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A neutron poison tritium breeding controller applied to a water cooled fusion reactor model

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HIGHLIGHTS

- The issue of a potentially producing a large tritium surplus inventory, within a solid breeder, is addressed.
- A possible solution to this problem is presented in the form of a neutron poison based tritium production controller.
- The tritium surplus inventory has been modelled by the FATI code for a simplified WCCB model and as a function of time.
- It has been demonstrated that the tritium surplus inventory can be managed, which may impact on safety considerations.

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ABSTRACT

The generation of tritium in sufficient quantities is an absolute requirement for a next step fusion device such as DEMO due to the scarcity of tritium sources. Although the production of sufficient quantities of tritium will be one of the main challenges for DEMO, within an energy economy featuring several fusion power plants the active control of tritium production may be required in order to manage surplus tritium inventories at power plant sites. The primary reason for controlling the tritium inventory in such an economy would therefore be to minimise the risk and storage costs associated with large quantities of surplus tritium. In order to ensure that enough tritium will be produced in a reactor which contains a solid tritium breeder, over the reactor's lifetime, the tritium breeding rate at the beginning of its lifetime is relatively high and reduces over time. This causes a large surplus tritium inventory to build up until approximately halfway through the lifetime of the blanket, when the inventory begins to decrease. This surplus tritium inventory could exceed several tens of kilograms of tritium, impacting on possible safety and licensing conditions that may exist.

This paper describes a possible solution to the surplus tritium inventory problem that involves neutron poison injection into the coolant, which is managed with a tritium breeding controller. A simple PID controller and is used to manage the injection of the neutron absorbing compounds into the water coolant of a stratified blanket model, depending on the difference between the required tritium excess inventory and the measured tritium excess inventory. The compounds effectively reduce the amount of low energy neutrons available to react with lithium compounds, thus reducing the tritium breeding ratio. This controller reduces the amount of tritium being produced at the start of the reactor's lifetime and increases the rate of tritium production towards the end of its lifetime. Thus, a relatively stable tritium production level may be maintained, allowing the control system to minimize the stored tritium with obvious safety benefits. The FATI code (Fusion Activation and Transport Interface) will be used to perform the tritium breeding and controller calculations.

1. Introduction

Tritium self-sufficiency is an absolute requirement for DEMO and commercial fusion power plants. Thus, the modelling of tritium breeding blankets must ensure the blanket is able to achieve a large tritium breeding margin with a high degree of certainty. However, the over-production of tritium is also of concern due to safety considerations, tritium storage issues and tritium licensing [1]. The risk associated with the under-production of tritium is greater than the over-production, however this issue still needs to be addressed. El-Guebaly [1] points out that the uncertainty related to the TBR can be broken down to nuclear data (6–10%), modelling (3–7%), design

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(0–3%) and tritium consumption (1–2%). An uncertainty of just 1% can translate to an over-/under-production of more than 1 kg/year of tritium, which could pose a problem for self-sufficiency or licensing/storage of tritium. As a result of the many aspects of uncertainty the over-production of tritium is likely to become more probable as the probability of achieving the required level of tritium production is increased.

The production issue can be resolved with the online control of tritium. Studies of the online control of tritium production have concentrated on LiPb liquid blankets [2,3], however, the online control of tritium production within solid-type breeders, such as WCCB, may avoid some of the technical issues associated with liquid breeders.

2. Reactor model

The use of liquid metal as a coolant/breeding material within fusion blankets is highly likely due to the reduced radioactive waste, increased plant availability and ease of tritium breeding control when compared with solid breeders. To date, solid breeders have been considered to have a predetermined, unchangeable tritium production scheme, with a study concluding that the online control of tritium production within solid breeders was not foreseeable [1].

As a result of the radiotoxic nuclides produced in liquid lithium-lead blankets, a solution is sought that combines the tritium breeding controllability of liquid breeders with the low activation of solid breeders. Thus, this paper describes a method, based on neutron poisons, which may enable the online control of tritium production within solid breeder blankets such as helium cooled pebble bed (HCPB) and water cooled ceramic breeder (WCCB).

Solid breeder blankets consist of tritium breeder and neutron multiplier pebbles that are fluid cooled. The breeding pebbles are sub-millimeter sized and are composed of a lithium ceramic, such as Li_4SiO_4 or Li_2TiO_3, and the neutron multiplier is usually beryllium. A cooling fluid, such as helium or water, also acts to purge the tritium from the blanket. This work focuses on the Water Cooled Ceramic Breeder (WCCB), which has been the focus of study of the Japanese fusion program [4,5].

2.1. Design

A simple water cooled ceramic breeder model, consisting of a 14.1 MeV point neutron source and a spherical blanket, is to be used in conjunction with the neutron poison based tritium controller. The key components of this simple model are the 2 GW point fusion source and a single spherical breeding module comprised of lithium orthosilicate (Li_4SiO_4, natural Li enrichment), and beryllium pebbles, which are cooled with water. A schematic diagram and composition of the model is shown in Fig. 1 and Table 1. This simple design has been chosen in order to test the concept of this paper, at a fundamental level with no external complications, which is using a neutron absorber to manage tritium production.

2.2. Neutron poison

For this study, boric acid (H_3BO_3) injection into water coolant has been chosen to reduce TBR in the blanket. The main principle of this paper is the application of the strongly absorbing thermal cross-section of the ^{10}B reaction in order to reduce the thermal neutrons available to create tritium via the $^6L(n,t)^4He$ reaction. ^7Li is produced as a result of the neutron capture by ^{10}B. While ^7Li contributes to the production of tritium, its $(n,n't)$ cross-section (and associated reaction rate) is less than the $^{10}B(n,\alpha)^7Li$ cross-section. Thus the ^7Li will contribute only a small fraction to the overall production of tritium. Boron trifluoride ($^{10}BF_3$) could be used to control the TBR in a HCPB blanket and is one of only a few gases that are suitable as a boron neutron poison. Boron is widely used in the fission industry [6] and is readily available and relatively cheap.

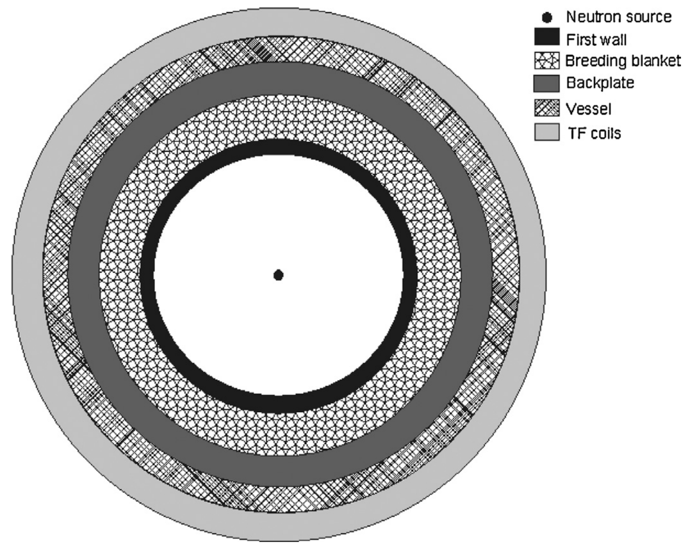

Fig. 1. Simple spherical WCCB model. Compositions and dimensions are shown in Table 1 (not to scale).

2.3. Computational method

Recent studies [7,8] have shown that Cyclic Coupling of Radiation-Transport and Burn-up (CCRTB – updating reaction rates as time evolves in order to account for nuclide burn-up) has a significant effect on the tritium self-sufficiency time (TSST - The duration for which the surplus tritium inventory is positive). Earlier work on tritium self-sufficiency and tritium production have comprehensively outlined uncertainties and potential issues relating to tritium breeding. However, these methods have either been analytical [9], based on non-time-dependent burn-up [10–12] or static radiation-transport and burn-up [13,14]. In some cases the TSST calculated by CCRTB is more than double that predicted by the non-CRTB calculations, which assume a constant neutron flux throughout the lifetime of the blanket. This is due to the depletion of ^6Li in the blanket, which leads to the growth of the thermal neutron population as a function of time. Thus, increasing the tritium production rate. Therefore, the use of CCRTB is recommended for time-dependent tritium breeding calculations. The coupling of radiation transport and burn-up has been performed by many codes and for many years in the fission industry (MCODE, MOCUP, MONTEBURNS, VESTA), however the use of such codes is less common within the fusion neutronics community.

The CRTB code utilised in this study is FATI (Fusion Activation and Transport Interface) [15], which currently interfaces MCNP5 [16] with FISPACT-II [17]. The intended primary application of FATI is the simulation of nuclide burn-up within fusion blankets.

2.4. Neutron poison controller

The PID (Proportional Integral Derivative) controller is one of the first control strategies to be implemented and is a commonly used feedback method [18]. The output of the PID controller, u(t), is given by:

$$u(t) = K_P e(t) + K_D \frac{de(t)}{dt} + K_I \int_0^t e(\tau) d\tau$$