Exploring Neutron Energy Capture for Deuterium-Tritium Fusion Rockets

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Abstract

Fusion rockets have the capability to efficiently power missions in both the solar system and interstellar space. In other studies, the fusion on deuterium and tritium has been discarded due to its high neutron output, with deuterium-helium-3 fusion preferred instead. However, deuterium-helium-3 fusion requires temperatures and energies an order of magnitude higher than deuterium-tritium. We explore methods to not only mitigate deuterium-tritium's neutron issue, but to make the neutrons work for us, both for recirculating energy and as a source of additional thrust.

Why a Fusion Rocket?

When looking at rockets, there are two main quantities of interest: thrust and specific impulse. Thrust is the force of the propelled mass out the nozzle. In this domain, traditional chemical rockets still reign supreme.

Specific impulse (I_{sp}) is the total impulse (thrust times the time the rocket fires) over the fuel weight, which reduces to the exhaust velocity over *g*, the terrestrial acceleration due to gravity. This ratio, with units of seconds, gives a measure of rocket efficiency. In this realm, the utility of a fusion rocket becomes clear. State of the art chemical rockets give a specific impulse of ~500 seconds; nuclear thermal rockets, a fission-based rocket type being studied by NASA, give a specific impulse of ~1,000 seconds; but the theoretical specific impulse of our fusion rocket is 100,000 seconds. Though lacking the trust necessary to achieve orbit, once in space, fusion rockets can provide thrust 200x more efficiently than our current chemical rockets.

Deuterium-Tritium (D-T) vs. Deuterium-Helium-3 (D-^{3}He)

The most achievable fuel cycle for fusion is D-T (into ^{4}He and a neutron). However, previous fusion rocket studies [eg. Cohen et al., 2019, & references therein] have selected D-^{3}He fusion (into ^{4}He and a proton) due to its aneutronic products. To reduce neutrons from inevitable deuterium-deuterium fusion, previous studies have often reduced concentration of deuterium while increasing the concentration of ^{3}He. This, plus the increased temperature required for D-^{3}He fusion, results in reduced densities and reaction rates compared to D-T.

We employ a moderator to capture the neutrons' energy. As a result, D-T fusion, with an output ~100 times the power of D-^{3}He fusion, becomes feasible, at the cost of mass in the form of the moderator. We seek to explore this trade space.

The Moderator

The purpose of a moderator in nuclear engineering is to capture neutron energy. Neutrons are a high-penetration, high-risk radiation hazard. Unlike most other forms of radiation, low-atomic-number materials are the most effective at slowing them. To capture the energy of the neutrons released by D-T fusion, we employ pyrolitic carbon.

As this is a rocket, our goal is to reduce mass. The goal of this project was to investigate how effective various thicknesses and masses of carbon are at absorbing neutron energy. We test two different geometries: a cylindrical shell with hemispheric shells at each end (a "pill"), and the same shape without the bottom hemisphere ("bottomless pill"). In addition to analyzing absorption, we investigate the additional thrust from the neutrons leaving the bottomless pill.

Note that we seek to absorb the neutrons' energy, not the neutrons themselves. Absorbing the neutrons will add mass to and change the structure of the moderator, which is unnecessary when we can simply radiate them into space.

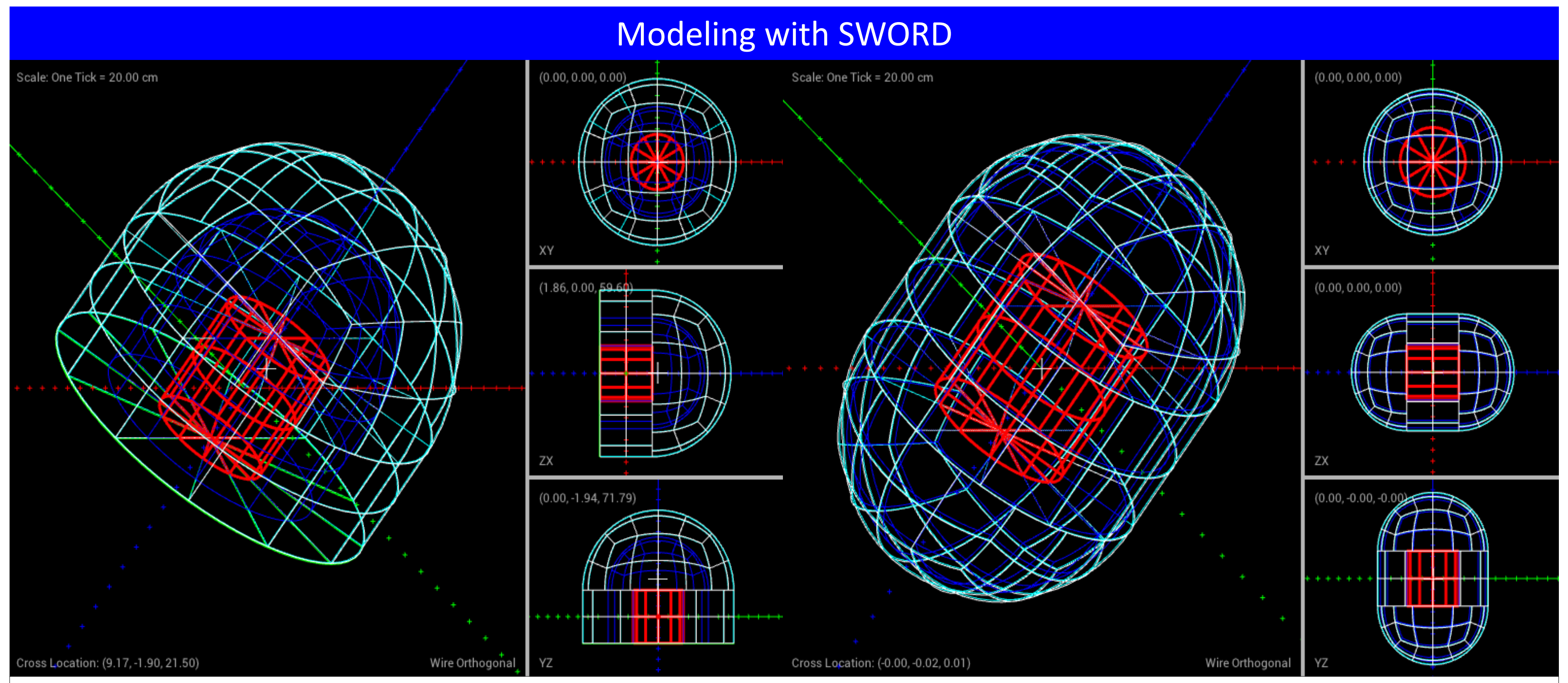
Citations

Cohen et al., 2019. *JBIS, 72,* 2, 37-50.

Duvall et al., 2019. *IEEE International Symposium on Technologies for Homeland Security (HST)*, 1-6.

Reinmann, John J. 1971. NASA Technical Memorandum TM X-67826

Modeling with SWORD



Figures A & B: Two examples of geometries built in SWORD. SWORD (a wrapper for GEANT-4) allows for the modeling of precise geometries with many different materials, and running radiation simulations. Figure A (left) is a 50-centimeter thick bottomless pill. Figure B (right) is a 5-centimeter thick pill. In both geometries, the fusion core is represented by a red cylinder.

The modeling for this project was done in SWORD, a user-friendly wrapper for the complex and versatile modeling software GEANT-4 [Duvall et al., 2019]. We tested geometries of 5, 10, 20, 30, 40, 50, and 100 cm thicknesses, both for the pill and bottomless pill geometries. Note: all these geometries have 50 cm of vacuum between the source and inner radius of the moderator, for reactor structure.

Our simulations ran 100,000 neutrons being released from the source, plus every interaction these neutrons had with the moderator, and the other particle types released thereby. We ignored the helium, due to its irrelevancy to the study. We began by running and analyzing six simulations for the 50cm bottomless pill, to check consistency, errors, and standard deviations for the simulation. The SWORD output was analyzed in the data analysis/visualization program IGOR.

Analysis and Results

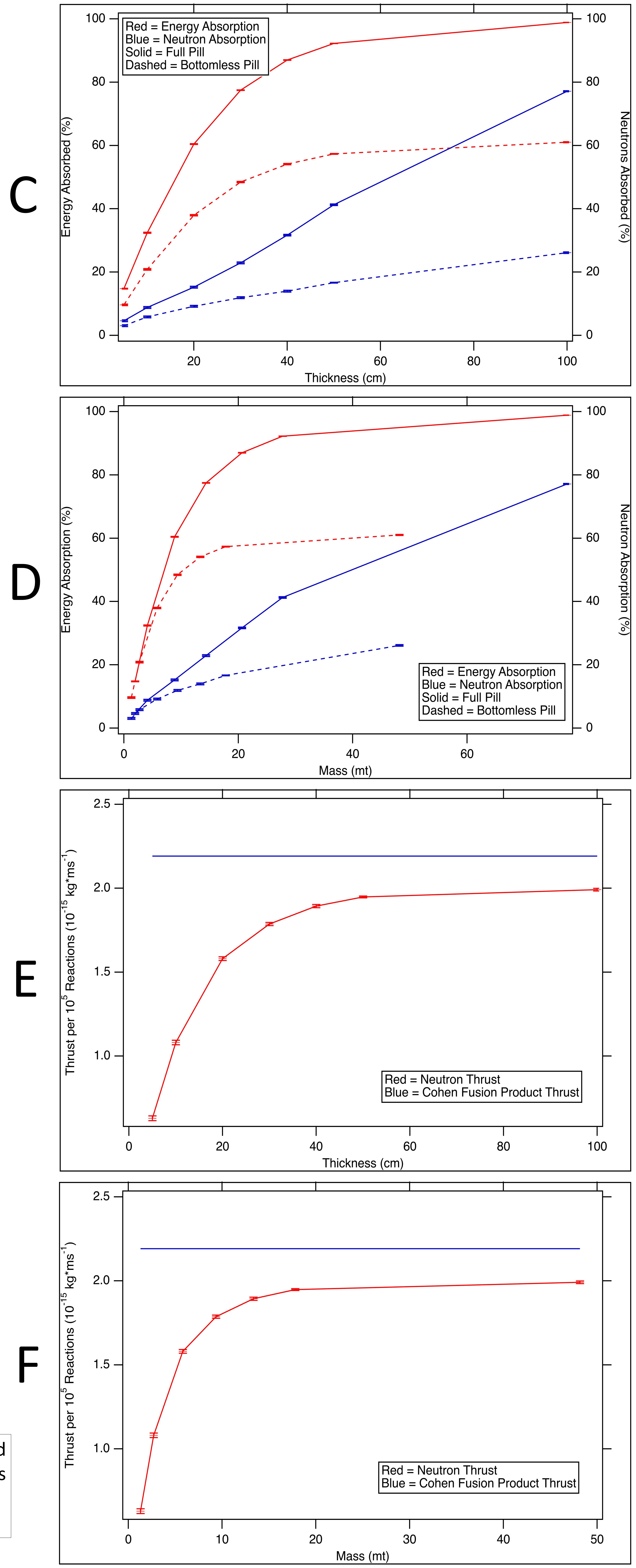
The necessary recirculating energy requirement for a given mission and reactor design will determine the necessary thickness for that mission's moderator. That said, we see significant diminished returns around thicknesses of ~30-40 cm (Fig. C, D).

Missions that require high specific impulse will turn to the bottomless pill, which has a high I_{sp} due to the additional neutron thrust. The neutron thrust can be significant as compared to D-^{3}He thrust (Fig. E, F). If higher thrust is desired, then the plasma can be diluted with hydrogen, at a cost of specific impulse, at which point neutron thrust becomes less significant. In this case, the pill may become the better choice due to its lower mass for the same energy recirculation.

Conclusions & Next Steps

Cohen's design [Cohen, 2019] has a specific power (power to mass ratio) of 1 MW/mt (megawatt per metric ton). We assume the same specific power for our system for comparison. Assuming a 60% recirculating energy requirement, which our 20 cm pill can provide, the moderator will have a mass of 8.86 mt, about 7.7% of the full power system's 115 mt (compared to the Boeing 747's 220 mt). The bottomless pill's 17.8 mt (for this energy requirement) is only 15% of the power system mass with neutron thrust. **The moderator therefore adds little additional mass.**

Having explored the trade space of specific impulse, mass, energy recirculation, and thrust, this project lays a groundwork for future studies. **Acknowledging that there are currently no working nuclear fusion reactors, D-T is far more achievable than D-^{3}He fusion, and will be developed sooner.** Besides, given that the only known source of sufficient ^{3}He is the surface of the moon, while tritium can be produced on Earth or in space, this opens up opportunities for fusion-based space travel much sooner.



Figures C, D, E, and F: Graphs of thickness, mass, energy absorption, neutron absorption, and neutron thrust, as well as a comparison to the thrust of the fusion products. Each of the points represents a modeling run with 100,000 neutrons. Note each point has very tiny error bars.