoretically possible to reduce the wall load of neutrons by a factor of ten thousand compared to a D-T Tokomak of similar power output [3]. However, some neutrons will inevitably be produced, so some shielding will be required in a FRC reactor.

The Princeton FRC reactor (PFRC) is an experimental reactor built by Sam Cohen and currently being studied at Princeton Plasma Physics Laboratory. Currently, the second version of the reactor, the PFRC2, has been built and is in the process of being tested. The PFRC4 reactor, currently being designed at Princeton Plasma Physics Laboratory, will produce more power than it consumes, but will still be considerably smaller than a traditional breakeven fusion device. This ellipsoidal reactor will burn a plasma that produces approximately 1MW per meter of reactor length. The reactor will have a semimajor axis of approximately 1.2m and a semiminor axis of approximately 0.3m without shielding, and will thus produce about 2.4 MW of power.

Traditional magnetic confinement fusion reactors require strong magnetic fields to maintain confinement, so they must use low temperature superconductors like Nb_3Sn because low temperature superconductors have higher critical field values. Because the PFRC4 will have a magnetic field of only 60-70 kG, it will be able to use high temperature superconductors like BiSCCO or YBCO without the concern of the critical field of the conductors being exceeded [4]. This means that instead of being cooled by liquid helium, they can be cooled with liquid nitrogen, as long as the conductors maintain a critical temperature below the evaporation point of liquid nitrogen, 77K. Using liquid nitrogen instead of liquid neon or helium will mean that far less power will need to be supplied to the conductor cooling system, so the reactor will be more efficient.

However, high temperature superconductors like BiSCCO and YBCO will not maintain a critical temperature below 77K, if they are subject to large neutron fluences [5]. Although small fluences of neutrons can improve the performance of a superconductor, large neutron fluences cause the critical current and the critical temperature to drop. Thus it is crucial that the superconductors are adequately shielded so that the conductors can maintain a high critical current and temperature.

Methods

The PFRC is still being developed and tested, so the PFRC4 is still in the preliminary design stage. In order to determine the effects of neutron radiation on the reactor, simulations using a model of the reactor must be used. The neutron radiation in the reactor and the effects on the materials of the reactor were simulated using computer model and particle simulation software. An initial model of the reactor was developed in SolidWorks to use for the simulations. This model was further developed and refined according to the results of these simulations.

In order to reduce the complexity of the calculation, geometric symmetries were used so that only a portion of the reactor had to be modeled. The initial model was a 90-degree cylindrical sector (see figure 1). This model assumed that the reactor was an infinitely long cylinder, since it used reflecting boundary conditions on the two end faces. For this study, the neutron radiation will be assumed to be uniform throughout a cylindrical region within the plasma with a radius of 25cm and spanning the length of the reactor. In reality, the neutrons will not be emitted uniformly, with a greater intensity coming from the center of the reactor, but this model will provide a good approximation because the reactor length is several times its diameter.

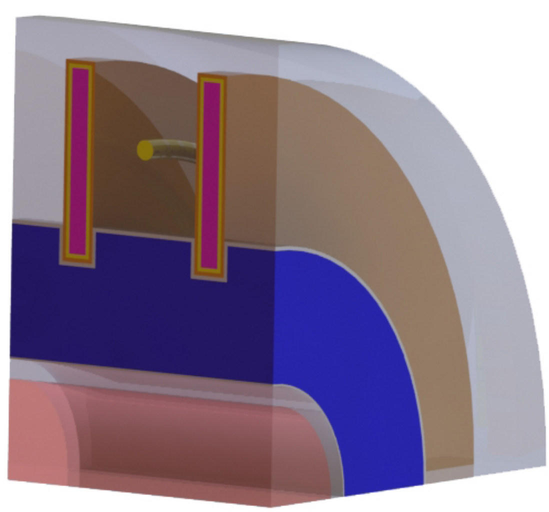

Figure 1: Initial solid model of reactor used for simulations. Model uses 90-degree symmetry of and model reactor as uniform, infinitely long cylinder.

Equation	Energy	%
${}^2D + {}^3HE \rightarrow {}^4HE + p$	18.3 MeV	98
${}^2D + {}^2D \rightarrow {}^3T + p$	4.03 MeV	1
${}^2D + {}^2D \rightarrow {}^3He + n$	3.27 MeV	1

Table 1: Energy and percentage of total fusion events for each reaction that will occur in the PFRC

The particle simulation software Attila was used to analyze the effects of neutron radiation on the materials of the reactor as well as potential hazards to humans in the vicinity of the reactor. Attila uses Chebyshev-Legendre quadrature to solve a particle transport problem in space, angle, and energy. The model geometry is given to the program and divided into a finite element mesh. The precision of the solution can be adjusted by refining the mesh as well as controlling the order of the polynomials used in both angular quadrature and the scattering of particles and the fineness of the energy groups of particles that are used.

In order to run the simulation in Attila, some parameters of the reactor's operation must be determined. The reactor produces 2.4MW of power, resulting in a small number of 2.45MeV neutrons. The number of neutrons produced can be estimated as either 1% of the reactor or produced by 1% of the fusion events in the reactor.

If 1% of the reactor power is released as 2.45MeV neutrons, there are 24000W of power released in the neutrons. Assuming the power is released as kinetic energy, there is 24000W, or $3.8452 \cdot 10^{17}$ MeV of kinetic energy released in the neutrons per second. With 2.45MeV of kinetic energy per neutron, this works out to $6.11413 \cdot 10^{16}$ neutrons released per second.

If 1% of the fusion events produce a neutron, 1% of the fusion events in the reactor are deuterium-deuterium reactions that produce a 2.45MeV neutron. Since 50% of deuterium-deuterium fusion reactions follow this chain, the profile for the fusion events taking place in the reactor is:

Therefore for every 100 fusion events, and thus every 2.45MeV neutron released, 824.62MeV of energy is produced by the reactor. In total, the reactor produces 2.4MJ, or $3.8452 \cdot 10^{20}$MeV of energy every second. This works out to $1.81655 \cdot 10^{16}$ neutrons released per second. For the purposes of this study, it is assumed that 1% of the reactor power is released in neutrons, and thus $6.11413 \cdot 10^{16}$ neutrons are released per second. This number is entered into Attila to properly scale neutron flux results.

Nuclear heating of the materials in the reactor will occur due to the neutron fluence. Attila results are output in the units of ev/s, so in order to scale this to usable units, the results must be converted to Watts, or J/s. This calculation must also be scaled for the reactor flux, since the Attila calculation is by default scaled for the emission of 1 neutron/s. The resulting scale factor is

$$1.60 \times 10^{-19} \text{ eV/J} \cdot 6.11 \times 10^{16} [.] = 9.80 \times 10^{-3} \text{ W-s/eV}$$

The displacements per atom reaction rate is unique to each material. Material specific reaction rates were taken from a material properties library prepared for the ITER project. Attila uses these reaction rates to output a value in displacements per sec per volume. These values are multiplied by the flux scale factor, $6.11413 \cdot 10^{16}$ neutrons/s. Then the values for each material must be divided by the atomic density of that material. The result then has units of displacements per atom per sec.

With all scaling factors calculated, useful results can be obtained from Attila. These scaling factors are multiplied by the associated Attila output to give the calculated results on the actual reactor in steady state.

To reduce computation time, we changed the model from a 90 degree sector to a 10 degree sector, which is equivalent because the reactor is axisymmetric (see figure 2). This makes the calculation slightly problematic in Attila, because the only boundary conditions that can be applied are the reflecting ones on the side faces of the slice. Thus, we extended the 10 degree model to the full length of the reactor and added caps with axial holes for the fuel supply and exhaust (see figure 2). This model still assumes the reactor is cylindrical, but adds the effects of the ends of the reactor. The fusion region of the actual reactor will be ellipsoidal within a cylindrical space due to the confinement of the magnetic fields. However, as stated before, because the length is several times the radius, the plasma will fill an approximately cylindrical region.

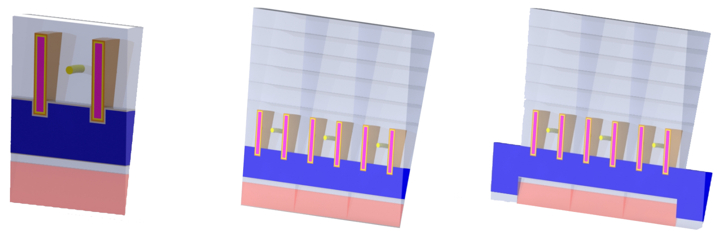

Figure 2: **Left:** Solid model of 10° solid model section of reactor. **Center:** Full-length solid model of 10° sector of reactor. **Right:** with end cap and axial ports; this model was the final model made for simulations

We gathered results from Attila for scalar flux, nuclear heating displacements per atom, helium production, and face flow across the inner faces of the superconductors and at distances of 20cm, 40cm, 60cm. 80cm, and 100cm from the top of the superconducting coils.

Results

The critical temperature of a YBCO superconductor decreases linearly with fluence [4]. It is desired that the critical temperature does not fall below the boiling point of liquid nitrogen, because this would require the implementation of a liquid neon or helium cooling system, which would add cost and complexity to the project. Liquid nitrogen boils at 77K at 1 atm. If the pressure inside the cooling system is maintained at 1atm or less, the boiling temperature of nitrogen will be 77K or less. Thus, maintaining a critical temperature above 77K is a conservative target when designing shielding.

When a YBCO superconductor is subject to a fluence of $5.38 \cdot 10^1 8$neutrons/cm^2, the critical temperature drops to 77K[4], the Carnot efficiency of the liquid nitrogen cooling system would be 0, and the superconductors would enter the ordinary conductor regime. Since conductor fluence and critical temperature are inversely related,

$$T_c = -2.406 \cdot 10^{-18} \times \text{fluence} + 89.94$$

a lower fluence results in a higher the critical temperature, and thus a lower power required for the cooling system. Thus minimizing shielding to decrease reactor weight and cost must be balanced with shielding the conductors enough so that the cooling system does not become inefficient and expensive. The fluence of $6.0 \cdot 10^{17}$ neutrons/cm^2 has been chosen as the maximum tolerable fluence because it results in a critical temperature of 88.50K, which yields an acceptable Carnot efficiency of 12.99%, and because it guarantees that the critical current will not be reduced by more than 5% [4] .

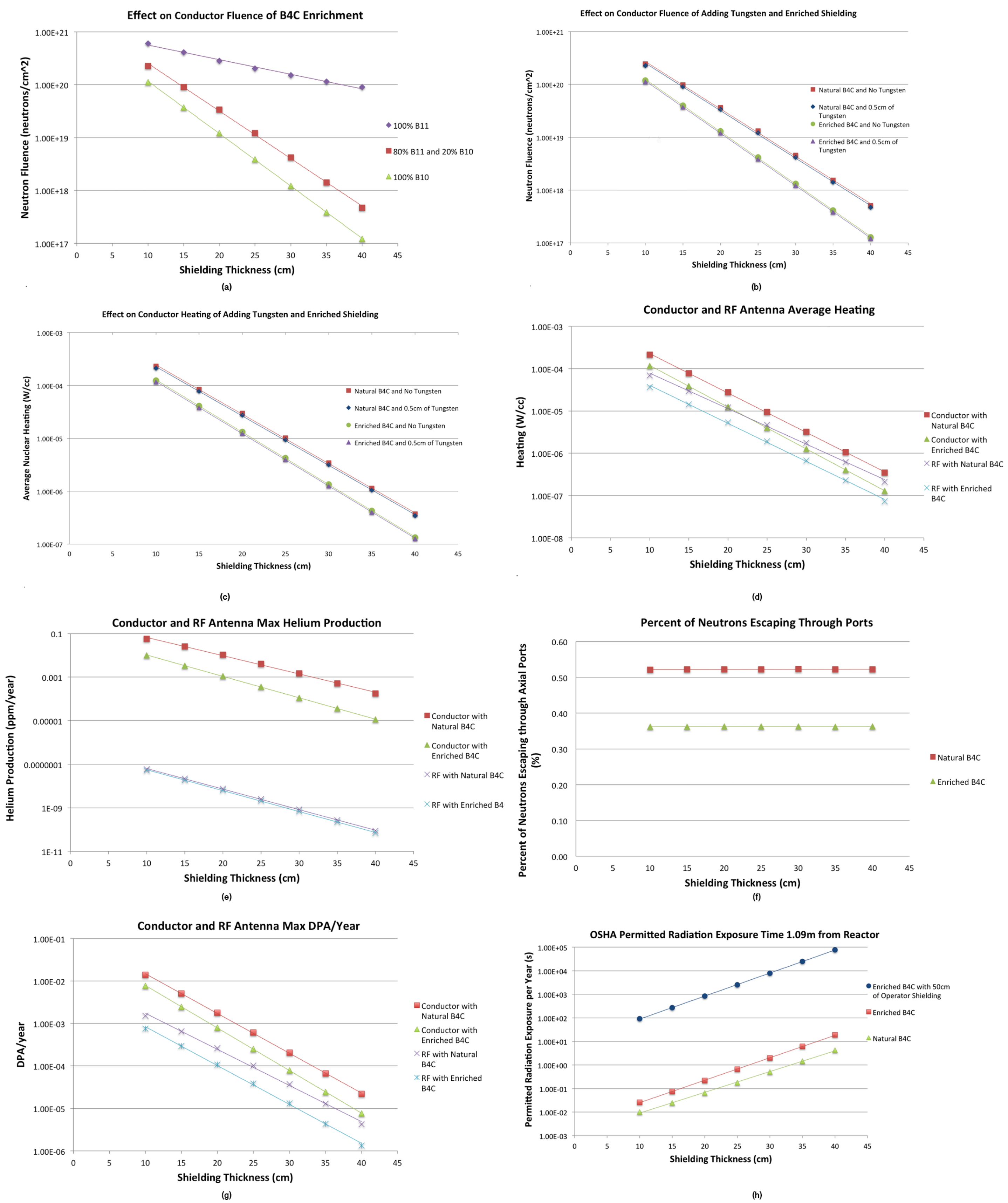

Figure 3: Graph of all results. All results calculated for a 2.4 MW, 2.4-m long, 25-cm plasma-radius D^{-3}He (1:3) fusion reactor with all tritium (fusion products) removed.

Conductor Fluence

The YBCO high temperature superconductors will be subject to fluences less than $6.0 \cdot 10^{17}$ neutrons/cm^2 will experience no more than a 5% loss in performance. Assuming a 30 year life span of the reactor, 32.85cm of enriched shielding or 38.87cm of natural B_4C shielding are needed to stay below this fluence (see figures 3a, 3b). Enriching the shielding from 80% B11 and 20% B10 to 100% B10 is more effective at decreasing conductor fluence than adding a 0.5cm tungsten layer between the plasma and the shielding. Enriching the shielding decreases conductor fluence by between 50.75% and 74.73% (depending on the shielding thickness). Meanwhile, adding a tungsten layer only decreases conductor fluence by between 6.55% and 13.65%. All three shielding grades provide adequate protection, but the B10 enriched shielding, as expected, yields the lowest neutron fluences and thus will provide the lowest losses in superconductor performance and the most efficient liquid nitrogen cooling system.

Nuclear Heating

Nuclear heating values due to neutron flux are low relative to the heating due to bremsstrahlung and synchrotron radiation, which together are about 30 times greater. When multiplied by the volume of the component, heating values for the conductors and RF antenna are less than 121 W, which is very small compared to the 2.4 MW output of the reactor and probably negligible (see figures 3c, 3d). The total heating in the shielding and tungsten cooling coils is about 40 kW, which is also small compared to the output of the reactor but likely non-negligble. Similarly to the effect for fluence, enriching the shielding is more effective at decreasing conductor heating than adding a tungsten layer. Enriching the shielding decreases conductor heating by between 45.81% and 63.94% (depending on the shielding thickness). Meanwhile, adding a tungsten layer only decreases heating by between 7.52% and 7.83%.

Helium Production

All helium production values are smaller than 1ppm produced per year. Copper is not noticeably embrittled at <1 He ppm [6] (see figure 3e). Steel is even more resilient to He embrittlement [7], so both the RF antenna and conductor coating that encases the YBCO superconductor ribbon will be insignificantly affected with any of these shielding thicknesses or materials. It is possible that the helium production will be a problem in the shielding, but could be mitigated with channels designed to carry helium out of the solid.

Neutron Losses

Fewer neutrons escape through the axial ports when enriched shielding is used. However, for both shielding materials the total percent of neutrons that are escaping is very small compared to the total number produced (see figure 3f).

Displacements per Atom

All values are exceptionally low (< .1dpa produced per year) and will not contribute to structural deterioration (see figure 3g). The superconductors will experience decreased performance at high DPA values [5]. Although tolerable DPA levels could not be determined exactly, the results from conductor fluence suggest that approximately 32.85cm of enriched shielding or 38.87cm of natural B_4C shielding are required to remain within 5% of maximum performance. Please note that the conductor DPA results are calculated using the material properties of Nb_3Sn because the material properties of YBCO were not available. Thus conductor DPA values are meant to be an approximation rather than a precise calculation. A detailed study of the effects of DPA on superconductor performance would be required to determine the DPA limits for the superconductors.

Human Exposure Results

Acceptable values depend on the how often and for how long human operators will be in the vincity and how close they will be to the reactor. Adding 50cm of shielding increases safe radiation exposure times by more than 3 orders of magnitude [8] (see figure 3h). After that, each additional 20cm of shielding outside around the coils increases safe exposure times by another two orders of magnitude. So with 1.1 m of total shielding, a human could safely spend 44% of their working hours 1.09m from the reactor.

Discussion and Conclusions

Particles and energy must be conserved within the simulation in order for Attila to converge and give a result. Thus, the simulation should be reliable, assuming all other input data is correct. Nuclear engineers at the Princeton Plasma Physics Laboratory working on the ITER project have compared results from Attila calculations to results from similar calculations performed with well established Monte Carlo Methods to validate the accuracy of Attila's solutions. However, back of the envelope comparisons to hand calculations are desirable in order to further verify results.

A calculation for how the neutron flux will fall off through the shielding material can be used to verify neutron flux results for the superconductor. The two causes of flux drop off are an increased surface area as distance from the reactor increases and collisions with shielding material atoms. The fusion region is a cylinder with radius 25cm. The superconducting coils will be 62.85cm from the center axis of this region. Thus, near the center of the cylinder, the surface area will be $62.85/25 = 2.514$ times as large for the same amount of flux, so the flux on the inner edge of the superconducting coils will be 39.78% of the flux at the edge of the fusion region, without taking into consideration shielding.

There are 6.114×10^{16} neutrons with an energy of 2.45 MeV produced in the reactor every second. The fusion region has a height of 240cm, so the average flux on the surface of this region will be

$$\frac{6.11 \times 1016 \text{ n/s}}{2\pi \cdot (25 \text{ cm})^2 + 2\pi \cdot 25 \text{ cm} \cdot 240 \text{ cm}} = 1.47 \times 10^{12} \frac{n}{cm^2 s}$$

These neutrons will collide with nuclei in the reactor according to the material cross sections for 2.45 MeV neutrons.

The number of particles that are absorbed as they travel through the shielding material is dependent upon the mean free path of the neutrons through the material, which comes from the material cross section. For this calculation, only the boron carbide shielding and tungsten cooling coils will be considered because they will receive the majority of the neutron flux. Additionally, boron carbide represents the majority of the volume of the reactor, so it will have the largest effect on neutron interactions. The mean free path can be calculated from the macroscopic cross section,

$$\lambda = \frac{1}{\Sigma}[9]$$

$$\Sigma = N \cdot \sigma[9]$$

Where N is the atomic density and sigma is the microscopic cross section of the target material (see table 2). According to the Beer-Lambert Law, the probability that a particle will not be stopped a distance x through the material is

$$P = e^{x/\lambda}[9]$$

The shielding thickness is 32.85cm, and the tungsten thickness is .5cm, so the total percentage of 2.45 MeV neutrons and

$$\% = (1 - e^{-.5/36.14}) \cdot (1 - e^{-32.85/27.49}) = 29.86\%$$

Some neutrons will also collide with other neutrons as they radiate out of the reactor. These collisions will transfer some energy between the neutrons, and thus cause some neutrons to fall to lower energy groups. For a rough approximation, we will assume that about 1% of the neutrons will lose sufficient energy on the way out of the plasma region to be absorbed or thermalized by the boron carbide shielding with near certainty. The shielding thickness is 32.85cm, and the tungsten thickness is .5cm, so the total percentage of 2.45 MeV neutrons not stopped will be

Combining all of these factors, we get

$$\text{flux in superconductors} = (\text{flux on surface of plasma}) * (\text{drop due to area expansion}) * (\text{drop due to absorption}) * (\text{drop due to collisions})$$
$$\text{flux in superconductors} = 1.46882 \cdot 10^{12} \cdot (.3978) \cdot (.2986) \cdot (.99) = 1.72716 * 1011 \frac{n}{cm^2 s}$$

This flux is about two orders of magnitude higher than the Attila results indicate. However, the total percentage of neutrons absorbed is about 90%. Attila results indicate that about 99.9% of the neutrons will be either absorbed or dropped to a low enough energy group that they will not be damaging to the superconductors. Thus, there is only about a 10% error in this comparison. For a back of the envelope calculation, an error of 10% is most likely sufficient to verify the results.

To verify heating results, we will calculate the amount of energy expected to be absorbed by the reactor, and conservation of energy must hold. In conventional applications, energy conservation would simply mean that the amount of energy output

Neutron Energy (MeV)	B4C sigma	B4C lambda	Tungsten Total	Tungsten lambda
2.466	0.264873	27.49	0.43877	36.14
1.8268	0.264873	27.49	0.43877	36.14
1.3534	0.281497	25.87	0.431171	36.78
1.0026	0.320781	22.7	0.422113	37.57
0.74274	0.395014	18.43	0.418685	37.88
0.55023	0.487201	14.95	0.419057	37.84
0.40762	0.583135	12.49	0.433065	36.62
0.30197	0.620232	11.74	0.449713	35.26
0.22371	0.637968	11.41	0.476403	33.29
0.16573	0.637131	11.43	0.509701	31.11
0.12277	0.630921	11.54	0.546939	28.99
0.067379	0.633876	11.49	0.391753	40.48
0.031828	0.682746	10.67	0.282651	56.11
0.015034	0.803657	9.06	0.249178	63.64
0.0071017	1.00228	7.27	0.236262	67.12
0.0033546	1.29961	5.6	0.224624	70.6
0.0015846	1.7369	4.19	0.279535	56.73
0.00074852	2.37316	3.07	0.243554	65.11
0.00035358	3.29962	2.21	0.293405	54.05
0.00016702	4.64881	1.57	0.469814	33.75
0.000078893	6.61024	1.1	0.320754	49.44
0.000037267	9.46298	0.77	0.61479	25.79
0.000017603	13.6165	0.53	4.18461	3.79
8.3153E-06	19.6654	0.37	1.48754	10.66
3.9279E-06	28.4609	0.26	0.770592	20.58
1.8554E-06	41.251	0.18	0.583534	27.18
8.7642E-07	59.8631	0.12	0.507059	31.28
4.1399E-07	86.9444	0.08	0.567829	27.93
1.00E-07	188.261	0.04	0.827014	19.18
1.00E-11	392.077	0.02	1.19492	13.27

Table 2: Neutron interaction cross sections and mean free paths for B10-enriched boron carbide and natural tungsten, the primary reactor materials for interactions with neutrons. Cross sections in barns, mean free paths in centimeters

equals the amount of energy dissipated plus the amount of energy escaped. However, because particle interactions are involved, the calculation is not so straightforward. Neutrons have energy due to their mass in addition to their kinetic energy, thus, when a neutron is absorbed by a nucleus, it is possible for the atom to receive more energy, and thus be heated, more than the kinetic energy of the neutron.

A neutron emitted by the reactor has 2.45 MeV of kinetic energy. The mass of the neutron provides

Hand Calculations

A comparison to hand calculations is desirable in order to verify results.

To verify that particles are conserved, an analysis of the particle interactions with the reactor materials must be combined with a measurement of the net flow out of the reactor. The number of particles exiting the reactor must equal the number of particles produced in the plasma plus the net change in particles from collisions with nuclei of other atoms.

$$p_{out} = p_{in} + \triangle_{interaction}$$

There are $6.11413 \cdot 10^{16}$ neutrons with an energy of 2.45 MeV produced in the reactor every second. Within the 10-degree slices, assuming the plasma is axisymmetric, there are therefore $1.69837 \cdot 10^{15}$ neutrons produced every second. These neutrons will collide with nuclei in the reactor according to the material cross sections for 2.45 MeV neutrons, and some will be absorbed by the material nuclei, depending on the corresponding scattering ratios (insert cross sections table). Because the majority of the neutrons at this energy will interact with either tungsten or Boron Carbide, the other materials may be neglected.

The neutrons absorbed by the reactor can be calculated by

$$n_{\text{absorbed}} = \sum \text{flux}_i \cdot \sigma_i \cdot \text{atomic density}_i \cdot \text{volume}_i$$

Which yields $1.54945 \cdot 10^{14}$ neutrons absorbed per second in the 10-degree slice. The subsequent reactions caused by neutron absorption in the boron, carbon, and tungsten nuclei determine the effect on total flow out of the reactor. 11B, 12C, 182W, and 183W can all absorb a neutron and remain stable, and will release a gamma ray by doing so.

$$e = m_n c^2 = 939.57 \text{ MeV}$$

Thus, it is possible for the amount of observed heating to exceed the energy released in the neutrons, which only accounts for the kinetic energy of the neutrons.

To estimate the amount of energy absorbed by the reactor, we must calculate the amount of energy absorbed from scattering neutrons and the energy absorbed by neutron and gamma absorption. For fast neutrons, collisions with atomic nuclei will be very nearly elastic, and the mean fraction of energy loss by a neutron in a collision with a nucleus of atomic weight A is

$$\xi = 1 + \frac{(A-1)^2}{2A} \cdot \ln\left[(A-1)/(A+1)\right]$$

The subsequent reactions caused by neutron absorption in the boron, carbon, and tungsten nuclei dictate the amount of energy absorbed by the target nucleii. ^{10}B, ^{12}C, ^{182}W, and ^{183}W can all absorb a neutron and remain stable. However, ^{11}B, ^{13}C, ^{184}W, and ^{186}W will all undergo beta decay if they absorb a neutron

$$\begin{aligned}
^{12}B &\rightarrow \beta^- + {}^{12}C \\
^{14}C &\rightarrow \beta^- + {}^{14}N \\
^{185}W &\rightarrow \beta^- + {}^{185}Re \\
^{187}W &\rightarrow \beta^- + {}^{187}Re
\end{aligned}$$

To estimate the energy absorbed for heating from each of these reactions, we must look at the mass difference in the reactants and products. For simplicity, we will assume that secondary reactions between daughter nucleii from radioactive decay occur in a small enough quantity to be negligible. We will thus focus only on reactions with the original nucleii in the reactor and assume that all energy from beta particle decay is converted back into heat.

Now, we must calculate the rate of these events occurring and multiply the rate by the energy per event to get the absorbed power. Some of these neutrons will scatter and fall into lower energy groups, and some will be absorbed by the material nuclei, depending on the corresponding cross sections and scattering ratios (see tables 2, 5).

The percentage of neutrons stopped in a material layer includes both neutrons absorbed and scattered by the material. The rapid decrease in scattering ratio for boron carbide suggests that neutrons that scatter off of an atom are very likely to be absorbed after a few collisions, so we will assume that the majority neutrons that are scattered are eventually absorbed. For these neutrons, all of their kinetic energy will be converted to heating.

We will only look at the 2.45 MeV neutrons, since we are assuming that most scattered neutrons will be absorbed. From earlier, 1.37% of neutrons will be stopped as they travel through the tungsten channels and 69.7% of the remaining neutrons, which is 68.8% of the total neutrons, will be stopped in the boron carbide shielding. All of the tungsten reactions yield about 9

Nucleus/Nuclei	Boron-10	Carbon-12	Tungsten
ξ	0.187	0.158	≈ 0.1

Table 3: mean fractional energy drop of neutrons per collision for the nucleii with which the neutrons are most likely to collide.

Nucleus	Mass of nucleus + m_n (u)	Mass of Products (u)	Net Energy (MeV)	Total Heating (MeV)
^{10}B	11.022	11.009	11.45	13.90
^{11}B	12.018	12.000	16.74	19.19
^{12}C	13.009	13.003	4.946	7.396
^{13}C	14.012	14.003	8.333	10.78
^{182}W	182.96	182.95	6.191	8.641
^{183}W	183.96	183.95	7.412	9.862
^{184}W	184.96	184.95	6.186	8.636
^{186}W	186.96	186.96	6.777	9.227

Table 4: Total heating calculation from neutron absorption by the nucleii of materials in the reactor.

Energy Group	Enriched Scatter	Tungsten Scatter
2.466E+00	3.927E-01	6.229E-01
1.827E+00	3.927E-01	6.229E-01
1.353E+00	3.991E-01	6.518E-01
1.003E+00	4.084E-01	7.212E-01
7.427E-01	4.106E-01	7.742E-01
5.502E-01	3.923E-01	7.875E-01
4.076E-01	3.834E-01	7.900E-01
3.020E-01	3.659E-01	8.089E-01
2.237E-01	3.420E-01	8.555E-01
1.657E-01	3.201E-01	8.914E-01
1.228E-01	3.014E-01	9.187E-01
6.738E-02	4.554E-01	9.349E-01
3.183E-02	4.232E-01	9.265E-01
1.503E-02	3.463E-01	9.186E-01
7.102E-03	2.748E-01	9.049E-01
3.355E-03	2.115E-01	8.898E-01
1.585E-03	1.589E-01	8.954E-01
7.485E-04	1.161E-01	8.603E-01
3.536E-04	8.368E-02	8.926E-01
1.670E-04	5.949E-02	8.903E-01
7.889E-05	4.189E-02	8.834E-01
3.727E-05	2.930E-02	9.043E-01
1.760E-05	2.037E-02	6.660E-01
8.315E-06	1.411E-02	7.020E-01
3.928E-06	9.754E-03	1.249E-01
1.855E-06	6.733E-03	4.032E-01
8.764E-07	4.643E-03	5.954E-01
4.140E-07	3.200E-03	5.417E-01
1.000E-07	1.110E-03	3.652E-01
1.000E-11	9.752E-04	2.038E-01

Table 5: Scattering ratio for B-10 enriched boron carbide and tungsten cross sections for neutron interactions.

MeV of heating. For neutrons stopped in the boron carbide, 80% will collide with a boron-10 nucleus, and 20% will collide with a carbon-12 or carbon-13 nucleus (about 99% will collide with a carbon-12 nucleus, so we will take this value for heating) Using the the numbers in table 4 for heating, the resulting heating will be:

$$
\begin{aligned}
6.114 \times 10^{16} (n/s) \cdot (.0137 \cdot 9MeV + 0.688 \cdot (0.8 \cdot 13.90MeV + 0.2 \cdot 7.40MeV) &= 5.3756MeV/s \\
&= 33.552KW
\end{aligned}
$$

Attila results predict about 40 KW of nuclear heating through the entire reactor. With the addition of the caps on the end of the reactors, the superconducting coils and cases, and secondary reactions, the predicted heating value will rise because there will be more collisions to absorb energy. Thus, the heating results are verified to first order approximation.

Different shielding configurations will be necessary for different reactor applications. Applications that do not require human operators to be in the vicinity - for example, unmanned space missions - will need far less shielding than applications that will have human operators in the vicinity of the machine, such as small power plants. The most sensitive components of the reactor, will be exposed to tolerable neutron fluences after 4 years of operation with 32.87cm of shielding. However, while the superconductors will be adequately protected with this amount of shielding, a human could only spend 29.8 seconds each year at a distance of 1.09m from the machine without violating the Occupational Safety and Health Administration (OSHA) regulations [8], and thus being exposed to an intolerable amount of radiation. More shielding is thus needed for applications with human operators in the vicinity.

By adding an additional 50cm of shielding, between and above the conductors, the allowed exposure time from 1.09m increases to 19,400 seconds per year. With an additional 20cm of shielding the safe exposure time increases to 3,180,000 seconds, or 882 hours out of the 2000 hours in a work year. Adding shielding between the reactors will increase the neutron flux through the superconductors, however, which must be considered if designing the reactor for human operation. The boron carbide essentially funnels neutrons through the superconducting coils, which have a smaller cross section. A few additional centimeters of shielding would be required between the coils and the reactor to compensate for this increase in flux. Still, with this much shielding the minor radius of the machine is still only 139.5cm. Thus, small (relative to other fusion reactors) amounts of enriched shielding can make it safe to work in close proximity to the PFRC4.

$$
\begin{aligned}
{}^{13}B &\rightarrow \beta^- + {}^{13}C \\
{}^{185}W &\rightarrow \beta^- + {}^{185}Re \\
{}^{187}W &\rightarrow \beta^- + {}^{187}Re
\end{aligned}
$$

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