Neutron Shielding for a *Small* D-^{3}He-fueled FRC Fusion Reactor Rocket Engine

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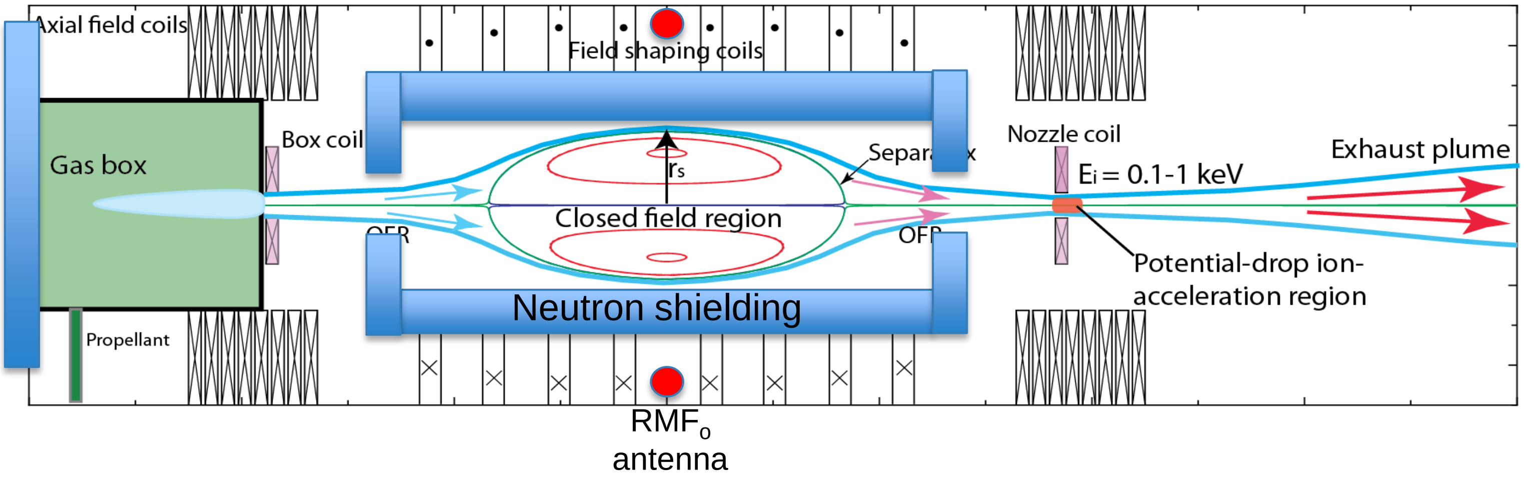
Presentation Overview

- A PFRC-type rocket engine is expected to produce ~ 1 MW/m of power and ~30 Nts thrust at I_{sp}~ 10^6 s, suitable for many interplanetary missions.
- By burning D-^{3}He fuel, PFRC reactors could produce 100x fewer neutrons/MW than a D-T burning reactor.
- We describe methods to achieve the lower neutron wall load and evaluate the shielding requirements for the residual neutron flux:
  - The materials in the PFRC reactor will be able to withstand this level of neutron irradiation for 30 years of continuous operation.
  - Reactor operators could safely stand less than a meter from the reactor for extended periods.

Basic configuration



Princeton Field Reversed Configuration

PFRC – RMF$_o$-heated fusion-reactor rocket engine operates with D-^{3}He reaction, generating all charged particles:

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

Charged particles can be contained in magnetic field, so more energy and directed momentum are available for power and thrust.

The *residual* neutron problem with D-^{3}He

Neutrons are produced from side fusion reactions:

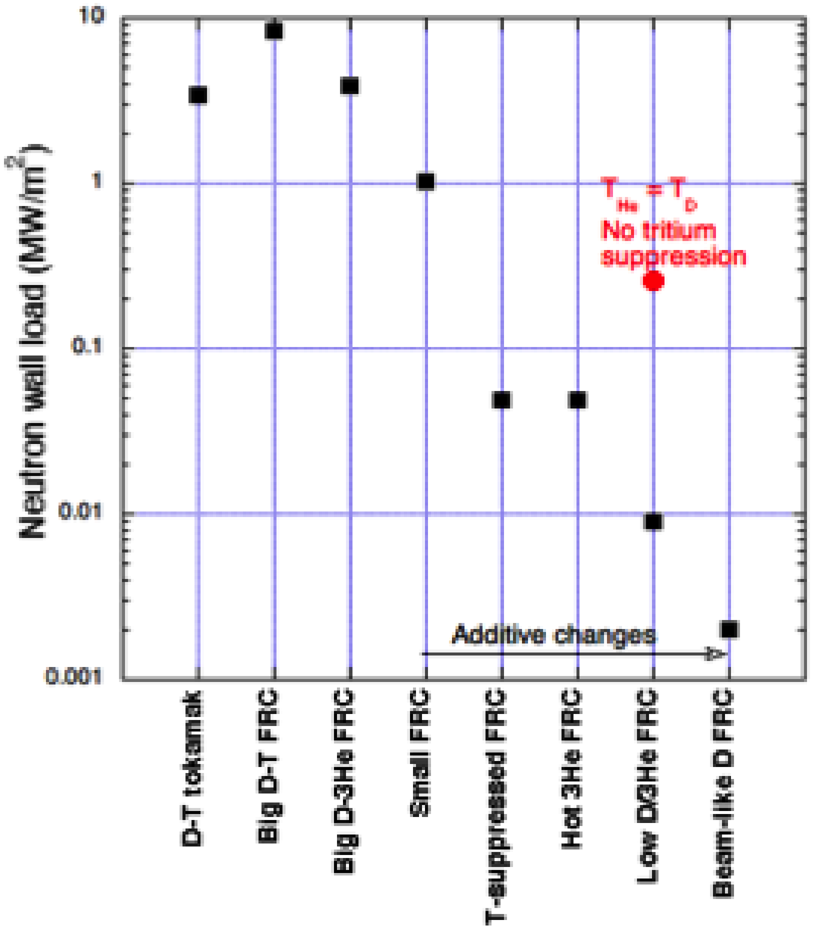
^{2}D + ^{2}D -> ^{3}T (1.01MeV) + ^{1}p (3.01MeV)
-> ^{3}He (.82MeV) + ^{1}n (2.45MeV)

^{2}D + ^{3}T -> ^{4}He (3.5MeV) + ^{1}n (14.1MeV)

Reducing Neutron Production *via* a PFRC

PFRC reduces neutron production by:

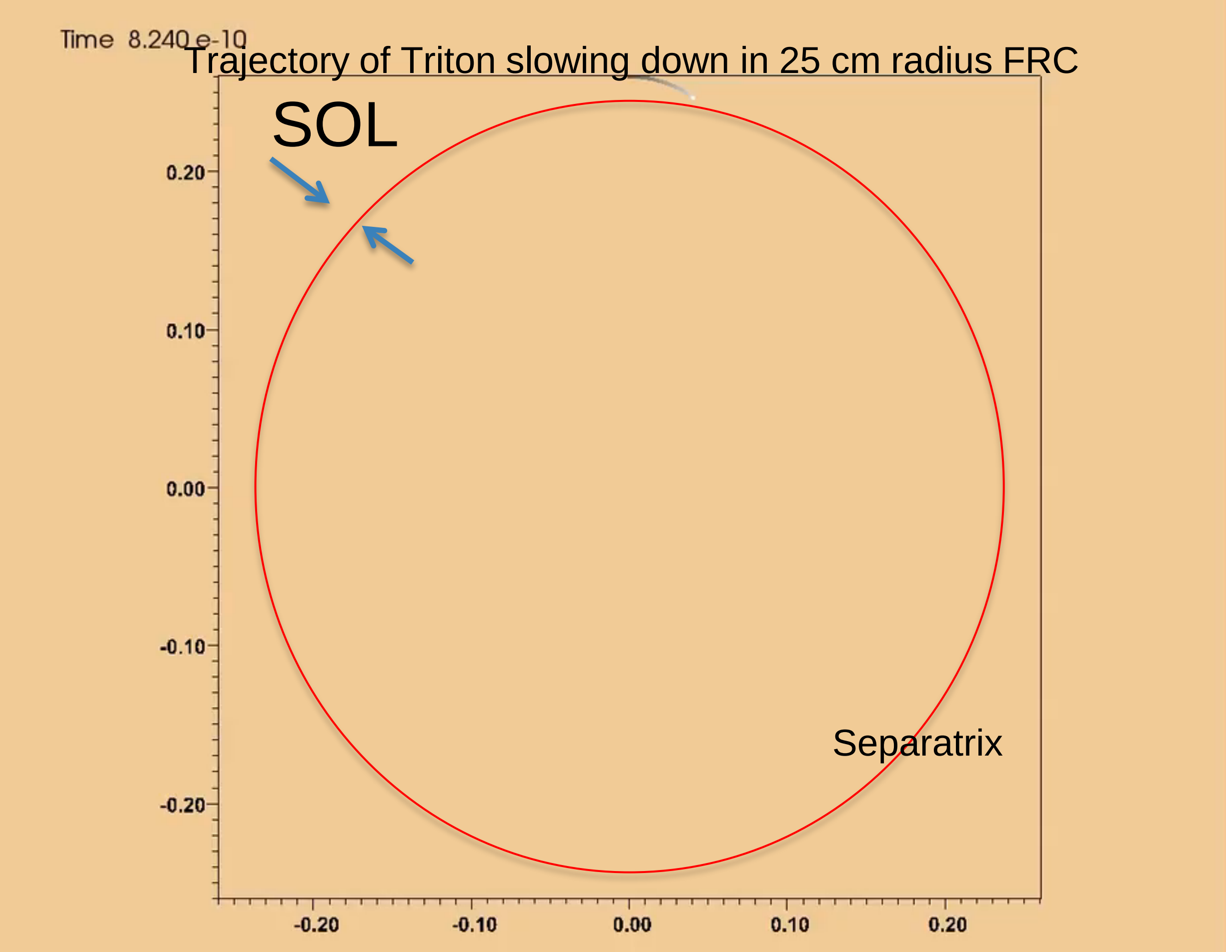
1. Burning D-^{3}He
2. Being smaller (x4)
3. Removing produced tritons (x20)
4. Using a ^{3}He-rich fuel mixture (x6)
5. Operating with different D and ^{3}He energy distributions



RAPID triton loss into SOL of *small* FRC

$s = 0.3 r_s/\rho_i$

Fusion product	s
^{3}He	8.05
T	3.65
P	3.63
^{4}He	3.38



M. Chu-Cheong

PFRC rocket engine parameters

Parameter		Units
Separatrix radius, r_s	0.3	m
Elongation, E	7	
Magnet inner radius	0.66	m
Electron density, n_e	$7x10^{20}$	m^{-3}
Electron temperature, T_e	30	keV
Ion temperature, T_i	120	keV
n_{3He}/n_D	3	
Plasma current	16	MA
Current drive efficiency	16	A/W
Central axial field, B_0	6.8	T
S*/E	3.5	
Energy confinement time, τ_E	8.7	s
$\tau_E/\tau_{E,classical}$	0.3	

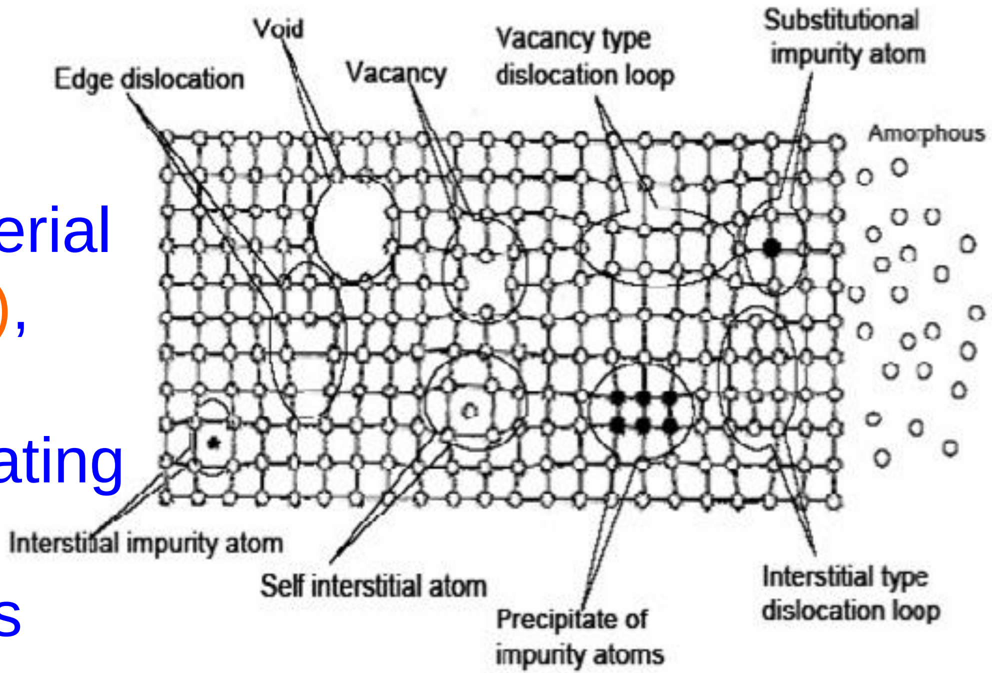
Parameter		Units
RMF penetration criterion	7.2	>2 rqrd
RMF_o frequency, $\omega_{RMF}/2\pi$	0.3	MHz
RMF_o strength, B_{RMF}	0.036	T
RMF_o power absorbed	1	MW
Bremsstrahlung power	2.1	MW
Synchrotron power	4.8	MW
Divertor power	1	MW
Fusion power	12.1	MW
Power in neutrons	0.11	MW
Neutron wall load	0.006	MW/m^2
Energy conversion efficiency	0.5	
Electrical power generated	4.0	MW
Thrust power	4.1	MW

Triton losses: 30-cm radius, 6.8-T FRC

82% lost in 0.1 s, then 17% lost in next 0.1 s, while T burn-up time ~ 12 s

Neutron Radiation Damage to Materials

- Microscopic:
  - Changes in the lattice organization of the material (displaces atoms (DPA), creates interstitials)
  - Excitation of atoms, heating
  - Activation - induced radioactivity in materials



Examples of Defects in Lattice Structure

Source: "Neutron Radiation."

Types of Neutron Radiation Damage

- Macroscopic:
  - Embrittlement
  - Swelling - problem for ceramics, can complicate coolant flows especially in small channels
  - Production of He, later forming gas bubbles
  - Production of heat
  - Lowering of superconductor critical current (I_c), critical magnetic field (B_c), and critical temperature (T_c).

Source: "Development of Radiation Resistant Reactor Core Structural Material."

Neutron risks to humans

- Considered most dangerous type of radiation to humans due to high kinetic energy
- Up to 10x more damaging than gamma or beta particles
- Activation causes release of gamma and beta radiation

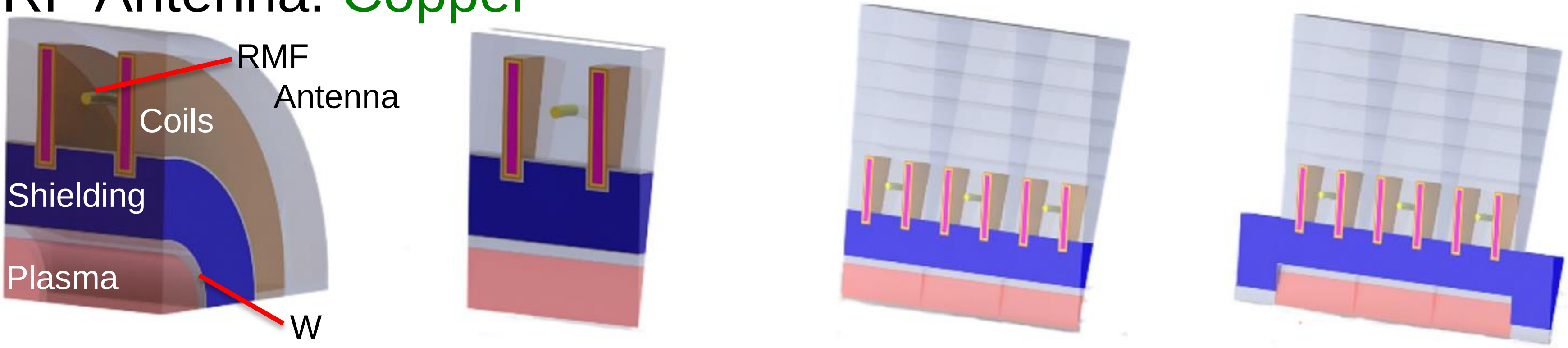
Source: "Neutron Radiation."

Background Summary

- Neutron wall load would be far smaller in the PFRC than in D-T burning reactors
- Nevertheless, some neutrons will be produced
- Damaging neutron effects to both materials and nearby people should be mitigated by shielding

Reducing the residual neutron risk: Reactor Materials

- Shielding: Boron Carbide (B_4C): B-10 enriched reduces required thickness (and weight)
- Cooling Channels with Tungsten foil inserts (for absorbing Bremsstrahlung), modeled as thin innermost layer
- Superconducting Coils: YBCO - superconductivity to 105K, but planned operation at 77K
- RF Antenna: Copper



Neutron Shielding with B_4C

Very large absorption cross section by ^{10}B.

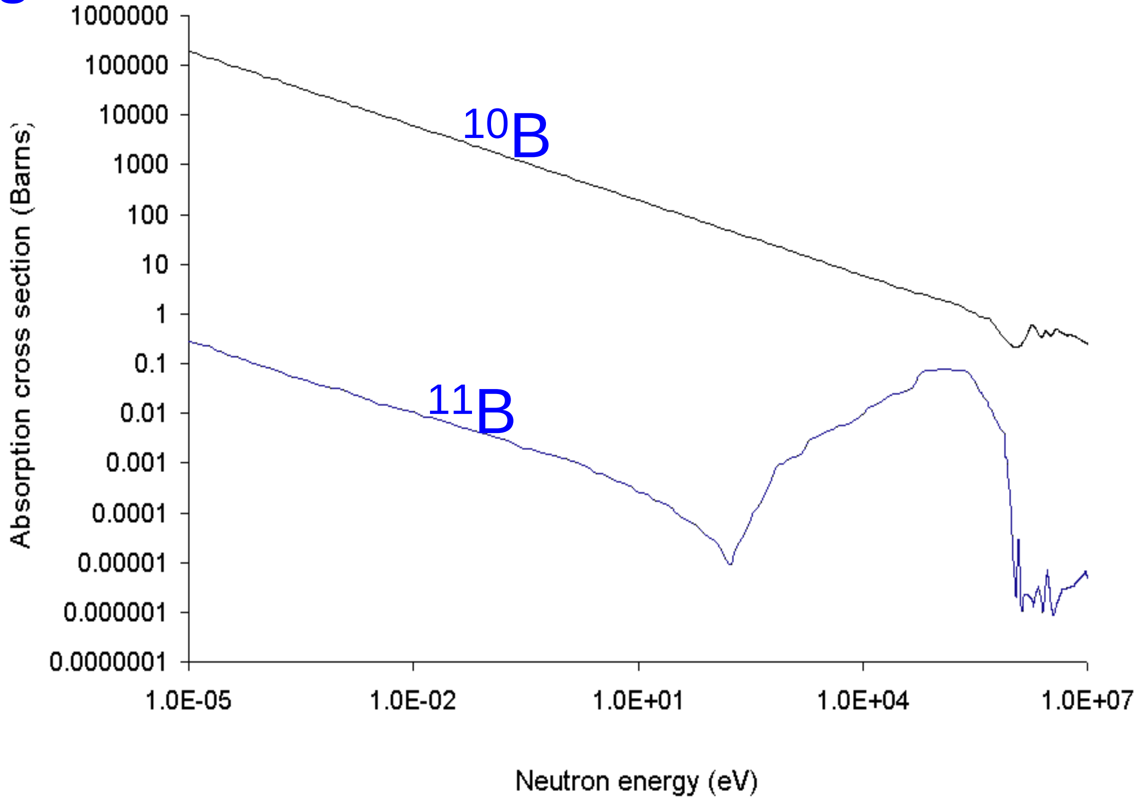
Naturally occurring Boron mixture:

20% B-10

80% B-11

Future work will consider moderators, *e.g.*, H_2 or D_2 or H_2O.

Absorption Cross Sections of B-10 (above) and B-11 (below)



Device Dosage Tolerances

Heating

- Nuclear heating very small relative to Bremsstrahlung & synchrotron radiations (1% of energy compared to 40%)
- Minor concern for high temperature superconductors

DPA

- Structural degradation in steels at ~ 50 DPA ~ $7x10^{26}$ n/m^2
- High-T superconductors: limited data: improved performance at low doses but 10% degradation in I_c at $6x10^{22}$ n/m^2
- Not well studied for B_4C

Device Dosage Tolerances

Swelling

- Material swelling of even a few % would increase lengthwise dimension by several cm
- Ideally keep this << 1% in shielding
- Difficult to estimate, requires detailed experiments

Flux

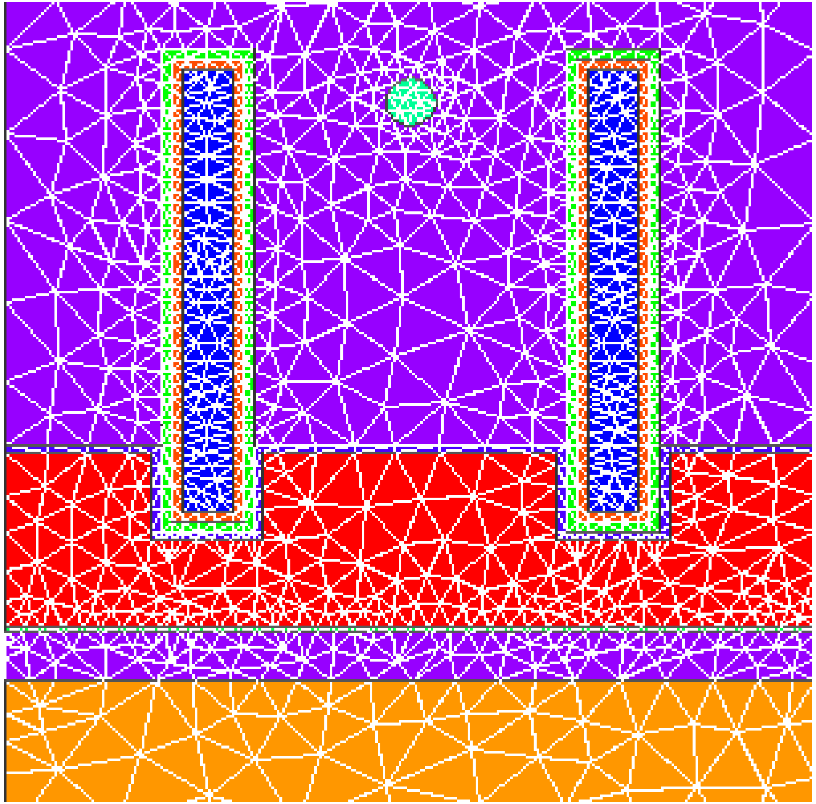
- Concern for superconductor materials, human operators. Can be a form of ionizing radiation
- Fluence limit for YBCO of 6×10^{21} n/m^2 (with KE > 0.1 MeV) for a T_C drop ~ 5%
- According to OHSA for 2.5 MeV: limit of 3.7×10^{13} neutrons/m^2 per calendar quarter for humans

Attila http://www.transpireinc.com/html/attila/

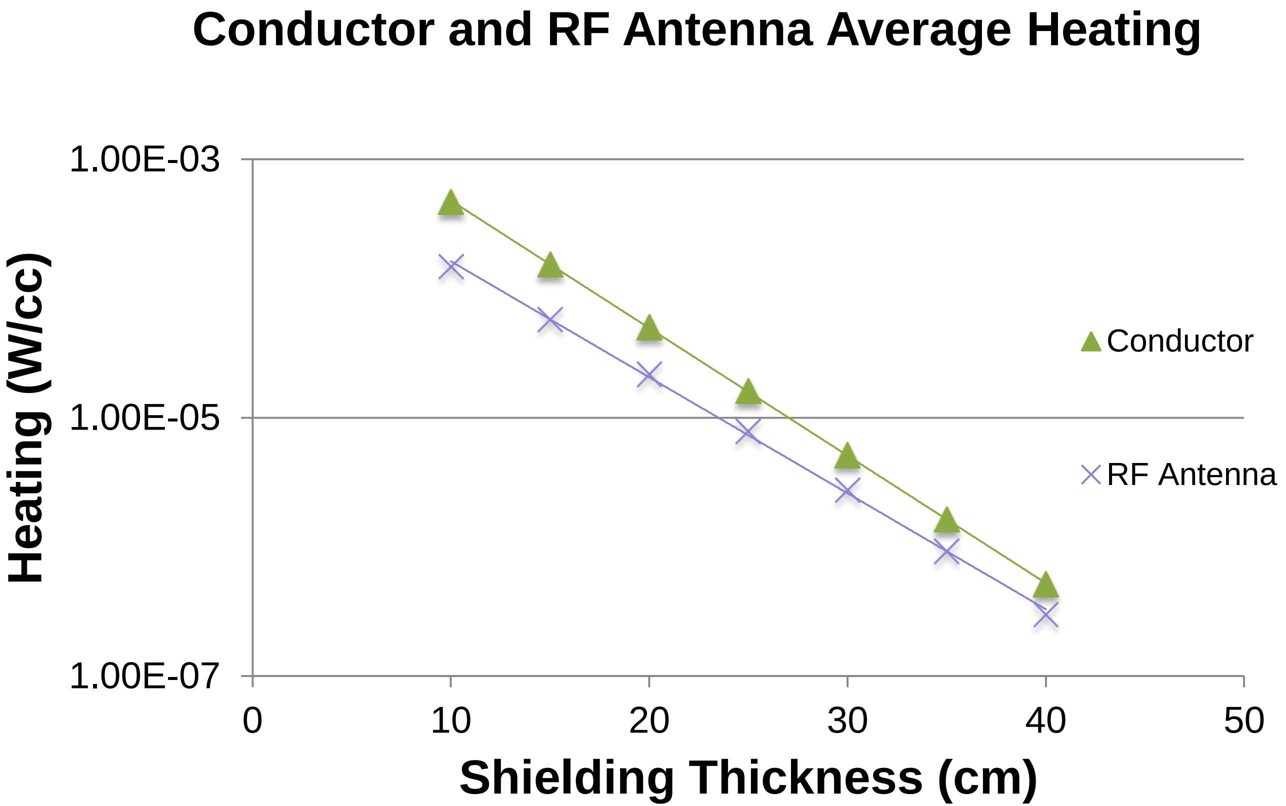
Particle simulation (neutron transport) code that solves problems in space, angle and energy

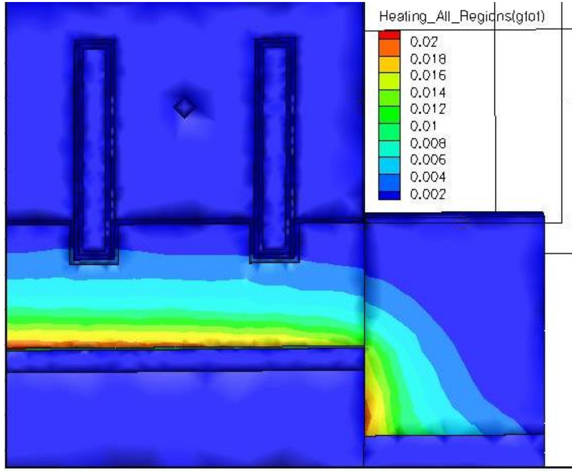
- A model mesh is a refinement in space
- The scattering order refines the angles considered in particle interactions.
- Energy groupings split different energy neutrons into groups that are evaluated together.

Attila Generated 3D Mesh (113,000 Cells)



Average Nuclear Heating

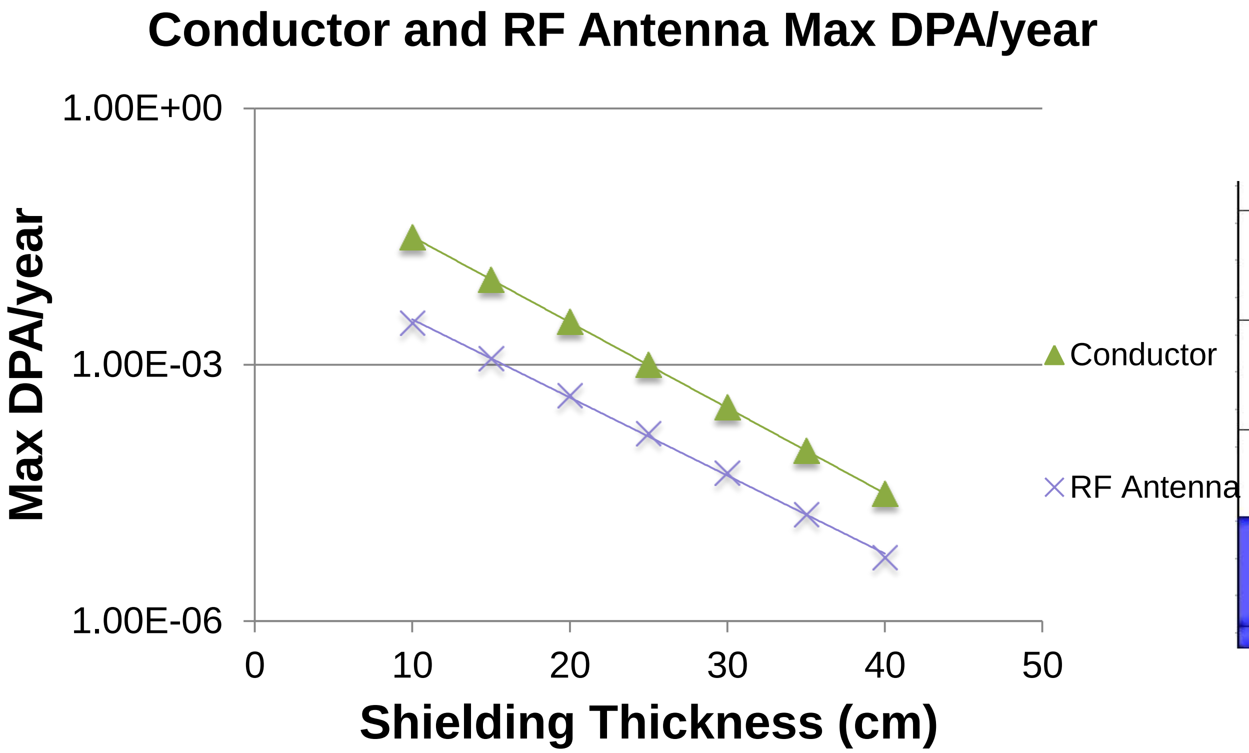




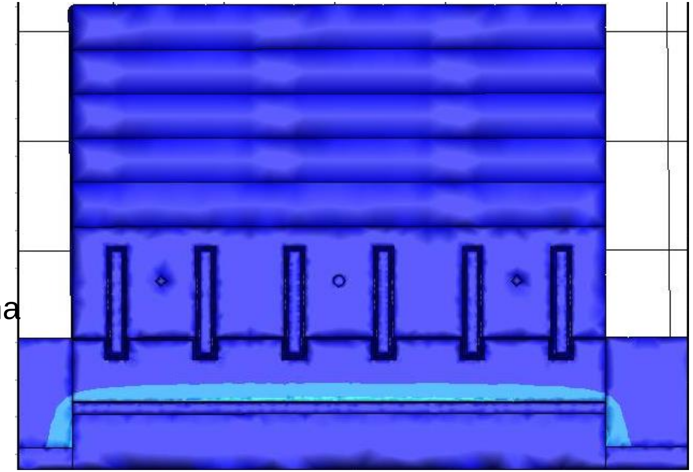
Heating for Model with 20cm of B_4C

DPA

DPA limit for steel ~ 50.

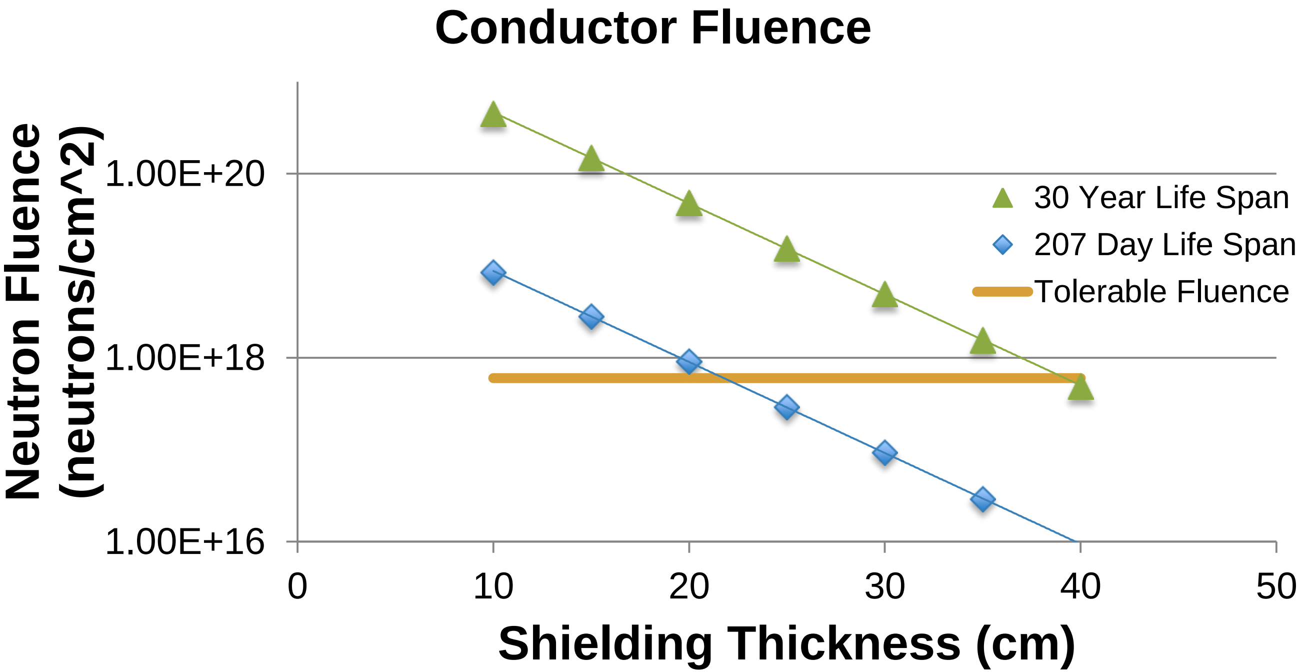


DPA for Model with 20cm of B_4C

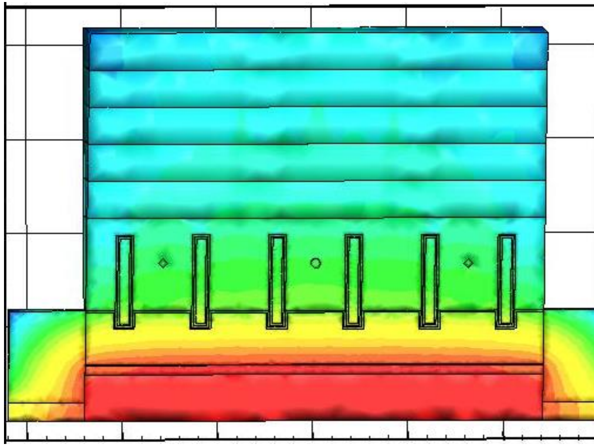


Neutron Flux

With 39.2cm of enriched shielding, 30-year peak fluence in superconductors ~ $6x10^{21}$ m^{-2}. A 1- year mission would require 21.8 cm of enriched B_4C, corresponding to $1.1 x10^3$???kg/m for $\rho(B_4C)$ = 2.4 gm/cc.

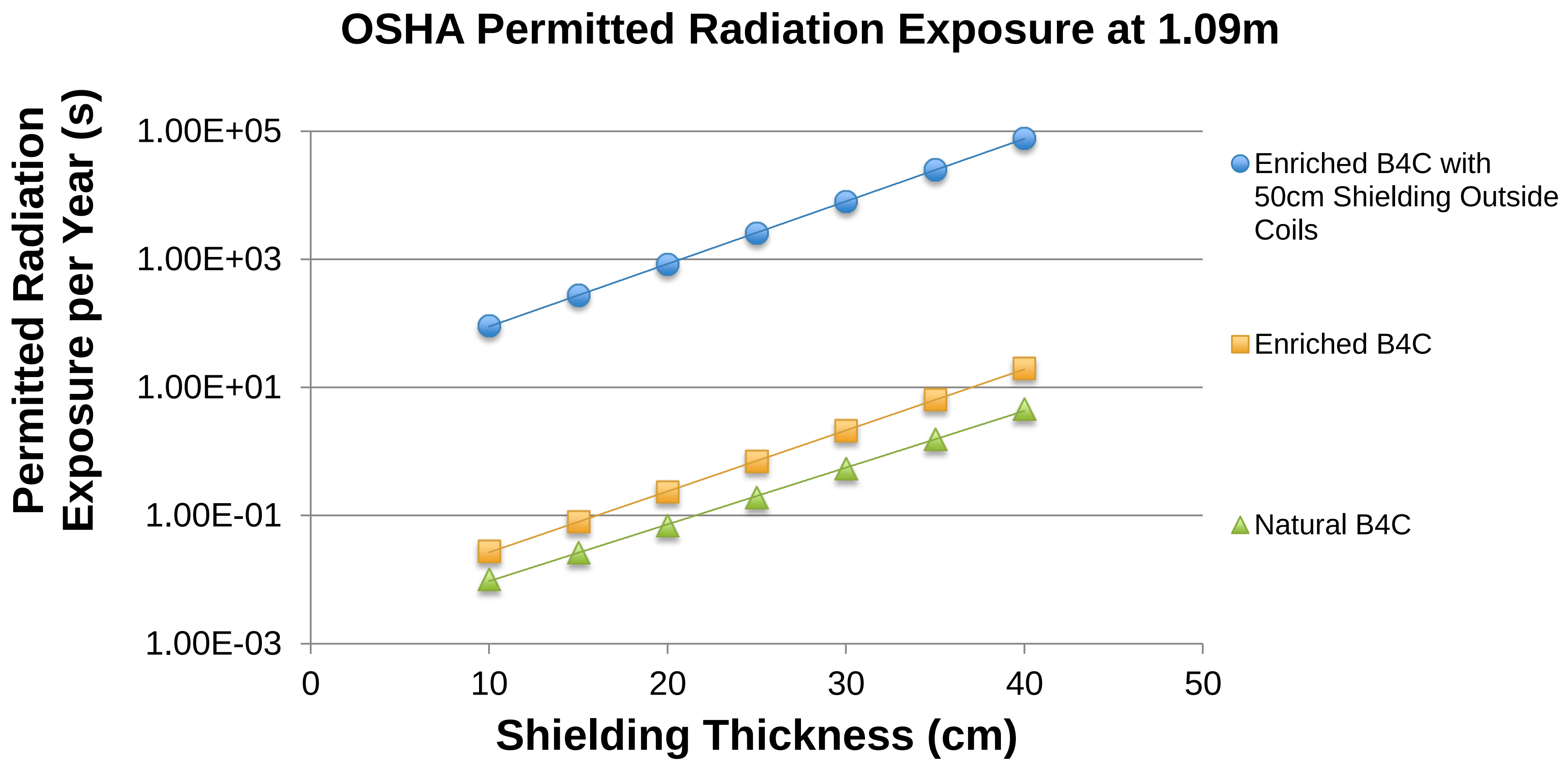


log(Flux) for 20cm of B_4C



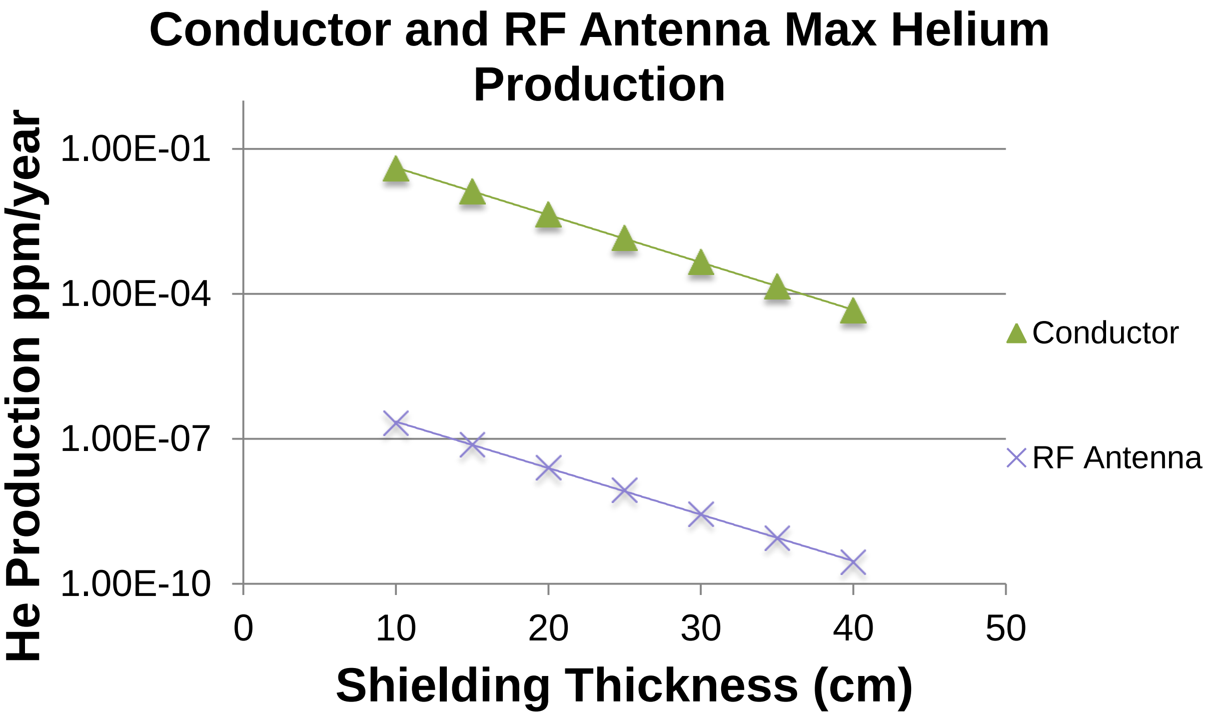
Human exposure: Neutron Flux Regulations

OSHA Regulations- 2.5 MeV neutrons: 3.7x 10^{13} neutrons/m^2 per quarter year

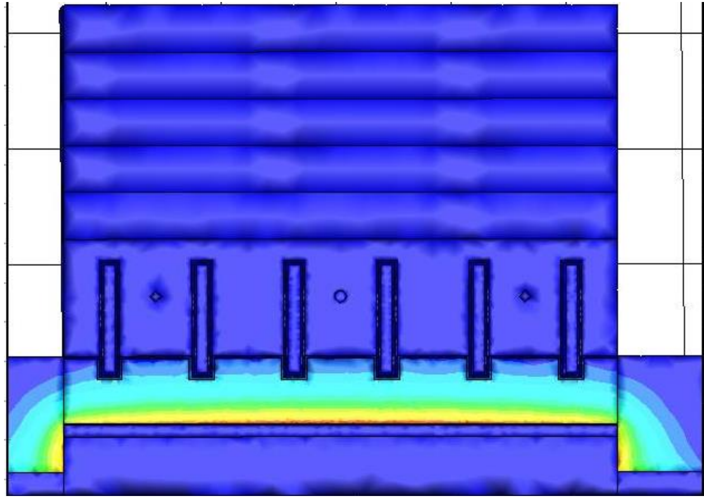


Helium Production

The majority of He production occurs in B_4C. With proper channeling, this amount could be easily removed from the shielding.



He production for model with 20cm of B_4C



Conclusions

- Neutron flux, nuclear heating, DPA, and helium production are at least 100 times less in the PFRC than in a D-T reactor.
- With modest shielding, materials in the PFRC could withstand 30 years of operation.
- Enriched B_4C would decrease the amount of shielding needed but is not essential.

Future Areas of Research

- Examine activation of materials.
- How do results change with addition of 14MeV neutrons from D-T reactions?
- Investigate effects of neutron irradiation on new materials in detail (YBCO, BiSCCO)
- Consider use of low Z moderators.

Sources

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