Modelling of a Neutron Source Test Bed for the Fusion Fuel Cycle

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Abstract

Predicting with high accuracy (low uncertainty) the performance of tritium breeding systems is a must for design engineering of future fusion devices. Current modelling relies on scant experimental data and is known to have uncertainties that if realised in a real system would potentially create a tritium shortfall in the fuel cycle of a fusion power plant. LIBRTI is a UK programme to develop a combined experimental test platform and model verification architecture to reduce these design uncertainties. A simple, but flexible pincell geometry containing industry standard ceramic breeder material surrounding a market-leading DT-based neutron source is found to produce sufficient levels of tritium to be readily measurable with the well-established liquid scintillation techniques for tritium accountancy. Modelling of the potential for interference of the measurements due to permeation of tritium from the neutron source itself indicate that, depending on scenario, there will be at least hours, and potentially days or more, of viable measurement data in each experiment even before considering any special design to mitigate the permeation. The analysis is used to demonstrate that LIBRTI will be able to meet its objectives of providing a platform for measurable testing of larger scale tritium breeding experiments.

Keywords — Tritium breeding, neutron modelling, tritium diffusion, LIBRTI test facility

I. INTRODUCTION

High confidence in the performance of the engineered solutions for tritium breeding inside a fusion power plant will be an essential prerequisite for future fleets; without this high confidence in the ability of a power plant to produce a closed fuel cycle for tritium (i.e. without needing any supplement from an external source) it will be very challenging or even impossible to build a commercially viable fusion ecosystem.

Tritium breeding has been proven at the lab scale on a number of occasions. For example, the test blanket module (TBM) programme within Europe has previously performed experiments at the Frascati Neutron generator in Italy for the helium-cooled pebble bed TBM [1] and is working towards an equivalent test for the water-cooled lithium lead (WCLL) concept [2] (these are the two main technology concepts being developed for EU-DEMO). The primary objective of such experiments is to prove that simulation tools and nuclear data are capable of predicting tritium production rates in samples of static lithium compounds within a simplified section of a blanket module. More recently, the MIT LIBRA (Liquid Immersion Blanket: Robust Accountancy) experiment in the US, has performed the first dynamic experiments to measure integral (total) tritium production in a flowing lithium molten salt [3]. These experiments have been successful but are small scale, both in terms of physical size of the test modules used in the experiments but also in terms of the scope of the studies where often only single or few experiments have been performed for single geometries exposed to very low neutron fluxes forcing either integral tritium measurements (LIBRA) or measurement of tritium in encapsulated, isolated samples (EU-TBM). Thus, providing a platform for larger (physical) scale experiments to repeatably test tritium breeding systems in a dynamic environment – the primary objective of the Li Breeding Tritium Innovation (LIBRTI) programme – would represent a significant improvement in testing capability for the fusion fuel cycle.

Meanwhile, engineering-scale designs of tritium breeding modules for full-scale machine deployment are being developed in silico [4, 5, 6, 7, 8]. However, uncertainty in the predicted tritium production (and recovery) from such designs is significant. For example, the uncertainty due to nuclear data has been found to be in the range 3-9% for DEMO-HCPB [9], which is borne out by analyses of, for example, the experimental HCPB TBM data, which found a ∼10% uncertainty when comparing the measurements to neutronics predictions [1, 10]. An uncertainty of 1% in TBR could lead to a shortfall of the order of 1 kg per year for 2-3 GW of fusion power [11], which would be difficult for the fusion community to accommodate for more than 1 or 2 power plants (the estimated global tritium production in heavy water reactors (including CANDUs) being of the order of 1-4 kg per year in the 2030s and beyond [12, 13]). Thus, it is clear that there is an urgent need to improve computational predictions, which can only be practically achieved through experimental benchmarking. LIBRTI's goal of providing a flexible test platform will enable a dramatic increase in the generation of data points for a variety of tritium breeding scenarios under different environmental conditions (temperatures, pressures, etc.), which can be used to both train and test computational models, thereby increasing the accuracy with which they are able to predict the performance of tritium breeding components for future fusion plants.

The aim of this paper is to demonstrate the scientific basis for the LIBRTI programme by addressing the key questions concerning the feasibility of performing experiments to test tritium breeding technology mock-ups. LIBRTI is a programme which will combine the use of an industry leading 14 MeV neutron source with a world leading multi-physics simulation tool box to predict and validate the performance of tritium breeding blankets, where the multi-physics simulation tool box will be underwritten by engineering relevant breeder mockups.

LIBRTI has a unique potential to perform experiments and simulations of the complete cycle from neutron down scattering to tritium production and (limited) tritium extraction, with the aim to underwrite simulations which can subsequently be used to deliver operational tritium breeder blankets for fusion power.

To demonstrate the anticipated performance of LIBRTI we analyse the effectiveness of a modular pincell breeder blanket concept to confirm that experiments at the facility will produce measurable amounts of tritium and thus add to the scientific knowledge and/or technology development of tritium breeding systems. Further, using simple tritium transport models, we will consider whether LIBRTI experiments will suffer interference from the tritium used in the adjacent neutron source. This endeavour is a larger scale solid breeder experiment that builds on the principles of the pioneering MIT LIBRA [3] experiment which performed real time tritium detection of irradiated FLiBe. It also builds on the existing solid breeder tritium production experiments [1, 10, 14, 15, 16, 17, 18] where compact lithium compound devices were irradiated and their subsequent tritium production was sampled. This paper begins with a description of the modular blanket mock-up, then describes the analysis of its predicted tritium production performance, taking in to account tritium contamination from the neutron source and finally discusses the viability of tritium detection.

II. MODULAR PINCELL DESIGN CONCEPT

II.A. Engineering Description

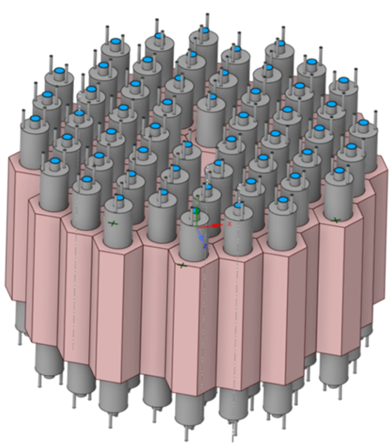
UKAEA is developing a modular pincell blanket for the testing of a variety of breeder and neutron multiplier materials, and which will have spatial resolution of tritium production. The motivation behind this blanket is to produce vital scientific insights into tritium production, neutron down scattering and tritium extraction. Further to this, the current development of the modular pincell blanket has also been fundamental in helping with the design of the LIBRTI facility.

The modular pincell blanket is based on the DEMO Helium-Cooled Pebble Bed (HCPB) design [19], which is a key concept in fusion technology. The modular pincell blanket consists of a hexagonal assembly of pincells arranged in a circular pattern and oriented vertically (Figure 1). Each pincell has three standard-sized concentric tubes containing 316 Stainless Steel. While the length of each pincell aligns with the HCPB design, the cross-section has been optimised to standard pipe sizes to allow easy manufacturing. Surrounding each pincell is a 2 cm thick layer of Pb, arranged in a hexagonal shape with a side length of 10 cm, serving as a neutron multiplier for improved performance, and to reflect a scaled version of the neutron environment within a DEMO HCPB. It must be noted that other neutron multipliers, such as beryllium, as well as alternative structural materials for the tubes themselves could also be used in alternative pincell designs. This modular pincell design will allow for the integration of multiple experimental setups within a single framework.

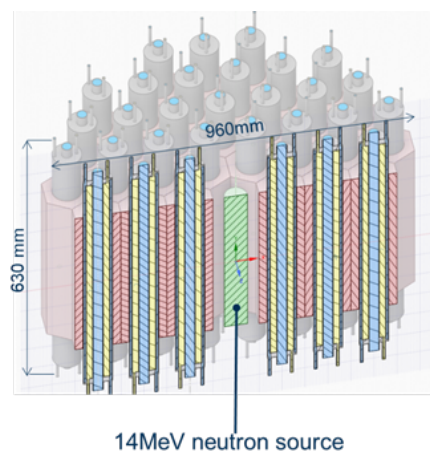
Each pincell is designed to accommodate solid breeder materials and coolant, allowing for effective heat management. In the initial, baseline design, the breeders will be heated up to 650°C, which is hot enough to release tritium in a large range of materials. Each pincell will operate with a helium sweep gas at pressures reaching up to 50 bar, facilitating efficient cooling and tritium extraction. The flexibility of the design allows for the pincells to be configured either to operate independently or to be piped together during an experiment, significantly increasing the experimental throughput and flexibility. This adaptability enables multiple experiments to be conducted within a single irradiation campaign, maximising the utilisation of the LIBRTI facility.

The pincells can be filled with a breeder material and then sealed with a fixed volume of purge gas inside, simplifying the experimental setup and minimising the risk of contamination. In this case, once irradiated, these pincells could be safely handled (up to nuclear safety), allowing for easy distribution to universities and other research entities for further experimentation. The modularity of the design ensures that the pincells can be individually managed, promoting versatility in experimental applications.

The design's motivation extends beyond just experimental versatility; it also aims to drive down costs while maintaining high engineering standards and safety. The modular pincell blanket has been strategically developed to initiate neutronics analysis and modelling efforts related to tritium transport in solid breeders. As a result, it is poised to play a critical role in advancing the understanding of tritium breeding systems, ensuring that LIBRTI experiments yield meaningful and quantifiable results.



(a) The modular pincell blanket consisting of 54 pincells.



(b) Cut-through view of the modular pincell blanket.

Fig. 1. Modular pincell geometry. Moderating material (Pb) in pink, stainless steel container (grey), breeder material (KALOS-generated) in yellow, coolant in blue. The neutron line source is denoted by the region in green.

The modular pincell blanket (Figure 1(a)) comprises 54 individual pincells surrounding a central neutron source tube (Figure 1(b)), capable of housing various breeder materials and activation foils as necessary. One potential benefit of the arrangement's discreet symmetry is the option to measure the neutron spectrum entering a pincell (for example, with a set of activation foils) and

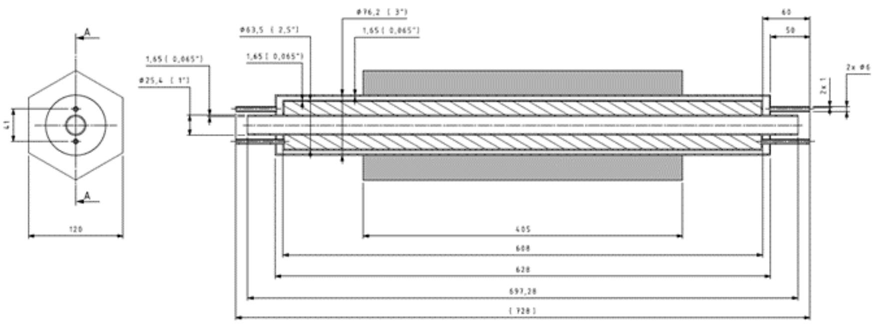


Fig. 2. Prototype dimensions of the pincell.

use this as the calibrated input neutron environment for the set of symmetrically equivalent pincells containing breeder experiments. The development of the modular pincell blanket represents a significant step forward in the practical application of tritium breeding research, facilitating comprehensive investigations into tritium production and transport dynamics. It also unloads the safety engineering requirements off the individual experiments, increasing experimental turnover of the LIBRTI facility.

II.B. Neutronics Analysis

Neutron transport simulations for the modular blanket geometry (Figure 1) have been performed, using both MCNP [20] and OpenMC [21] using a modelled generated using the prototyped dimensions of the pincell (Figure 2). Here we will present the OpenMC results which match the MCNP results. For these simulations and analyses, the ceramic produced via the KALOS [22] process was selected as the tritium breeding material as it is a leading breeder candidate which can be produced at large scale. The KALOS (KArlsruhe Lithium OrthoSilicate) process produces advanced ceramic breeder (ACB) pebbles containing lithium metatitanate (Li_2TiO_3) in addition to the more typical lithium orthosilicate (Li_4SiO_4), where the metatitanate is added to improve mechanical performance. The helium purge/cooling gas was considered to be at 50 bars of pressure. For the line source, two source rates of 5.4×10^{15} and 5.4×10^{11} n/s were investigated to represent the two proposed stages of neutron flux of 10^{13} n/cm^2/s and 10^9 n/cm^2/s for the LIBRTI facility, which are the aspirational target flux goal for the programme and the market-leading flux provided by the deuterium-tritium version of Shine Technologies' NDAS (neutron driver assembly system)

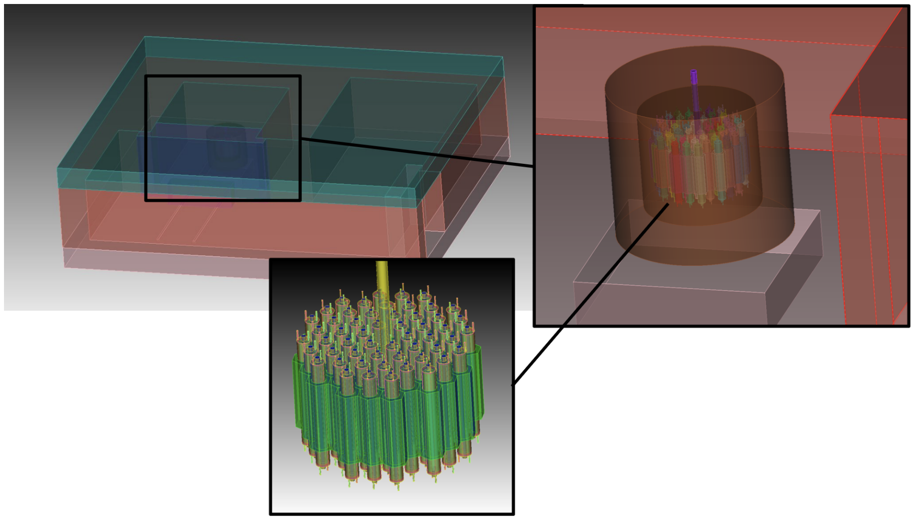


Fig. 3. The modular pincell blanket consisting of 54 pincells placed within a mock-up of a test facility.

that UKAEA has procured for the LIBRTI facility, respectively. The structural components of the LIBRTI facility will have an effect on the neutron environment that the blanket is exposed to, therefore we modelled the modular pincell blanket within a conceptual facility design (Figure 3 – this is not the design of the LIBRTI facility). To further improve the tritium production rate, in some of the simulations we investigated adding a 30 cm thick graphite reflector encasing the modular pincell blanket. This acted as a a neutron reflector, and meant that more low-energy neutrons interacted with the Lithium-6 within the breeder material, which has a higher tritium production cross section at low energy, thus boosting tritium production.

Table I shows the results from these simulations, where tritium production rates (TPR) are given as the metric of performance. The calculations were performed with sufficient neutron histories to ensure the statistical uncertainty in tritium production was less than 10%, but typically 5% or lower. For the present analysis we have not considered the equivalent tritium breeding ratio (TBR) that would be achieved from such a set-up, since this is not appropriate for a LIBRTI irradiation where there will be significant (and, as yet, unknown) neutron losses from the source due to geometry. It may be possible in more detailed analyses to equate a TBR to the number of neutrons entering the breeder mock-up; or alternatively, a local measure of (neutron path length)/(tritium production) could be considered (an integral of this would be comparable to a power plant TBR).

Figure 4 shows that the distribution of tritium in the non-reflected geometry looks as one

TABLE I
Nominal tritium activities when considering a high power and low power neutron source, showing the tritium production rate (TPR) and tritium activity rate.

	High Power	Low Power
Neutron Source Rate (n/s)	5.4431×10^{15}	5.4431×10^{11}
Flux into pincell (n/cm^2/s)	1×10^{13}	1×10^{9}
TPR (1/s) without reflector	$4.35851 \times 10^{14} \approx 0.78$MBq/s	$4.35851 \times 10^{10} \approx 78$Bq/s
TPR (1/s) with reflector	$2.50849 \times 10^{15} \approx 4.5$MBq/s	$2.50849 \times 10^{11} \approx 0.45$KBq/s

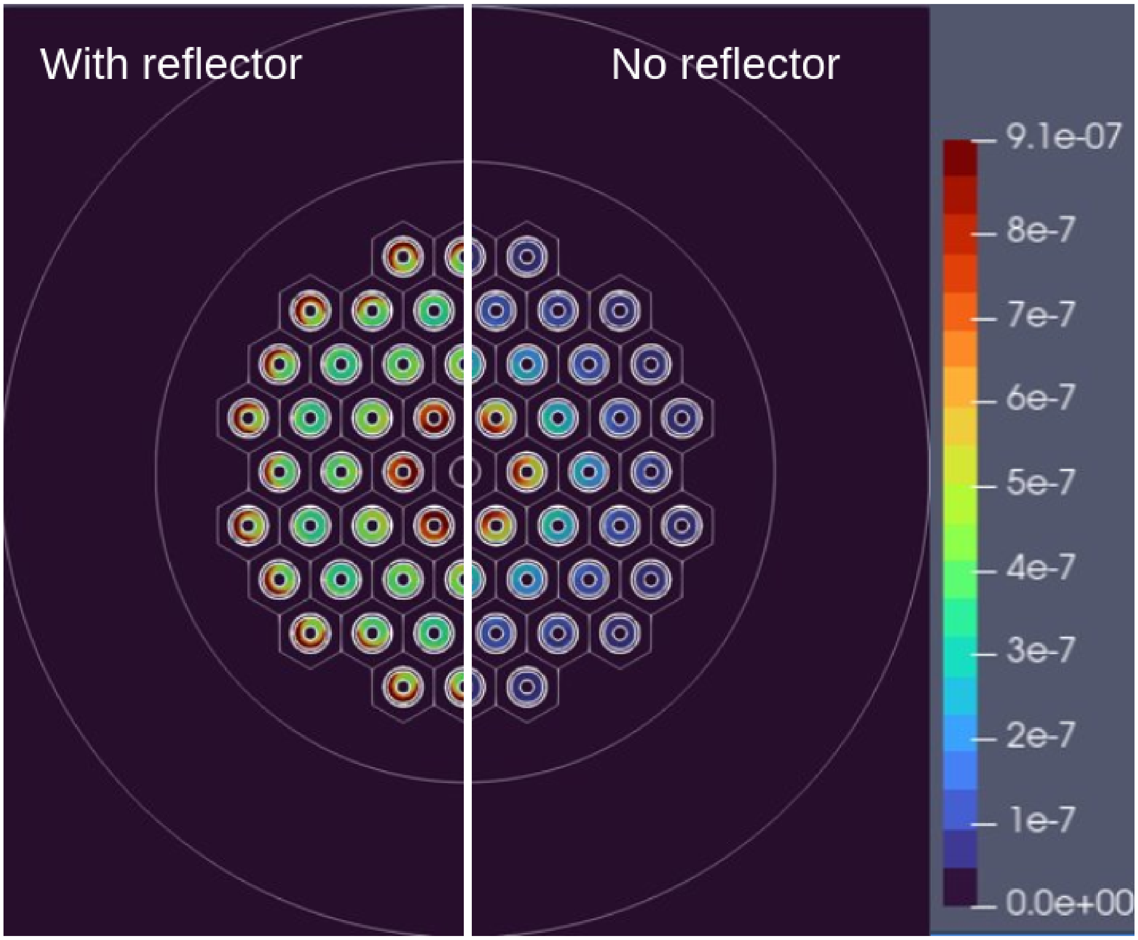


Fig. 4. The impact of using a graphite reflector can be seen on the distribution of tritium production, left shows the system with reflector and right shows the system without.

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would expect from the line neutron source. The version with a graphite reflector has an increased tritium production at the outer periphery due to the increased thermal neutron flux because of the reflector. From a validation perspective, it should be noted that this leads to a non-blanket like neutron distribution. However, the distribution is flatter which will lead to smoother gradients and of course in this case almost six times higher tritium production rate.

II.C. Neutron Source Tritium Contamination of the Experiment

There is a chance that tritium from within the neutron source's target chamber might permeate into the tritium breeder material of a LIBRTI blanket mock-up, introducing noise into the experiment and misleading results. The permeation rate of tritium out of the neutron source target chamber is not known, and to mitigate the risk of tritium permeating into an experiential blanket the current proposal is for a vacuum interspace between the neutron source and breeder mock-up. Such a setup should reduce the tritium noise risk. Another possibility is to install a second cylindrical steel case around the neutron source's tritium target in order to substantially slow down tritium diffusion. The rate of permeation out of this case can be estimated from diffusion equation:

$$\frac{\partial C}{\partial t} = \nabla(D\nabla C). \tag{1}$$

Here, C is the concentration of tritium in the target chamber, and D is the diffusion coefficient. The boundary conditions on both surfaces of the case are determined from equilibrium between the tritium in the gas and in the metal (Sieverts' law):

$$C = S\sqrt{P}, \tag{2}$$

where S is the solubility of tritium in the metal and P the partial pressure of tritium gas. Temperature dependence of both the diffusion coefficient and the solubility follows the Arrhenius law:

$$D = D_0 e^{-E_A/RT}, \tag{3}$$

$$S = S_0 e^{-E_S/RT}, \tag{4}$$

where D_0 and S_0 are pre-exponential coefficients, E_A the diffusion activation energy, E_S the heat of solution, R the universal gas constant and T the temperature.

The case of a hollow cylinder with a constant diffusion coefficient across it was considered by Carslaw and Jaeger [23] (see also Crank [24]) and the solution is given in terms of Bessel functions of the first and second kind. However, in the case where cylinder thickness is much less than the radius, permeation across it can be considered as a one-dimensional problem. In order to estimate the time needed for the diffusional flux of tritium from the source to become greater than the production rate in the breeder pin, numerical modelling was performed using FESTIM [25] (Finite Element Simulation of Tritium In Materials), which is an open source program for solving coupled hydrogen transport - heat transfer simulations. It was assumed that the steel case is held at temperature 100 °C (Pb multiplier temperature) and the partial pressure of tritium in the chamber is 533 Pascal (40 Torr – the typical pressure for the tritium gas target of Shine Technologies' neutron source being deployed into the LIBRTI facility), while it is negligibly low on the opposite side of the case (i.e. as it would be in the case of a flowing purge gas with negligible [but still measurable] concentrations of tritium).

FESTIM modelled the tritium flux across the wall as a function of time and wall thickness under these conditions. This flux can be compared with the rate of tritium production in a pincell for the higher flux rate and without a graphite reflector. Neglecting the effects of the facility's structure, for a spatially separated blanket, neutronics simulations predict an average tritium inventory of 1.3×10^8 Bq after a continuous 4 day irradiation for a pincell adjacent to a source with an output of 5×10^{13} n/s (an intermediate value between low and high power neutron source rate in Table I) in the same configuration as considered in Section II.B. This corresponds to an average production rate per pin of 374 Bq/s. For the purpose of comparison, the area of a pin exposed to the flux of tritium from the neutron source was estimated as 60 cm $\times$ 63.5 mm = 0.0381 m^2 (i.e. the length of the pincell described in the previous section multiplied by the width [diameter] of the breeding zone inside it). Several sets of experimentally obtained diffusivities and solubilities of hydrogen in relevant austenitic stainless steels shown in Table II were used in simulations.

TABLE II

Material parameters of several 316 austenitic stainless steels used for estimating tritium diffusion.

Steel	**D_0 (m^2/s)**	**E_A (eV)**	**S_0 ($mol/(m^3Pa^{0.5})$)**	**E_S (eV)**	**Ref.**
316L, commercial	3.82E-07	0.47	0.471	0.19	[26]
316L, heat treated	7.66E-08	0.44	1.46	0.21	[26]
316L	6.20E-07	0.58	0.419	0.11	[27]
316L(N)-ITER grade polished	6.00E-07	0.53	0.1	0.07	[28]
316L(N)-ITER grade roughened	1.00E-07	0.49	0.7	0.17	[28]

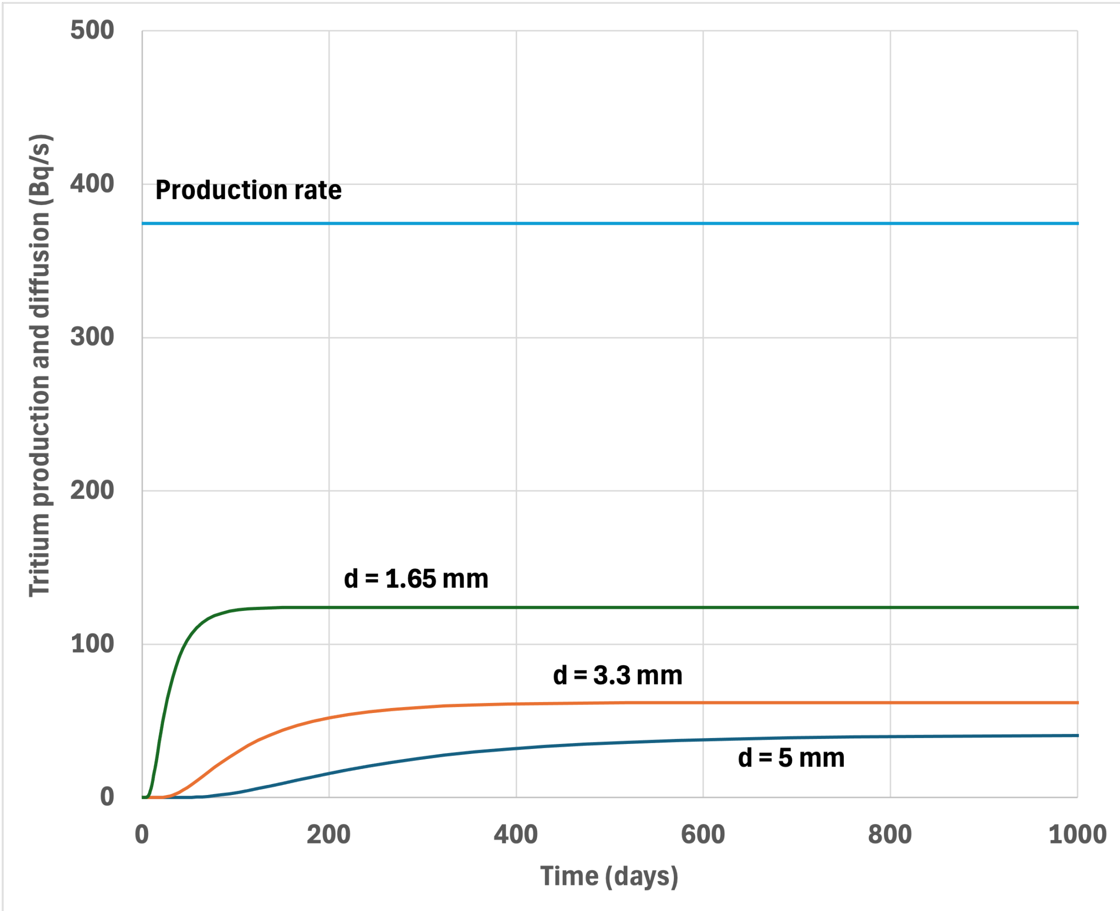

Fig. 5. Tritium diffusion rate into a pin (Bq/s) vs time (days) for three values of steel (commercial grade 316L) casing thickness compared to production rate in the breeder. Temperature T = 100 °C, material parameters correspond to the top row of Table II.

Figure 5 shows the tritium diffusion rate across different thicknesses of steel case into a neighbouring pin at a temperature 100 °C compared to the estimated production rate of tritium in the pin. The simulations were performed for commercial 316L stainless steel (first row of Table II). The estimates were obtained assuming Sieverts boundary conditions (Equation 2) on the neutron source side (partial pressure of tritium 533 Pa) and on the opposite side (partial pressure and concentration of tritium in steel being 0). For all values of steel thickness, contamination fluxes of tritium from the neutron source are much less than the production rate. For example, for the case of 5 mm thick steel, contamination from the neutron source would be negligible over first 100 days of operation (Figure 5). Next, in order to estimate an uncertainty range, all five sets of material parameters from Table II were used. Figure 6 shows the uncertainty band of tritium diffusion into the pin corresponding to different sets of parameters for the case material with a 5 mm thickness.

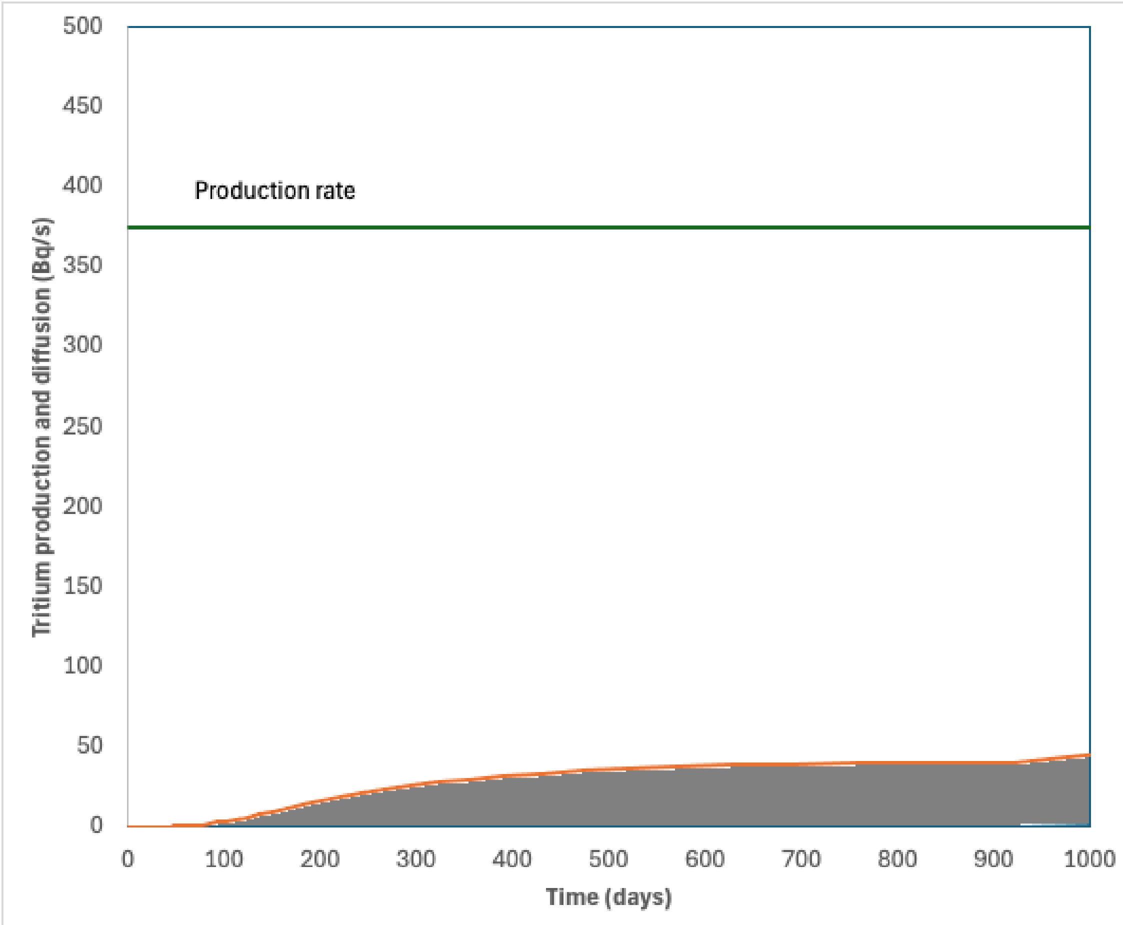

Fig. 6. Grey: band showing tritium diffusion rate into a pin (Bq/s) vs time (days) for steel casing thickness of 5 mm and temperature T = 100 °C compared to production rate in the breeder. The material parameters taken from Table II, with the upper bound curve the same as that in figure 5 for commercial grade 316 L.

Note that with increasing the temperature of the steel, the equilibrium flux of tritium from the source increases by several orders of magnitude, while the time to reach this flux decreases. Figure 7 shows the range of predictions for a simulation performed for 5 mm thicknesses of steels at a temperature of 600 °C. Here we have estimated an uncertainty range (grey band in the figure), by considering all five sets of material parameters from Table II. By comparison, the corresponding result at 100 °C results in an uncertainty band filling the area under the 5 mm curve for the 316L commercial grade - see Figure 6.

In the 600 °C case, diffusional flux becomes higher than the production after less than one hour of operation, regardless of the choice of steel, which would be of the same order as the typical residence time for tritium in ceramics such as Li_4SiO_4 (measured to be around 1 hour at 600 °C in [29]) – in such circumstances, careful experimental planning would be required to ensure that useful measurements could be performed before cross contamination became a problem or, alternatively the experiment could be redesigned to slow the contamination flux. For example, coating the steel case with a thin tritium permeation barrier, such as yttria (Y_2O_3) would delay the onset of contamination. Note also, that it is likely that the target chamber of the neutron source will be cooled during operation, further reducing the tritium permeation rate.

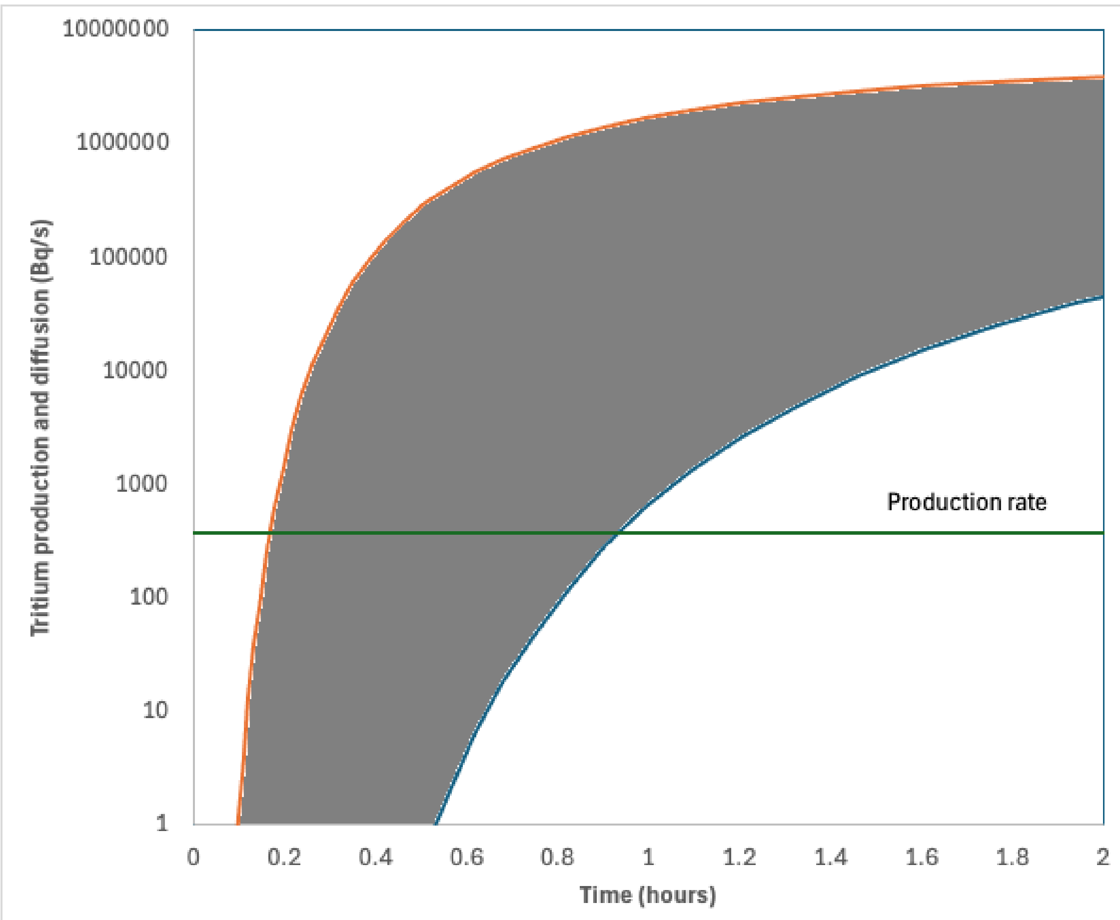

Fig. 7. Grey: band showing tritium diffusion rate into a pin (Bq/s) vs time (hours) for steel casing thickness of 5 mm and temperature T = 600 °C compared to production rate in the breeder. The material parameters taken from Table II.

Even if the contamination of pins in direct contact with the source is (too) high to allow reliable measurements in certain scenarios, the permeation of tritium into pins that are further away from the neutron source will be both delayed and much less due to the tritium having to pass through the multiple layers of steel and Pb separating such pins from the source, and a $1/r$ geometric dispersion. This creates a possibility to monitor the tritium contamination of nearest pins by comparing the amount of tritium in them with that in periphery pins (after correction for different tritium production rates).

Note that the tritium leakage analysis performed here is an effective model to establish the principle phenomena at play and is expected to over predict the amount of tritium leaking from the neutron source and into the pincells. This is because the transport model neglects the delay in contamination caused by tritium also needing to pass through the multiplier material (Pb in the present calculations) and steel container immediately surrounding the breeding materials. The modelling also assumes that the purge and cooling gases do not reduce the tritium concentration in their respective regions and that the neutron source's target canister is hot.

III. NEUTRON DIAGNOSTICS MEASUREMENTS

Direct measurement of the neutron spectrum at varying locations during an experiment can be critical to support model verification (i.e. testing a models ability to predict the neutron field variation will go a long way to testing its ability to predict tritium production) and so it is instructive to consider their feasibility. To evaluate the performance of neutron diagnostics for the proposed modular pincell blanket experiment, a study was conducted to assess the viability of activation foils. These were selected as the primary neutron diagnostic due to their resilience in high radiation environments and UKAEA's extensive experience using them in previous experiments, such as those conducted on JET through the EUROfusion WP3 and PrIO programmes [30, 31]. The primary aim of the study was to confirm the suitability of activation foils to provide reliable neutron spectrum measurements under experimental conditions and to determine the required measurement times for statistically significant results.

The neutron spectrum and total flux were calculated using MCNP in 709 energy groups, with measurements taken from the voids between the pincells. Yttrium (^{89}Y) activation foils, 15 mm in diameter, were selected for neutron diagnostics, particularly for the ^{89}Y(n,2n)^{88}Y reaction. This reaction was chosen because it has an energy threshold that lies between typical DD and DT neutron energies, making it an ideal candidate for confirming the presence of DT neutrons in the system.

The activity of ^{88}Y produced in the foil was calculated using the UKAEA FISPACT-II inventory code [32], assuming a 4-day neutron irradiation period. The foil was modelled to be extracted using a pneumatic rabbit system and counted with a high-purity germanium (HPGe) detector 5 seconds post-irradiation. To assess the statistical significance of the measurements, the time required to record 10,000 counts in the gamma-ray photopeaks at 898 keV and 1836 keV was calculated. Achieving 10,000 counts ensures a 1 percent statistical uncertainty, a commonly accepted threshold for reliability in such measurements.

For a conservative estimate of the foil's performance, it was placed in a region of lowest neutron flux—adjacent to an outer pincell. The results of this analysis, shown in Table III, illustrate the relationship between neutron source strength, tritium production, and the time required to measure ^{88}Y activity with a 1 percent uncertainty. As expected, the time required for statistically significant results decreases with increasing neutron flux, with the method proving to be effective even at lower neutron source rates.

Source strength (n/s)	**Tritium (Bq)**	^{88}Y **(Bq)**	**Time (hrs)**
1.00E+08	1.40E+04	1.65E-02	1.44E+05
1.00E+09	1.40E+05	1.65E-01	1.44E+04
1.00E+10	1.40E+06	1.65E+00	1.44E+03
1.00E+11	1.40E+07	1.65E+01	1.44E+02
1.00E+12	1.40E+08	1.65E+02	1.44E+01
1.00E+13	1.40E+09	1.65E+03	1.44E+00
5.00E+13	7.02E+09	8.27E+03	2.88E-01

TABLE III
Times required to achieve a 1% statistical uncertainty on the measurement of ^{88}Y from an yttrium activation foil diagnostic, following a 4 day irradiation, as a function of neutron source strength, for configuration 1. The total tritium inventory in Bq produced is also reported.

In addition to individual foil measurements, determining information on the neutron energy spectrum will require an array of activation foils, each with unique neutron reaction channels measurable by gamma spectroscopy. These measurements will provide the necessary data to unfold the neutron spectrum using a response matrix and a neutron spectrum unfolding algorithm such as SPECTRA-UF [33]. Further investigation is required to optimise the foil selection and irradiation schedules, as well as to ensure the timing of measurements is aligned to reduce data loss from radioactive decay. Once the design of the experiment reaches a sufficient level of maturity, a formal optimisation loop should be undertaken to fine-tune these parameters.

Finally, activation foil measurements offer indirect but crucial insights into tritium production and transport within the pincell blanket. Neutron interactions with the breeding material will generate tritium, and the activation foil data will help confirm the neutron flux and spectrum needed for these reactions.

IV. TRITIUM DETECTION WITHIN THE PINCELL GEOMETRY

During an irradiation the solid breeder material within the pincells will be heated (up to 650 °C). This will help the material release the tritium which is produced within it. In real time the tritium will be purged with the helium (or similar) purge gas, which will then be made to pass through liquid bubblers for subsequent liquid scintillation counting or LSC. For the quantification to attain good statistics (i.e. to have small error bars in the tritium quantification) the counting will take time, so we propose to sample the tritium concentration in the helium purge gas at different time intervals, which can be achieved by changing the liquid scintillation cocktail that it is being passed through. This will result in a measurement of tritium concentration, within the purge gas, as a function of time, even if the time to measure the tritium activity within the scintillation fluid is longer than the gas sampling periods. The (quasi-)real time measurement of tritium is highly desirable from a scientific and validation perspective; the setup of bubblers and liquid scintillation facilities should reflect this by having sufficient arrays of bubblers and available counters.

In terms of detection thresholds, a recent review of techniques for measuring tritium in aqueous media [34] identified LSC as the best approach for measuring tritium and highlighted the recent enhancements to the technique using coincidence correction with multiple low-background LSC systems that achieve an expected minimum detectable activity (MDA) of 0.6 mBq/g during a 195-minute count. As we have seen in the calculations presented earlier, the total tritium production rates in an individual pincell should be comfortably above this limit. However, we should also consider the impact of tritium residence time in the breeding material, in this case pebbles of KALOS ceramic.

Measurements performed at the Karlsruhe Institute of Technology (the developers of KALOS) found tritium release rates from tritium-loaded KALOS pebbles (with diameters of the order of 0.5 mm) into a helium purge gas with 0.1% H2 were of the order of 1000 Bq/g/s at 600 °C [35], although maximum release rates in those experiments were only attained at higher temperatures and the samples were saturated with very high tritium concentrations during the loading phase. On the other hand, single $\sim$ 1 mm diameter lithium metatitanate pebbles irradiated at the fusion neutron source (FNS) in Japan (a now closed facility that could achieve fluxes of the order of 1×10^{10} n/cm^2/s [36] – similar to what will be achieved in early phase of LIBRTI operation) produced maximum release rates (also into He+0.1%H_2) of the order of 0.7 Bq/s during a 5-hour irradiation at 600 °C [37]. Such values, scaled up to a pincell containing a large number of pebbles and leading to 10s of Bq (or more) of tritium production per second (table I), would produce detectable tritium measurements as a function of time via water bubbling and LSC.

V. SUMMARY

In this paper we have tested aspects of the scientific measurement basis for a tritium breeding test bed as the new LIBRTI programme at UKAEA. We have modelled a concept for a modular pincell geometry as a representative experimental mock-up around the neutron source that will be the foundation of the LIBRTI facility. We have assumed the expected DT neutron output from that source and a future aspirational performance that could be realised via further R&D. In either case, tritium production rates in the industrially proven ceramic breeding material produced via the KALOS process will reach detectable levels even when accounting for the residence time of tritium in ceramic materials. Furthermore, at low temperatures the rate of contamination flux from tritium in a close by neutron source is likely to be too slow to impact on the measurements from within breeding mock-ups, while at higher temperatures further design work is needed to understand the potential requirement for mitigation steps (barrier coatings, additional containment walls, cooled target, cooler inner pincells etc.) to allow sufficient measurements of the evolving tritium concentration before the signal becomes contaminated.

With the pincell geometry described here and these simulations we have established a basis for LIBRTI to provide a test platform for tritium breeding mock-ups; one that will achieve detectable tritium levels and generate the needed repeatable data points to provide validation cases towards the ultimate goal of accurate models for tritium breeding design engineering for future fusion fuel cycles. In addition to the modular pincell blanket enabling detailed scientific experiments, it will also allow a large range of materials to be tested within the LIBRTI facility at low cost. This will allow a much larger space of materials (and other parameters) to be tested, underpinning the modelling and hence improving the predictive power of UKAEA's breeder blanket simulation tool box.

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