Modelling Neutron Transport and Tritium Production in a Simulated Fusion Breeder Blanket

MPhys Research Project

Rhodri Peters 10848618

The University of Manchester

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Abstract

Test.

1 INTRODUCTION

1.1 *Nuclear Fusion*

Deuterium-Tritium fusion has been of considerable interest since it was first proposed in 1942 by Emil Konopinski as a candidate for a fusion based atomic bomb [1].

$$d + t \rightarrow n + \alpha + 17.6MeV. \tag{1}$$

The postwar boom in nuclear physics research led to early designs for a fusion based energy producing reactor, hoping to replicate the success of the already ubiquitous fission power plants [2]. The D-T reaction quickly emerged as the frontrunner for use in a commercial reactor due to its high fusion cross section (σ_f) at low plasma temperatures (figure 1). Additionally, due to the significant mass difference between the emitted particles, 80% of the output energy (14.1MeV) is carried away by the neutron [3]. Such a high energy neutron is very desirable from a practical fusion standpoint since it allows most of the energy produced by the reaction to be extracted from the plasma.

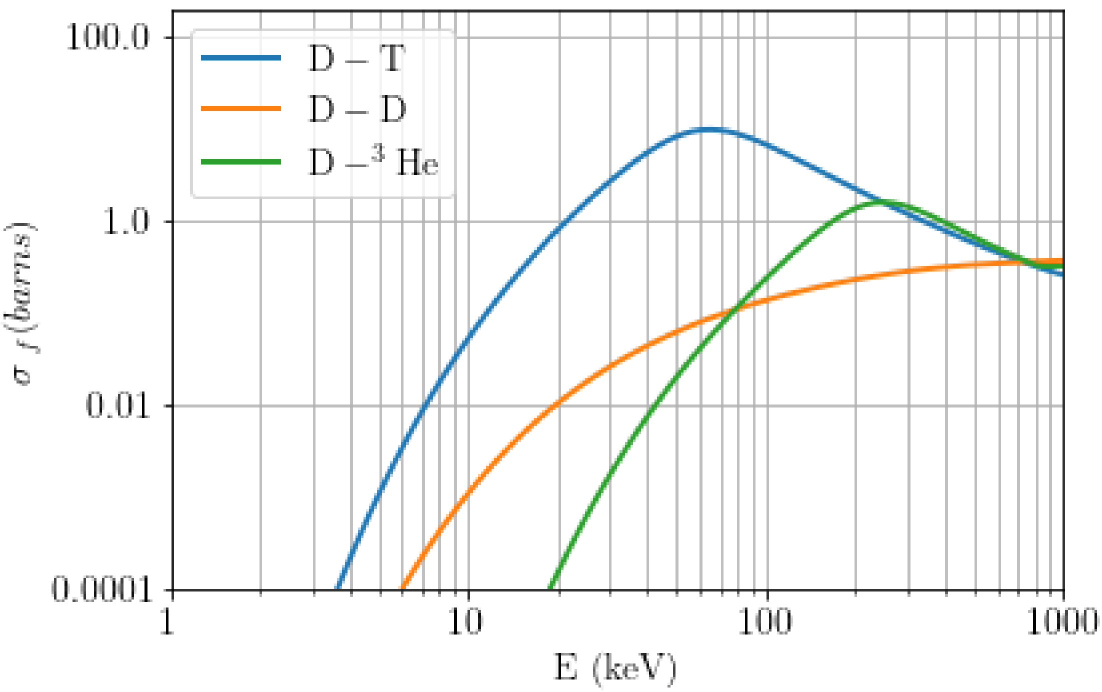

Figure 1: A graph showing the fusion cross sections (σ_f) of D-T, D-D and D-^{3}He fusion for a range of energies.

Unfortunately, while deuterium is very abundant and easy to obtain tritium is not found in nature since it only has a half-life of 12.32 years. Thus, tritium must be produced. Most of the world's current tritium supply is generated in heavy water moderated fission reactors when neutrons are absorbed by the deuterium in the water. However, this process is costly and requires dedicated Tritium Removal Facilities (TRF's) of which only two exist (in Canada and South Korea) with another under construction (in Romania). In short, global tritium stockpiles are facing serious shortages even without demand from fusion reactors [4] [5]. This has incentivised the design of an in-situ method of tritium production known as a breeder blanket. Initially envisaged as a method of creating fissile materials for nuclear reactors [6] [7] [8], a breeder blanket is a structure that produces desirable isotopes upon interacting with fusion neutrons. Crucially for us, the neutron induced decay of lithium isotopes produces tritium. This is the basis of modern breeder blanket design and our project. By simulating neutron transport throughout the structure of the reactor it is possible to calculate a Tritium Breeding Ratio (TBR). Essentially the ratio between the amount of tritium produced by the blanket to the amount consumed during fusion. TBR is a very effective method for comparing the wide variety of blanket materials and designs [9] [10] and it will be the primary method by which this project investigates the physics of breeder blankets.

1.2 Breeder Blankets

Breeder blankets can be divided into two main categories, liquid breeders consisting of molten lithium compounds and solid breeders based on ceramic lithium oxides. The key differences between these solid and liquid breeders are in terms of thermal properties and tritium extraction [11], qualities that have limited impact on our project but are of considerable importance to the design of practical breeder blankets. A great deal of the available literature on breeder technology can be found in the journals Nuclear Fusion and Fusion Engineering and Design. Established in 1960 and 1984 respectively, these publications reflect the mid-century explosion of interest in fusion research and the subsequent development of practical reactor designs. While they are certainly not the only publications we have drawn from, their presence in the field means that they are our most common sources. A significant amount of said sources have been published in the last 10 to 15 years in anticipation of a series of test reactors planned for the 2040's and 50's. Strategy documents are already outlining conceptual designs for blankets on ITER's prospective DEMO reactors [12], the envisaged Chinese Fusion Engineering Test Reactor (CFETR) facility [13] and the Spherical Tokamak for Energy Production (STEP) planned for the UK [14], to name just a few.

The simplest possible breeding blanket is one made of pure molten lithium. However, D-T fusion only produces one neutron and only one tritium atom is produced per lithium decay. Any neutron losses from this system would inevitably lead a tritium deficit. To overcome this, most blankets include a neutron multiplier, an isotope which releases additional neutrons. This will be discussed in more detail later in the report. A popular solution involves a eutectic lithium-lead alloy [15] [16], typically chosen to be $Li_{17}Pb_{83}$. A eutectic mixture has a melting point lower than its constituent materials [17], a key property in liquid systems that require proper circulation. This is the basis of the Dual Cooled Lithium-Lead system currently being explored as an option for the DEMO reactor project [18]. Systems involving more chemically complex molten salts are seeing significant interest as a breeder for the Affordable Robust Compact (ARC) reactor developed by the Massachusetts Institute of Technology (MIT). The ARC project is dedicated to utilising an FLiBe ($2LiF - BeF_2$) blanket, combining breeder and multiplier in a fluorine salt mixture with the goal of a reducing reactor size and increasing efficiency [19] [20]. In general liquid breeders are compact and chemically simple. However, liquid metal systems induce strong magnetohydrodynamic (MHD) currents that inhibit circulation [21].

Solid breeder designs have been proposed for several breeder projects, typically consisting of a lithium based ceramic mixed with a multiplier. Most notably the CFETR is exploring a Water Cooled Pebble Bed (WCPB) design utilising a mixture of lithium metatitanate (Li_2TiO_3) and beryllide ($Be_{12}Ti$) pellets [13] [22]. Alternatives using lithium orthosilicate (Li_4SiO_4) ceramics are also being explored as candidates for test modules including ITER's DEMO program [23] [24]. It is important to note here that due to its existence as an international venture the DEMO program has several test blankets of different designs and materials planned [25]. While planned designs are coalescing around Li_2TiO_3 and Li_4SiO_4, a wide variety of lithium ceramics exist along with even more beryllium and lead based multiplier solids [26]. This wealth of choice and material stability are the key selling points of ceramic breeders however, they tend to struggle with tritium extraction and often require complex water or helium based cooling systems.

With the construction of full scale test reactors and functional blanket modules anticipated within the next few decades a majority of the literature is focussed on a small selection of breeder materials and designs. These have been chosen not only for their tritium breeding properties but also for availability and structural reasons. More than 30 years ago some basic blanket designs and materials had already been narrowed down to fit these criteria [27]. This allows our project to venture into less explored territory, studying compounds that have been discarded or overlooked due to their material properties, availability or cost. However, that is not to say that our project is unprecedented. The systematic modelling of TBR for a different blanket and properties has been explored before in detail [26], [28] [29]. These studies serve as useful sources of breeder materials and points of reference as the project progresses. They also provide us with an opportunity to expand on our project in ways that they did not, namely exploring the behaviour of the TBR with varying enrichment, chemical balance and blanket thickness.

When evaluating our results there was some difficulty in finding a definitive TBR for certain materials. This is because no currently operating fusion test reactors have built in breeder blankets and simulation results are dependent on the modelling software and geometry used. However, there are some small scale experiments that aim to study the functionality of practical blanket modules. An exploration of TBR for a 1000ml molten salt module, [30], and a mockup WCPB module, [31], are just some of the practical blanket modules that have been built and tested. These studies do not play a direct role in the progress of our project however they emphasize the present difficulty of performing full scale breeder experiments and explain the computational nature of our project and the majority of blanket research.

2 THEORY

2.1 Nuclear Fusion and Neutron Interactions

At sufficiently high temperatures and pressures deuterium (^2H) and tritium (^3H) undergo fusion in the reaction,

This reaction and its products are of particular interest in fusion research. As shown in figre X, D-T fusion has a comparably high reaction cross section (σ_f) at low plasma temperatures. Additionally, due to the significant mass difference between the emitted particles, 80% of the output energy (14.1MeV) is carried by the neutron. Such a high energy neutron is very desirable from a practical fusion standpoint since it allows the vast majority of energy produced by the reaction to be extracted from the plasma. Furthermore, once ejected from the plasma it can interact with matter in very interesting ways. As well as scattering, neutrons can be absorbed by a nucleus, increasing the atomic number or, more importantly for this project, inducing charged particle emission. Thus, it is possible to use fusion neutron flux to produce light isotopes that are not found in nature. This process is called ‘breeding’ and one such isotope is tritium, which has a half-life of only 12.32 years. By irradiating lithium isotopes with neutrons, it is possible to produce tritium as seen in equations (2) and (3).

$$^6Li + n \rightarrow \alpha + t + 4.8MeV \tag{2}$$

$$^7Li + n \rightarrow \alpha + t + n - 2.5MeV \tag{3}$$

Lithium-6 is seen as the tritium breeding compound of choice due to its much larger reaction cross section. Lithium also has the potential to form a wide variety of solid and liquid compounds, providing many possible materials with which to construct a functional tritium breeding blanket. The design and material basis for some of these are outlined in the literature review. Different breeder structures can be evaluated by comparing their Tritium Breeding Ratio (TBR), defined as the ratio between the amount of tritium produced and the amount consumed in D-T fusion.

Charged particle emission is not the only interaction plays a key role in breeder blanket design. Neutron multiplication or ‘spallation’ is the process by which an incident neutron causes the emission of another. Thus, by including a multiplier within the structure the tritium production is no longer reliant only on fusion neutrons. Lead-208 (equation (4)) and beryllium-9 (equation (5)) are considered to be the best multiplier materials, once again due their high reaction cross sections.

$$^{208}Pb + n \rightarrow {}^{207m}Pb + 2n \tag{4}$$

$$^9Be + n \rightarrow {}^8Be + 2n \tag{5}$$

2.2 Monte Carlo Simulations

Developed by Stanislaw Ulam and John von Neumann in the 1940's, Monte Carlo (MC) simulations provide a useful process for modelling a wide variety of physical systems [32]. Named for the seaside municipality and its famous casinos, MC calculations rely on probabilities. By applying statistical sampling methods, they can be used to solve a variety of mathematical and scientific problems. With the advent of modern computing, it is now possible to simulate very complex and multivariable processes very quickly. Nuclear physics, finance and traffic management are just a few of the many fields that have benefitted from MC simulations.

The MC process is based on the principle that a random sample of a population tends to retain the properties of the whole. Instead of precisely modelling each and every object a random selection can produce the same solution. By defining dependent and independent variables and assigning probabilities to the events under consideration a model of possible results can be constructed. Repeated simulation with different random numbers within a set range provides a very accurate solution. As the number of iterations increases so does the accuracy of the model. A record of the parameters for a simulated object called a 'tally' can then be called. It is easy to see how more complex systems can lead to a great deal of computational difficulty. To avoid this, objects in the system are often weighted, so that one object is used to simulate many. Statistical averaging ensures that the final outcomes of the model are preserved [33].

Clearly, MC simulations are ideal for predicting fusion neutron transport in a breeder material. Neutron can be described using the probabilities of interaction with surrounding materials. These probabilities are defined by various absorption and scattering coefficients (σ_a, σ_s). Key results such as neutron flux and, crucially, TBR are recorded as tallies and can be extracted for any point in the model. Thus, it should be relatively simple for an MC simulation to map out the possible flight paths and reaction rates of fusion neutrons with the aim of calculating a TBR [34].

Accurately describing neutron transport and interactions is key to evaluating the tritium breeding performance of fusion blanket designs. The probabilistic nature of neutron behaviour lends itself to modelling via a Monte Carlo simulation. Monte Carlo codes are regularly used to model the neutronics of breeder designs planned for full scale international ventures [16] [35]. This project uses OpenMC, a Monte Carlo code designed specifically for neutron transport in constructive solid geometry environments [36]. OpenMC has been shown to demonstrate very close agreement with other neutron transport codes when modelling neutron flux spectra, power distribution and TBR [37]. Our choice of programme is further justified by the examples of its use in studying the TBR of very complex blanket structures [38] [28]. A significant challenge of this project is accurately modelling the structure of a fusion reactor. Creating the models from scratch is too time consuming, especially if we want to introduce more complex designs and materials. Instead, we used Paramak, a CAD framework containing a suite of ready-built tokamak designs [39]. This allows us to work with realistic tokamak structures, lending more authority to our results without the time consuming process of building the whole system.

An unpublished paper, [40] also functions as a useful comparison to our project, in particular for its use of OpenMC and the Paramak Python module to model the TBR. Once again it contains useful details while providing us with interesting avenues for further study.

3 METHODOLOGY

4 RESULTS

Table 1 is an example of a referenced LaTeX element.

And this is table 2.

For example, chlorine based lithium salts which have received very little attention due to concerns around solubility and neutron absorption may be subject to a revaluation as a result of research into ^{37}Cl enrichment [41].

Liquid Breeder TBR					
Material	Ratio (molar %)	Li (molar %)	ρ (g/cm^3)	TBR	Reference
Li	-	100	0.47	x	[28]
Li-Pb	17:83	17.00	11.00	x	[9]
LiF-BeF_2	2:1	28.57	2.04	x	[29]
LiF-BeF_2*	1:1	20.00	2.06	x	[29]
LiF	-	50.00	2.64	x	[26]
Li_3N	-	75.00	1.30	x	[26]
LiF-PbF_2	2:3	15.38	3.55	x	[29]
LiF-BeF_2-NaF	1:1:1	14.29	2.15	x	[29]
Lif-NaF-KF	46.5:11.5:42	20.17	2.02	x	[28]
LiF-LiBr-NaBr	20:73:7	46.50	3.16	x	[28]
LiF-LiBr-NaF	14:79:7	45.69	3.20	x	[28]
LiF-LiI_2	83.5:16.5	50.00	3.68	x	[28]
LiF-NaF-ZrF_4	55:22:23	20.45	2.72	x	[28]
$LiCl$-$BeCl_2$	1:1	20.00	-	x	[29]
$LiCl$-$PbCl_2$	1:2	12.50	4.50	x	[29]
LiCl-KCl	7:3	35.00	1.60	x	[29]
LiCl-KCl*	52:48	26.00	1.60	x	[29]
LiCl-NaCl	72:28	36.00	1.60	x	[29]

Table 1: Table to test captions and labels.

Solid Breeder TBR				
Material	Li (molar %)	ρ (g/cm^3)	TBR	Reference
Li_4SiO_4	44.44	2.40	x	[26]
Li_2TiO_3	33.33	3.43	x	[26]
Li_8PbO_6	53.33	4.28	x	[26]
Li_8SiO_6	53.33	2.20	x	[26]
Li_8CoO_6	53.33	2.47	x	[26]
Li_8GeO_6	53.33	2.64	x	[26]
Li_8ZrO_6	53.33	2.98	x	[26]
Li_8SnO_6	53.33	3.41	x	[26]
Li_8CeO_6	53.33	3.25	x	[26]
Li_6MnO_4	54.55	2.50	x	[26]
Li_6CoO_4	54.55	2.77	x	[26]
Li_6ZnO_4	54.55	2.86	x	[26]
$Li_6Zr_2O_7$	40.00	3.56	x	[26]
Li_5AlO_4	50.00	2.25	x	[26]
Li_5FeO_4	50.00	2.64	x	[26]
Li_4TiO_4	44.44	2.57	x	[26]
Li_4GeO_4	44.44	3.16	x	[26]
Li_2MnO_2	40.00	3.90	x	[26]

Table 2: Table to test captions and labels.

5 DISCUSSION

6 CONCLUSION

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