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DEMO tritium fuel cycle: performance, parameter explorations, and design space constraints

M. Coleman[a,b,c,*], Y. Hörstensmeyer[d], F. Cismondi[c]

[a] United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, United Kingdom
[b] Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, United Kingdom
[c] EUROfusion Consortium, Boltzmannstraße 2, 85748 Garching, Germany
[d] Institute for Technical Physics, Karlsruhe Institute of Technology (KIT), 76344 Eggenstein-Leopoldshafen, Germany

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ABSTRACT

One of the overarching goals of a DEMO-class device is to demonstrate tritium self-sufficiency in a fusion power plant for the first time. A future power reactor will necessarily require a start-up inventory of tritium, $m_{T_{\text{start}}}$, before commencing fully fledged D-T operations for electricity production. In Europe, it is also presently considered necessary for DEMO to provide a tritium fuel start-up inventory for a subsequent prototype fusion power plant at a certain doubling time, t_d. At present, there is no model capable of estimating $m_{T_{\text{start}}}$ or t_d for the EU-DEMO, which features a Direct Internal Recycling (DIR) loop in its fuel cycle, and is characterised by low load factors (~ 0.2-0.3). This paper introduces a simplified dynamic tritium fuel cycle model capable estimating $m_{T_{\text{start}}}$ and t_d, which has been specifically designed to take into account the effects of low reactor load factors and irregular operation. Results with and without DIR are presented. The fuel cycle design space is explored, and the sensitivity of the performance (in terms of $m_{T_{\text{start}}}$ and t_d) to variations in key parameters and parameter combinations is analysed. Minimum recommended values are suggested for the required tritium breeding ratio ($\Lambda_r \geq 1.05$), load factor ($A_{glob} \geq 0.2$), and DIR separation factor ($f_{DIR} \geq 0.6$), for the assumptions made herein, based on the response of the fuel cycle performance in the explored design space.

1. Introduction

Achieving tritium self-sufficiency is a significant challenge for any DEMO-class fusion power reactor. It is a multi-disciplinary problem, and depends upon the performance of many different sub-systems. Here we aim to gain an understanding of the relative importances of some prominent parameters in the fuel cycle and their impact on the performance in terms of the start-up inventory, doubling time, and tritium release rate to the environment.

In this work, we:

(i) Briefly introduce some of the relevant European DEMO (EU-DEMO) high-level requirements related to tritium self-sufficiency.
(ii) Introduce aspects specific to the EU-DEMO reactor and fuel cycle design.
(iii) Introduce a dynamic fuel cycle model capable of estimating the tritium start-up inventory and doubling time, which we run in a Monte Carlo approach on multiple partially randomised fusion load signals.
(iv) Explore some important parameter combinations and determine their impact on the tritium start-up inventory and reactor doubling time.
(v) Discuss how the performance of some key systems and the overall reactor behaviour affect the performance of the fuel cycle.

1.1. High-level fuel cycle requirements

Work on the EU-DEMO device [1,2] has gone some way in defining the high-level plant requirements.

The goal of tritium self-sufficiency can be broken down into a number of lower-level requirements, some of which are in conflict:

(i) The DEMO plant shall produce sufficient tritium such that it can guarantee its planned operational schedule (including any unplanned shutdowns) without ever having to purchase tritium from an external supply (after the start-up inventory).
(ii) DEMO shall produce sufficient tritium to be able to start up another fusion reactor during its lifetime.

* Corresponding author at: United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, United Kingdom.
E-mail address: matti.coleman@ukaea.uk (M. Coleman).

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(iii) DEMO shall minimise its required start-up inventory.
(iv) DEMO shall minimise its overall tritium inventory (which shall be below some regulatory limit, to be determined).
(v) DEMO shall release less than X grams of tritium per annum to the environment. This requirement is likely to be regulatory in origin, and follow the principles of "As Low As Reasonably Achieveable", therefore the exact number cannot be known today. Based on preliminary work (see [3]) we assume $X = 9.9\ g_T$/annum here.

In this work, we address the above requirements from the perspective of the fuel cycle, with particular focus on (i), (ii), and (v).

1.2. Tritium start-up inventory: $m_{T_{\text{start}}}$

The tritium start-up inventory, $m_{T_{\text{start}}}$, is the amount of tritium required for a DEMO-class device to complete its mission without ever requiring an external supply of T. It is theoretically possible to start up a reactor in D-D, and progressively breed sufficient T to operate a D-T reactor normally [4]; however, the time, cost, and complexity of such an endeavour have yet to be comprehensively assessed. A commissioning phase prior to full-power D-T operations (likely to be mostly D-D plasma operations) will undoubtedly produce some net tritium, although at present it is generally assumed that a certain amount of tritium will need to be purchased from an external supplier. Konishi et al. have done some modelling work assuming extensive D-D commissioning activities and claim that trivial amounts of externally sourced T would be required to begin D-T operations in earnest [5].

Here, we operate on the basis that the origin of the tritium is irrelevant: an amount, $m_{T_{\text{start}}}$, will be needed regardless.

Previous studies over many decades point to a large uncertainty in $m_{T_{\text{start}}}$, with estimates ranging from 0.5 to 25 kg for a 1–2 GW fusion power reactor [6,7]. Recent developments in the EU-DEMO tritium fuel cycle design, most notably with the advent of the Direct Internal Recycling (DIR) cycle [8], have aimed to drastically reduce the cycle time and inventory, although to what degree has not yet been made clear.

1.3. Reactor doubling time: t_d

Here we define the doubling time, t_d, as: the duration, from the date of first commercial operation to the first moment in time at which a reactor generates a surplus of T, equal to $m_{T_{\text{start}}}$, without affecting its own operational schedule. This assumes that a future reactor would need the same amount of tritium as a DEMO device. Although possibly incorrect, it is nonetheless a reasonable assumption in the absence of any better information. Note that the "doubling" does not actually correspond to a doubling of the T inventory in a DEMO device, but of the number of reactors.

Whilst the need to provide tritium for a future reactor is widely accepted, exactly when such a need might arise in the life of the reactor has never been seriously considered in design studies. It would be relatively trivial for DEMO to provide tritium for a new reactor at the end of its life, as it no longer requires tritium for its own operations. Without any further guidance, we propose some reasoning to frame this requirement further. A fusion reactor beyond DEMO will only be built if DEMO is a success. It is likely that DEMO will only be considered a success after several years of operation, which we suggest here should to be (as a minimum) somewhere in the second phase of operation, with the second blanket set installed.

Note that if one believes that a DEMO-class reactor can create enough tritium from commissioning in D-D as Konishi et al. suggest [5], then the issue of reactor doubling time is a moot point.

1.4. Required tritium breeding ratio: Λ_r

The breeding blanket in a DEMO-class device must produce sufficient tritium to offset the losses in the system through burning, decay, and sequestration, and losses to the environment. Several studies have investigated what tritium breeding ratio (TBR), Λ_r, would be required to achieve this overarching requirement, with values typically in the range $\Lambda_r = 1.05$–1.15. However, in the recent EU-DEMO studies a "target" value for the TBR has been set at $\Lambda_t = 1.10$ [9]. These authors discuss and analyse a range of uncertainties and margins surrounding the EU-DEMO TBR, before allocating two "loss budgets" for the TBR. The authors assign a 5% loss budget to the fuel cycle (which we will refer to here as Δ_{FC}), followed by another 5% loss budget for ports and penetrations. No rationale or supporting analysis is given for the 5% allocated to the fuel cycle, other than it accounts for approximately 1 year of tritium decay, which the authors of [9] qualify as being "very conservative". The 5% allocated to the ports implies that the TBR being assessed appears to be, in fact, a virtual number based on maintaining an artificial axisymmetry in neutronics models and then assigning a budget to volumes later lost to non-breeding components/voids.

This work will attempt to provide supporting analysis for a reasonable design requirement for the required TBR, Λ_r, which will, in effect, amount to: $\Lambda_r = 1 + \Delta_{FC}$. The Λ values discussed here are actual TBR values; i.e. the number of tritons actually created in the system, for every D-T fusion reaction (on average), see Eq. (1).

$$\Lambda = \frac{\partial m_{T_{\text{bred}}}/\partial t}{\partial m_{T_{\text{burnt}}}/\partial t} \tag{1}$$

Although we note that Λ will vary over the life of the plant, as materials transmute, or batch processing breeding systems (e.g. pebble beds) deplete, we ignore these effects in our analyses.

Uncertainties due to design and modelling assumptions, nuclear data, and lithium burn-up must be accounted for above and beyond the TBR values we discuss here. Similarly, we offer no comment as to how to treat TBR estimations in neutronics models. Further gains on the required TBR for design margins (e.g. a loss budget for non-breeding volumes), Δ_M, and uncertainties, Δ_U, must be accounted for in the definition of the target TBR, where $\Lambda_t = \Lambda_r + \Delta_M + \Delta_U$.

1.5. Planned operations for the EU-DEMO

The total lifetime of the EU-DEMO device and its operational phases are defined in terms of material damage in the EUROfer first wall at the outboard equatorial midplane. A total lifetime of 70 dpa is assumed, with a "starter" blanket being used in a first operational phase, up to 20 dpa, followed by the second operational phase (with a second blanket set), running a further 50 dpa [10].

For a fusion power, P_{fus}, of 2037 MW [11], we assume a EUROfer damage rate of 10.2 dpa/fpy at the blanket first wall at the equatorial midplane, as per [12] and similar to values presented in [13], and for the divertors (CuCrZr), we assume a total lifetime of 5 dpa, with a damage rate of 3 dpa/fpy, as suggested in [14].

Once components reach the end of their (scheduled) lifetime, the reactor must be shut down, and the components must be remotely replaced. For the EU-DEMO we assume a full blanket replacement duration of 250 days, and a full divertor replacement duration of 150 days, which include all reactor shutdown and restart activities. Naturally, in-vessel components will need to be replaced before the end of their scheduled life (due to failures); however, these activities are technically unplanned maintenance activities and cannot be predicted.

In this work we take the EU-DEMO1 2015 design point [1,11] as a reference, which is a pulsed device, with a pulse length, t_{pulse}, of two hours. We assume that the inter-pulse duration will be dictated by the recharge time for the central solenoid (CS), t_{CS}, which we assume is 600 s. The other factor which could affect this time is the time needed to pump down the vessel back to its base pressure after the extinction of the plasma from the previous pulse.

Ramp-up and ramp-down periods are assumed during a pulse, in which the plasma current (and power) will be steadily brought up to full operational load. For simplicity, we assume here that no fusion takes place during this time. The ramp-up and ramp-down rates are assumed to be r_{ramp} = 0.1 MA/s, as in [15].

The EU-DEMO plasma current, I_p, is 19.8 MA, and, as such, the flat-top duration, $t_{flattop}$, is 1.89 h. In order to fulfil its target of 70 dpa, the EU-DEMO must operate for a duration, T_{fpy}, of 6.86 full-power years, the equivalent of approximately 32,000 full-power D-T pulses over the lifetime of the plant.

1.6. Load factor: A_{glob}

It is clear that the operation of a first-of-a-kind (FOAK) fusion power reactor will be fraught with difficulties, and that less than ideal operation should be anticipated.

For clarity, we define an overall fusion load factor target, A_{glob}, as the fraction of time spent operating at full plasma power over the lifetime of the plant from the end of commissioning to the end of all scheduled operations, see Eq. (2):

$$A_{\text{glob}} = \frac{T_{\text{fpy}}}{T_{\text{calendar}}} \tag{2}$$

where $T_{calendar}$ is the duration in years for DEMO to produce a total energy equal to $P_{fus}T_{fpy}$.

Assuming one blanket replacement, four divertor replacements, and otherwise perfect operation (i.e. two-hour pulses take place every 600 s except during maintenance), one can easily determine that, with the assumptions discussed above, the total, ideal reactor lifetime is 10.19 calendar years. In other words, the maximum achievable load factor of the EU-DEMO is 6.86/10.19 = 0.67.

This would, of course, be an unreasonable value to assume for a FOAK fusion power reactor. A target availability factor of 0.3 is presently assumed for the EU-DEMO [2]. Note that the above definition of load factor differs subtly from that of an availability factor, which is when the reactor is *able* to operate (not necessarily at nameplate capacity).

The fusion load factor in the first phase of operation after commissioning is likely to be very low (e.g. 10%), resulting in large ranges of intervals between pulses: from the minimum possible time between pulses, up to years if a serious failure occurs. This presents a unique challenge for the DEMO tritium fuel cycle, as it must cope with the pressures of rapid delivery during sequential pulses with no failures, while producing enough tritium to account for decay losses over long periods of time when none is being produced.

In this work, we assume that no reactor downtime is ever incurred due to a lack of tritium in the fuelling systems. This ambitious goal is inherent to the principle of tritium self-sufficiency and general power plant relevance; one can scarcely imagine a coal power station not producing electricity because of a lack of coal[1]. We suggest that this objective should be enshrined in a high-level requirement for DEMO and its tritium fuel cycle.

2. Tritium fuel cycle model

2.1. Literature and motivations

DEMO will be the first nuclear fusion power plant to demonstrate a closed fuel cycle, and as such will impose strong requirements on its tritium, fuelling, and vacuum (TFV) systems, as well as the breeding blanket, safety, and waste systems.

Previous seminal works by Abdou et al. [16], Kuan and Abdou [7], and colleagues [17,18] have for years been the reference(s) for tritium fuel cycle models for next generation devices. These authors have built very detailed analytical models of the global tritium fuel cycle, accounting for many and varied loss terms, and including a variety of system and sub-system parameters.

The situation as we see it today differs in two important respects from that addressed by these previous works.

Firstly, recent developments in the tritium fuel cycle in Europe have led us to consider a continuous DIR of the fuel cycle [8], and different fuel cycle parameters based on developments in R&D. This modifies the typical fuel cycle functional block diagram and the performance values for the TFV systems (most notably the plasma exhaust reserve time), and has the potential to reduce the complexity and size of the fuel cycle, and improve the performance of the system in terms of the required $m_{T_{\text{start}}}$ and t_d.

Secondly, although Kuan and Abdou's analytical model [7] includes terms for the overall reactor load factor, most calculations are done assuming high availability factors[2]. Though these authors show results for far lower load factors, the terms are applied as averages to make the model time-independent. This approximation is justifiable for the ranges of availability they considered as realistic at the time (50% to 100%), and the authors themselves note that the range of insensitivity is between 65% to 100% [7]. However, Kuan and Abdou's results for reactor availabilities around and below 30% are cause for concern: high TBRs ($\geq$1.3) are required to maintain the same performance. Yet in the EU, with present knowledge, we consider load factors similar to these values — and modern blanket studies do not indicate such high TBRs to be achievable.

Work on the Chinse Fusion Engineering Test Reactor tritium fuel cycle is also underway [19], in which a load factor of 100% is considered.

Given the substantially lower load factors considered in the EU-DEMO studies (typically $\sim 20-30\%$) we were motivated to consider a Monte Carlo approach for the simulation of randomised DEMO timelines, coupled with a simplified fuel cycle model to estimate the fuel cycle performance. For example, if, during the first operational phase, one or more lengthy unplanned outages take place, this could have a driving effect on the required tritium start-up inventory.

Finally, an additional motivation is simply that dynamic tritium fuel cycle models capable of estimating $m_{T_{\text{start}}}$ and t_d do not exist at present in the EU. More detailed studies of the EU-DEMO TFV systems are being carried out, as are much higher fidelity models of the full fuel cycle over the course of a single reactor pulse. However, these are too slow for us to model the performance over the lifetime of the plant, and are best used to inform a lower-fidelity model, such as the one presented here. We note that this approach is similar to that of Kuan and Abdou [7], who used more detailed dynamic models (e.g. CFTSIM [20]), which simulate phenomena at much shorter timescales, to estimate parameters in their global analytical model.

2.2. Global availability model

It is clear that, in its early stages of operation, DEMO will encounter various issues associated with the operation of a FOAK reactor. Given existing operational experience, it would be unwise to expect a high level of plant availability in these early phases, and even more unrealistic to expect predictable operation. Here we argue that it will be difficult for DEMO to stick to regular operational schedules, and that many unplanned maintenance phases are likely to occur, the likes of which we cannot meaningfully predict today.

Here we introduce additional definitions:

[1] Unless one lived through the 1972 miners' strike in the United Kingdom.

[2] We use the term load factor here, whereas Kuan and Abdou use availability. The two are closely related, and mathematically identical if the reactor is operated at nameplate capacity exactly whenever it is available to operate. In Kuan and Abdou's model, and the work presented here, the terms are equivalent.

(i) An operation period, defined as the period between two planned maintenance intervals (of either the divertors or the blankets).
(ii) The operational load factor, a_n, which is defined as the fraction of time spent operating at full plasma power within a given operation period, n.

In order to obtain a realistic view of how the availability of a FOAK might develop throughout its life, we posit that the operational availability of the plant will evolve over time following a sigmoid-like function. General experience with reliability, availability, maintainability, and inspectability (RAMI) issues leads us to expect high failure rates and low availability at the start of life (infant mortality) and end of life (wear-out failures), and yet on FOAK systems we also expect a degree of learning and improvement with experience to take place. A sigmoid function for the operational load factor gives a flat performance at the start of life, and assumes some improvement in performance gained through operational experience, which is then limited by end of life component failures.

Thus, we propose a sigmoid (Gompertz) parameterisation of the operational load factor of the reactor over its life:

$$a(t) = a_{\min} + (a_{\max} - a_{\min})\exp\left(\frac{-\ln(2)}{\exp(-ct_{G_{\rm infl}})}\exp(-{\rm c}t)\right) \tag{3}$$

where t is time (fpy), a_{min} and a_{max} are the minimum and maximum operational load factors, $t_{G_{\rm infl}}$ is the inflection point of the Gompertz function (fpy), and c is the learning rate (fpy^{-1}). The choice of a Gompertz parameterisation was made to enable minimum and maximum value constraints to be implemented. Based on expert opinion, a_{min} and a_{max} were set at 0.1 and 0.5, respectively, and c was fixed at 1.

We then discretise Eq. (3) on a per-operation-period basis, maintaining the same overall load factor, A_{glob}. As the operation periods vary in duration, the discretisation cannot be done by simple integration of $a(t)$, and instead we apply a discretisation function g to get: $\bar{a}(i) = g(a(t))$ and then frame a simple optimisation problem to find $t_{G_{\rm infl}}$ which satisfies the constraints of a_{min} and a_{max} for the same total fusion duration:

$$\min_{\forall\, t_{\rm infl} \in [0, T_{\rm DEMO}]} A_{\rm glob} T_{\rm DEMO} - \sum_{i=0}^{n_{\rm periods}} a_i T_i \tag{4}$$

Solving Eq. (4) gives a vector of operational load factors, $\bar{a}$, per phase, where $\sum_{i=0}^{n_{\rm periods}} a_i T_i = A_{\rm glob} T_{\rm DEMO}$, where T_i is the total duration of the phase. Fig. 1 shows the operational load factors over the life of the plant for a given overall load factor.

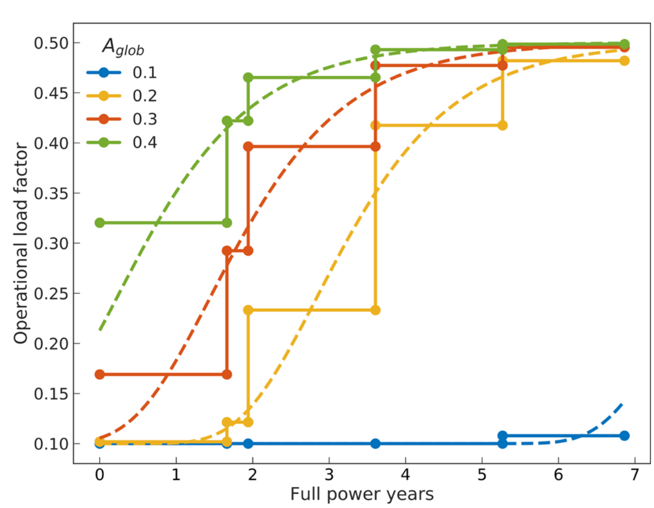


Fig. 1. Operational load factors in DEMO periods for specified global load factors, A_{glob}. The dashed lines shows $a(t)$ and the solid lines show the discretisation per operation period where $\int a(t) = \int g(a(t))$.

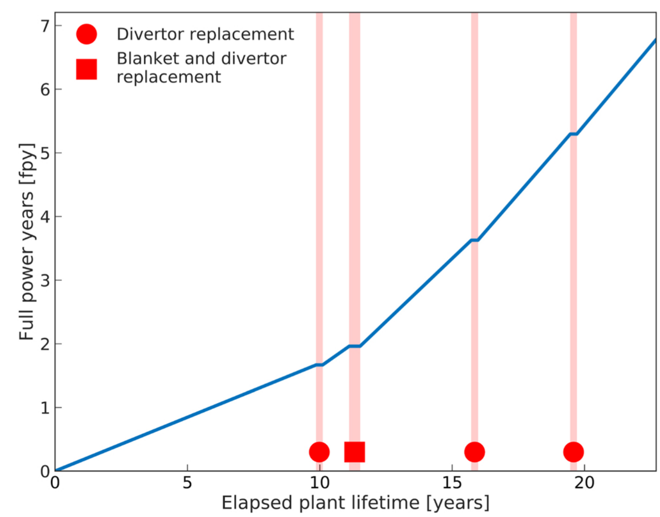


Fig. 2. Operation periods in a typical DEMO timeline. The blue curve shows the fpy accumulation as a function of calendar years; its slope in each operation period is equal to a_i.

Mapping these operational load factors to each period of DEMO operation, we can observe the progression in load factor throughout the life, assuming perfectly regular operation, see Fig. 2.

2.3. Timeline generation

In reality, however, the operation of DEMO is unlikely to be purely regular. A tokamak is a complicated machine, and DEMO will operate with dozens of systems functioning for the first time at their technological limits in a complex and hostile environment. We believe it is likely enough that the inter-pulse durations vary in a range of ways such that they may differ substantially from the ideal inter-pulse downtime, $t_{interpulse}$, of $t_{interpulse} = t_{CS}$.

To compensate for our fundamental lack of knowledge regarding RAMI issues for DEMO (see e.g. [21] for a frank summary of as much as we know), we have combined the known planned maintenance operations (those dictated by the levels of neutron damage in the in-vessel components) and inter-pulse/ramp durations with a series of random outages selected from a log-normal distribution. This approach is designed to mimic the relatively unpredictable operational schedules of FOAK devices and present-day tokamaks.

The total fusion time within a given operation period is prescribed (see Section 2.2 above), and the number of pulses is calculated to match this fusion time. The total duration of the non-fusion time is computed according to the prescribed availability. For simplicity and speed of computation, we assume that all pulses last the full pulse length, t_{pulse}. Although unrealistic, the effect of varying pulse lengths is relatively small, as the inter-pulse durations are assigned a wide variation thanks to the distribution selected. The duration of the outages is between t_{CS} and $+\infty$, although as the integral of the distribution and the number of samples are prescribed, in practice a single outage can last up to several months, depending upon the prescribed operational load factor. Fig. 3 shows an indicative distribution of randomly generated inter-pulse durations for an operation period.

The choice of a log-normal distribution here is relatively arbitrary, and it is worth pointing out that other distributions can significantly alter on the maximum duration of the outages. This in turn can have an effect on the tritium fuel cycle performance.

For each operation period, a distribution of inter-pulse durations is generated and is used to generate partly randomised operational timelines for DEMO, following the methodology above. From the fusion power, P_{fus}, one can then calculate the rate of neutron production during each pulse, integrate over time, and, from previously mentioned

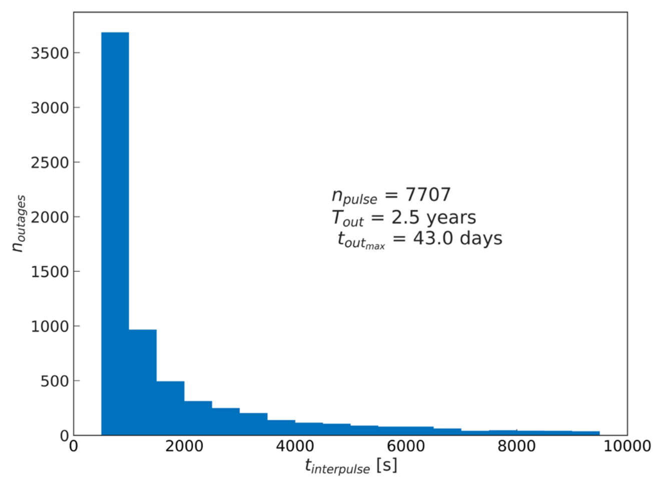


Fig. 3. A randomly generated log-normal distribution of inter-pulse durations, for $a = 0.41$. n_{pulse} is the number of pulses, T_{out} is the total outage time, and $t_{\text{out}_{\max}}$ is the maximum inter-pulse duration within the period.

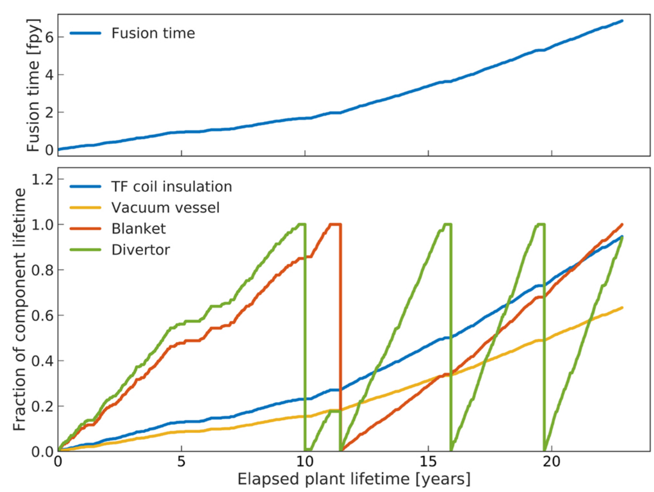


Fig. 4. Upper: reactor fpy as a function of calendar years; lower: component damage as a function of calendar years. The dips in the blanket and divertor curves indicate when these components are replaced.

neutronics studies, estimate the damage of the critical reactor components over the lifetime of the reactor. Fig. 4 shows for illustration purposes the fraction of component lifetime (the material damage at a point in time over the neutron budget for each component/material) for the divertors, the blankets, the toroidal field coils and the vacuum vessel. The latter two are irreplaceable lifetime components, and are shown for information only, assuming typical EU-DEMO neutron fluxes and maximum fluences (3.25 dpa for the vacuum vessel, 10 MGy for the TF coil insulation).

2.4. Simplified T fuel cycle

The simplified T fuel cycle modelled here is a reduced model: it contains no direct solution of any chemical balance equations. Instead, fuel cycle systems are modelled simplistically with a handful of parameters describing their performance. At this high level, no distinction is made in the fuel cycle block diagram for the different blanket types; instead our model is designed to be independent of technology choices, modelling differences in technologies simply as different performance parameters. Since many of the fuel cycle systems and technologies do not yet exist, we feel it is legitimate to model them as simple actuators with performance parameters that are indicative of the underlying physics processes taking place in them. For instance, we model the metal foil pumps simply as a separation fraction, f_{DIR}, where f_{DIR} of the flow entering the metal foil pumps is transported to the pellet injection system, and the remainder is transported to the exhaust processing system.

The block diagram of the simplified T fuel cycle model shown in Fig. 5 is based on the presently considered EU-DEMO TFV system design, described in [22]. The main features of this fuel cycle architecture are briefly summarised here:

(i) There are three main tritium recycling loops: the direct internal loop, the exhaust processing loop, and the outer detriation loop, in which progressively lower concentrations of tritium are managed.
(ii) The matter injection system supplies solid fuel to the plasma, and gas (D, T, and other gases) to the in-vessel environment for first wall protection purposes. The gaseous T is injected continuously during the pulse at a rate, $\dot{m}_{\text{gas}}$, is assumed never to be fused, and is not accounted for in the calculation of the burn-up fraction, f_b.
(iii) The solid fuel enters the tokamak vacuum vessel in the form of frozen pellets travelling at high speeds through pellet fuel lines. The process is lossy, with a fuelling efficiency, η_f. Dedicated pumps on the fuel lines recover some of the lost tritium back to the matter injection system, with an efficiency, $\eta_{f_{\text{pump}}}$. The rest is assumed to enter the vacuum vessel in gaseous form, and has no chance of entering the plasma or being fused.
(iv) Tritium bred in the breeding blankets is extracted in the tritium extraction and recovery system (TERS). Tritium which permeates to the blanket coolant(s) is extracted in the coolant purification system (CPS).
(v) The tritium which cannot be extracted from the flue gases eventually exits the system at the stack, where regulatory requirements on environmental releases of tritium will have to be met.

The tritium flows and parameterisations are summarised in Table 1.

Where reasonable, we have lumped parameters so as to reduce the number of variables in the model. For instance, the time for tritium to travel through the plasma, the in-vessel environment, the metal foil pumps, and the linear diffusion pumps (in either branch of the DIR loop) is one parameter: t_{pump}.

The TERS and the CPS have been lumped in the model, as the CPS in particular has almost no effect on $m_{T_{\text{start}}}$ or t_d. It does, however, play a role when it comes to determining the total release rate of tritium from the plant. The TERS recovers the tritium from the intended production stream (be it pebble beds or liquid lithium lead), whereas the CPS purifies the blanket coolant from any tritium which permeates into the primary coolant loop (be it helium or water). The design of the blanket, of course, has a significant effect on the performance of both of these systems, as the technologies being considered are very different. Simplifying these important differences out in our model, we model this part of the system as a leak rate of the tritium flow from the blanket, r_{leak}, which is handled by the CPS, and the rest, $1 - r_{leak}$, which is dealt with by the TERS. This is then simplified into a single factor in the model, see Eq. (5).

$$f_{\text{TERS+CPS}} = r_{\text{leak}} f_{\text{CPS}} + (1 - r_{\text{leak}}) f_{\text{TERS}} \tag{5}$$

Given that the TERS will handle most of the tritium flow coming from the blanket, the duration of the actions of the TERS, t_{TERS}, is modelled and the CPS duration is assumed to be the same. This simplification is only acceptable because it is assumed that r_{leak} is relatively small, i.e. that the CPS will feed very little tritium to the stores.

Tritium accumulators are modelled in the storage system to represent the long-term storage of the tritium inventory, in the form of uranium beds, and in the matter injection system. Here there will be a buffer storage of tritium to meet the minute-to-minute and day-to-day operational tritium storage requirements. The model is set up in such a

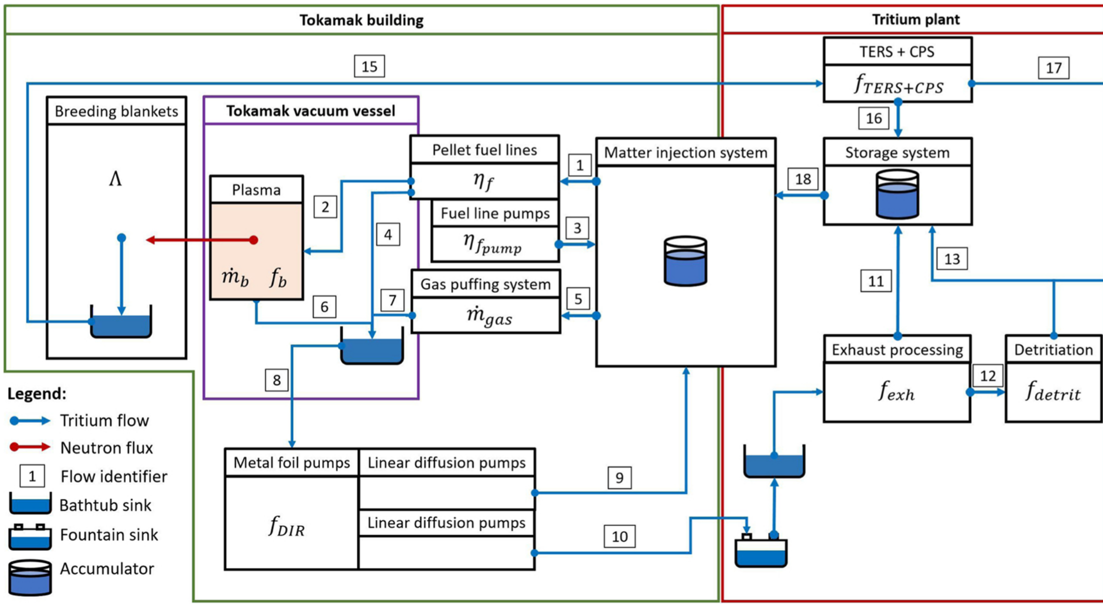


Fig. 5. Block diagram of the simplified T fuel cycle model, showing the modelled flows of tritium between sub-systems, the locations of the tritium sinks and accumulators, including the schematic locations of the sub-systems within the tokamak, tokamak hall, and the tritium plant.

Table 1
Simplified T fuel cycle model flows and durations, ignoring the contributions of the sink terms used to model tritium retention.

Flow identifier	$\dot{m}_i$	t_i
1	$\frac{\dot{m}_b}{f_b\eta_f}$	t_{freeze}
2	$\frac{\dot{m}_b}{f_b}$	0
3	$\eta_{f_{\mathrm{pump}}}(1-\eta_f)\dot{m}_1$	0
4	$(1-\eta_{f_{\mathrm{pump}}})(1-\eta_f)\dot{m}_1$	0
5	$\dot{m}_{\mathrm{gas}}$	0
6	$\dot{m}_b\left(\frac{1}{f_b}-1\right)$	0
7	$\dot{m}_{\mathrm{gas}}$	0
8	$\dot{m}_4+\dot{m}_6+\dot{m}_7$	0
9	$f_{\mathrm{DIR}}\dot{m}_8$	t_{pump}
10	$(1-f_{\mathrm{DIR}})\dot{m}_8$	t_{pump}
11	$f_{\mathrm{exh}}\dot{m}_{10}$	t_{exh}
12	$(1-f_{\mathrm{exh}})\dot{m}_{10}$	t_{exh}
13	$f_{\mathrm{detrit}}\dot{m}_{12}$	t_{detrit}
14	$(1-f_{\mathrm{detrit}})\dot{m}_{12}$	0
15	$\Lambda\dot{m}_b$	0
16	$f_{\mathrm{TERS+CWPS}}\dot{m}_{15}$	t_{TERS}
17	$(1-f_{\mathrm{TERS+CPS}})\dot{m}_{15}$	0
18	$\dot{m}_4+\dot{m}_{11}+\dot{m}_{13}+\dot{m}_{16}$	0

way that there is never a lack of tritium in the accumulators, which would mean the plasma would be unable to operate as scheduled.

An initial start-up inventory is assumed and the model is run over the full reactor lifetime. The point of minimum inventory is located and the model is re-run with an adjusted start-up inventory until convergence.

The radioactive decay of tritium is accounted for at all locations in the model.

The default parameters assumed for the model are listed in Table 2. Note that the default global load factor has been taken as $A_{glob}=0.3$, which is more optimistic than the present EU-DEMO assumption of an availability target of 30%. Note also that the assumed blanket sink inventory limit, $I_{\mathrm{BB_{max}}}$, is of the order of kilograms, whereas recent results [23,24] indicate that it may in fact be closer to $\sim$100 g. This conservative approach is justified by the large uncertainties surrounding key parameters, such as the T inventory in Be pebbles and the Sievert constant of PbLi. Moreover, $I_{\mathrm{BB_{max}}}$ also includes any inventory terms in the primary coolant loop, which in the case of water may reach the order of kilograms. The ranges of values considered for the blanket parameters are intended to cover all presently investigated blanket technologies.

This fuel cycle model has been fully integrated into the BLUEPRINT reactor design framework [25], and can be re-run for future EU-DEMO reactor design points and different parameter sets with relative ease.

2.5. Bathtub and fountain tritium retention models

Logical models are used here to mimic known tritium retention behaviour in some systems. These models have no basis in chemistry or in the physics of tritium transport.

The "bathtub" model is intended to mimic the retention of tritium in metal surfaces which are exposed to flows of gaseous tritium. In reality there are many complex physical phenomena governing this effect, in particular for materials undergoing irradiation, such as the tungsten first wall. We make no attempt to model these effects, and opt for an extremely simple model in which a certain fraction η ("release rate") of the tritium flow through an environment, $\dot{m}_{\mathrm{in}}$, over a timestep, Δt, is retained in the environment as a local T sink with inventory I, up until a certain maximum inventory I_{max} is reached, at which point the outgoing flow, $\dot{m}_{\mathrm{out}}$, equals the incoming flow, see Eq. (6). Note that exponential term after $(1-\eta)\dot{m}_{\mathrm{in}}$ accounts for sequestered tritium which decays within the timestep.

if $I \leq I_{max}$ **then**

$$I \leftarrow Ie^{-\lambda\Delta t}+(1-\eta)\dot{m}_{in}\frac{e^{-\lambda\Delta t}(e^{\lambda\Delta t}-1)}{e^{\lambda}-1}$$

$$\dot{m}_{out}=\eta\dot{m}_{in}$$

else

$$I \leftarrow I_{max}$$

$$\dot{m}_{out}=\dot{m}_{in}$$

end (6)

Other components, such as cryogenic distillation columns, require a certain minimum inventory in order to operate effectively. Here we reduce this behaviour to a simple minimum T inventory required for operation, a so-called "fountain" model, see Eq. (7).

$$
\begin{aligned}
&\textbf{if } I \geq I_{min} \textbf{ then}\\
&\quad I \leftarrow I e^{-\lambda\Delta t}\\
&\quad \dot{m}_{out} = \dot{m}_{in}\\
&\textbf{else}\\
&\quad I \leftarrow I e^{-\lambda\Delta t} + \dot{m}_{in}\frac{e^{-\lambda\Delta t}(e^{\lambda\Delta t}-1)}{e^{\lambda}-1}\\
&\quad \dot{m}_{out} = 0\\
&\textbf{end}
\end{aligned} \tag{7}
$$

In both tritium retention models, any sequestered tritium lost to decay must be replenished. This means that any saturated tritium sink can still draw tritium from the fuel cycle, as it will replenish any depleted tritium until its saturation point is reached.

Bathtub models have been used to represent tritium sequestration in the in-vessel environment (predominantly due to tritium take-up in the tungsten plasma-facing components) and the blankets. The sequestered tritium in the blankets is due to absorption in the structural materials (i.e. EUROfer), functional materials (e.g. pebbles/coatings), and the coolant and purge fluid loop(s). The importance of this sink depends on the blanket technology used; a helium-cooled pebble bed (HCPB) and a water-cooled lithium lead (WCLL) blanket are expected to behave rather differently. We ignore these differences in our model.

We use a single instance of the fountain model coupled to a bathtub model as a lumped parameter for the entire tritium plant exhaust processing systems, $I_{\mathrm{TFV_{min}}}$. In reality there will be several different processing systems handling the flow in the tritium plant. The TFV systems are likely to be operated continuously, so this parameter can be thought of as the overall amount of tritium flowing through the tritium plant at any one time in steady-state operation. While this is a significant simplification, it keeps the number of parameters low enough to perform comprehensive design space exploration exercises. Given the importance of this parameter in determining the start-up inventory, in future work this number must be derived from more detailed modelling work, with accurate representations of the various TFV systems.

Note that during a reactor shutdown, all tritium which is not sequestered in the sinks would be moved into long-term storage (uranium beds) for safety purposes. We do not model these flows as we assume that no tritium is gained or lost (except for decay) during these movements.

2.6. Legal tritium release limits

In the fuel cycle model, there is only one point where the tritium can be released to the environment: the stack. Based on the mass flows in each stream, and assuming that all sinks are saturated, a conservative analytical relation can be derived for the amount of tritium released to the environment over a given annual period, see Eq. (8):

$$
\begin{aligned}
\dot{m}_{release} = A_{max}\Bigg[&\left(\dot{m}_b\left[\left(\frac{1}{f_b}-1\right)+(1-\eta_{f_{pump}})\frac{1-\eta_f}{f_b\eta_f}\right]+\dot{m}_{gas}\right)\\
&\times(1-f_{DIR})(1-f_{exh})(1-f_{detrit})\\
&+\Lambda\dot{m}_b(1-f_{TERS+CPS})\Bigg]
\end{aligned} \tag{8}
$$

where $\dot{m}_b$ is the burn rate dictated by the fusion power, and A_{max} is the peak load factor achieved over any one-calendar-year period in the DEMO lifetime, see Eq. (9).

$$
A_{\max} = \max\left(\frac{\mathrm{dt_{fus}}}{t_j - t_i}\ \forall\ t_i \in \langle 0,\ T_{\mathrm{DEMO}}-1\rangle\right),\ \text{where } t_j = t_i + 1 \tag{9}
$$

According to present assumptions, the total legal limit within any given calendar-year period is 9.9 g of T (gaseous and liquid forms) [3]. The above equation enables a relative understanding of the importance of sub-system performance parameters in determining the tritium release rate. Additional contributions from in-vessel component detritiation and accidents should also be accounted for, yet lie beyond the scope of this simple parameterisation.

3. Results with and without DIR

In this section we present the results for the default parameter values listed in Table 2, with DIR (f_{DIR} = 0.8).

Fig. 6 shows the evolution of the DEMO plant and tritium sink inventories over the lifetime of the reactor. The upper plot shows the total site tritium inventory (blue line), the total unsequestered tritium inventory (yellow line), and the tritium in the storage system (grey line), $m_{T_{\mathrm{store}}}$. The high frequency oscillations in $m_{T_{\mathrm{store}}}$ are due to the tritium being circulated around the system during operation.

The start-up inventory is found by solving the fuel cycle model using Picard iterations: starting from an an initial guess of the tritium start-up inventory, the model is run until the point of minimum inventory is equal to $I_{\mathrm{TFV_{min}}}$, see Eq. (10). The point of minimum tritium inventory is also referred to as the inventory inflection point, which occurs as t_{infl}, see e.g. Fig. 6.

$$
\begin{aligned}
&m_{T_{start}} = 0\ \mathrm{kg}\\
&\textbf{while } \Delta_m \not\approx 0 \textbf{ do}\\
&\quad m_{T_{store}}[0] = m_{T_{start}}\\
&\quad \text{run fuel cycle model}\\
&\quad \Delta_m = \min(m_{T_{store}}) - I_{TFV_{min}}\\
&\quad m_{T_{start}} \leftarrow m_{T_{start}} - \Delta_m\\
&\textbf{end}
\end{aligned} \tag{10}
$$

The doubling time is calculated as the first point in time at which the reactor is able to release an amount $m_{T_{\mathrm{start}}}$ from the storage system, without affecting the reactor's ability to operate. In other words, when the T inventory in the stores permanently exceeds a threshold of: $I_{\mathrm{TFV_{min}}} + m_{T_{\mathrm{start}}}$, see Eq. (11).

$$
t_d = t\,[\max(\mathrm{argmin}(|m_{T_{\mathrm{store}}} - I_{\mathrm{TFV_{min}}} - m_{T_{\mathrm{start}}}|))] \tag{11}
$$

This method to calculate t_d is flawed as it relies on knowledge of the full reactor life. In reality, such "future" information would not be available, and a decision to release large amounts of tritium to a future reactor without jeopardising the operational capabilities of the existing DEMO would be more complex. This simplification is, however, trivial in the light of the other uncertainties in the model and our assumptions.

The lower plot in Fig. 6 shows the amount of tritium sequestered (i.e. trapped) in the various sinks. The in-vessel tritium sink (blue line) saturates almost immediately as it sees the highest flux of tritium and has a relatively low saturation limit in this default case. The TFV systems (orange line) start with the minimum inventory specified and eventually saturate at the maximum. The blanket inventory (yellow line) does not saturate in this example, and is reset to zero (along with

Table 2
Assumptions, parameter values, and parameter explorations.

Parameter name	Variable	Default / mode μ	Range $\pm\ \sigma$
Reactor			
Fusion power	P_{fus}	2037 MW	n.a.
Global load factor	A_{glob}	0.3	0.15
Load factor learning rate	r_A	1 fpy^{-1}	0.5
Pulse length	t_{pulse}	2 h	n.a.
Flat-top duration	$t_{flattop}$	1.89 h	n.a.
Minimum dwell time	t_{CS}	600 s	n.a.
1st blanket life	L_{BB_1}	20 dpa	n.a.
2nd blanket life	L_{BB_2}	50 dpa	n.a.
Divertor life	L_{DIV}	5 dpa	n.a.
Blanket damage rate	r_{BB}	10.2 dpa/fpy	n.a.
Divertor damage rate	r_{DIV}	3 dpa/fpy	n.a.
Full maintenance duration	t_{RMFULL}	250 days	n.a.
Divertor maintenance duration	t_{RMDIV}	150 days	n.a.
Plasma/in-vessel environment			
Burn-up fraction	f_b	0.015	0.01
Sink release rate	η_{IVC}	0.9995	0.0004
Maximum sink inventory	I_{IVCmax}	0.3 kg	0.1
Matter injection systems			
Gas puff flow rate	$\dot{m}_{\mathrm{gas}}$	50 Pa m^3/s	n.a.
Pellet fuelling efficiency	η_f	0.7	0.2
Pellet fuel line pump efficiency	$\eta_{f\mathrm{pump}}$	0.6	0.3
Pellet freezing time	t_{freeze}	0.5 h	0.25
Vacuum pumping systems			
DIR factor	f_{DIR}	0.8	0.15
Flow duration	t_{pump}	150 s	100
Exhaust processing			
Flow duration	t_{exh}	5 h	2
Exhaust processing factor	f_{exh}	0.99	0.009
Sink release rate	η_{TFV}	0.9995	0.0004
Minimum sink inventory	$I_{\mathrm{TFV_{min}}}$	3 kg	1
Maximum sink inventory	I_{TFVmax}	5 kg	1.5
Detritiation			
Detritiation factor	f_{detrit}	0.9995	0.0004
Flow duration	t_{detrit}	20 h	5
Blanket, TERS, and CPS			
TBR	Λ	1.05	0.03
Flow duration	t_{TERS}	10 h	5
TERS/CPS factor	$f_{TERS+CPS}$	0.99995	0.00004
Sink release rate	η_{BB}	0.995	0.04
Maximum sink inventory	I_{BBmax}	3 kg	2

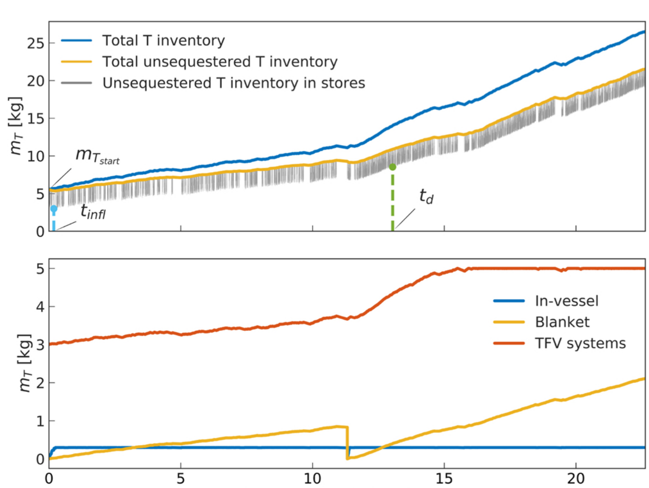


Fig. 6. Indicative time-series of the tritium fuel cycle model for the default DEMO values. Upper: moveable tritium inventories, showing the values of $m_{T\mathrm{start}}$ and t_d; lower: tritium sink inventories.

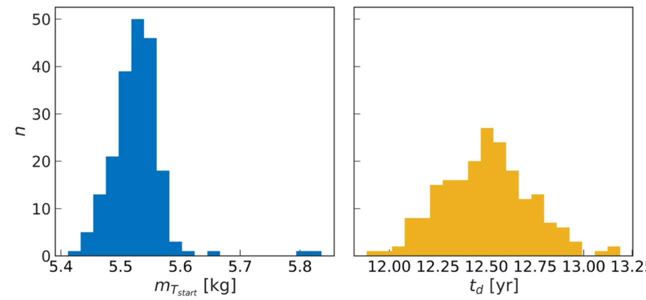


Fig. 7. Distributions of $m_{T\mathrm{start}}$ and t_d for 200 randomly generated timelines with default DEMO assumptions.

Table 3
Default results for $m_{T\mathrm{start}}$ and t_d, over 200 runs.

Value	$m_{T\mathrm{start}}$ [kg]	t_d [yr]
Mean	5.52	12.53
95th percentile	5.58	12.94
Maximum	5.78	13.14

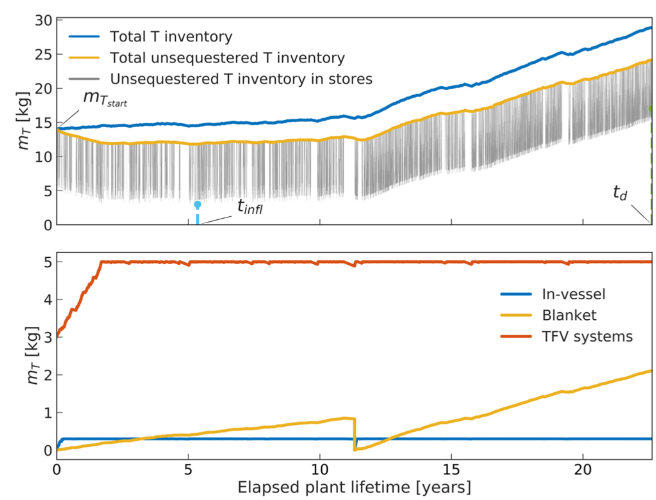


Fig. 8. Indicative time-series of the tritium fuel cycle model for the default DEMO values, with no DIR. Upper: moveable tritium inventories, showing the values of $m_{T\mathrm{start}}$ and t_d; lower: tritium sink inventories.

Table 4
Default results for $m_{T\mathrm{start}}$ and t_d, with $f_{DIR} = 0$, over 200 runs.

Value	$m_{T\mathrm{start}}$ [kg]	t_d [yr]
Mean	14.27	22.78
95th percentile	14.93	23.10
Maximum	16.07	23.19

the in-vessel inventory) when the blankets are replaced at the end of the first operational phase. The dip in the in-vessel and blanket inventories corresponds to the replacement of the in-vessel components (plasma-facing surfaces and blankets), where the sequestered tritium in the in-vessel components is not considered to be recovered in any way (a conservative assumption).

For a given design point (A_{glob}, P_{fus}, $t_{flattop}$, t_{ramp}, t_{CS}), 200 timelines are randomly generated. The fuel cycle model is then run for a given set of reactor and fuel cycle parameters (f_b, η_{fuel}, f_{DIR}, t_{DIR}, t_{freeze}, etc.) for the partly randomised fusion power signals, and $m_{T\mathrm{start}}$ and t_d are calculated from the time-series of the tritium inventories.

The distributions of $m_{T\mathrm{start}}$ and t_d for the default case are shown in

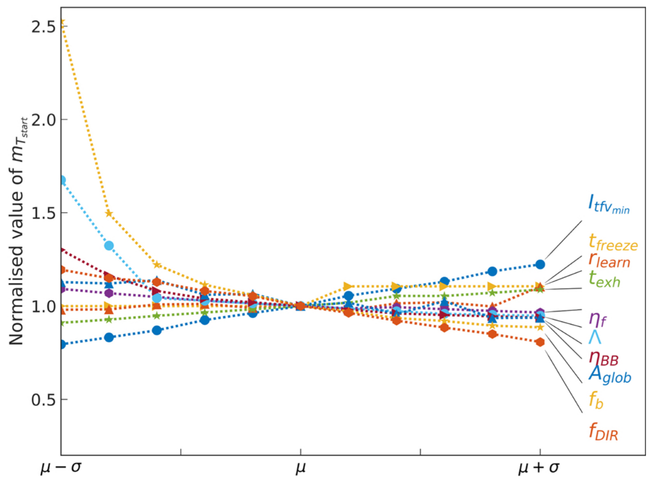


Fig. 9. Single parameter sensitivity study results for $m_{T_{start}}$ over the variable ranges $\mu \pm \sigma$, normalised with respect to the values at μ.

Fig. 7, and the results summarised in Table 3.

Using the same model and setting f_{DIR} to 0 describes a fuel cycle with no direct internal recycling. Indicative results with no DIR (using the procedure described above) are shown in Fig. 8 (for the same random timeline as in Fig. 6). The results of the full Monte Carlo set are shown in Table 4.

For the default parameters used in the simplified model, the results show that the start-up inventories required are a factor ∼3 higher than in the $f_{DIR} = 0.8$ case, and that the DEMO reactor can only deliver enough tritium to start up another reactor, at the very end of its operational life — which is hardly a "doubling time" at all, since the number of reactors is not actually doubled.

4. Parameter explorations

In this section, we perform a number of parameter explorations in order to gain a better understanding of the EU-DEMO tritium fuel cycle and the relative importance of the design parameters.

4.1. Single parameter sensitivity study

A parameter sensitivity study was performed, varying each of the variables in turn with the others held at default values, for the default values and ranges indicated in Table 2. The model was run over 200

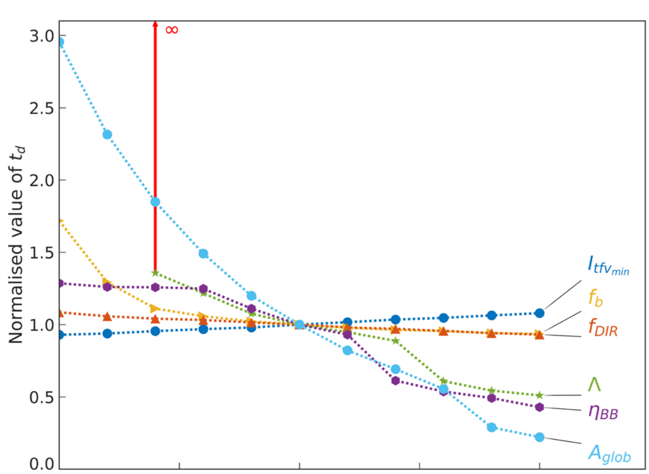


Fig. 10. Single parameter sensitivity study results for t_d over the variable ranges $\mu \pm \sigma$, normalised with respect to the values at μ.

randomly generated timelines at 11 different values of each parameter, and the maximum values for $m_{T_{start}}$ and t_d were retained. The results for parameters which had more than a 5% effect on the reference result (anywhere within the specified range) are shown in Fig. 9 for $m_{T_{start}}$ and Fig. 10 for t_d.

Note that the results appear insensitive to some parameters in the ranges explored. I_{mbb}, for example, has no effect on the result when varied across its full range from the reference point. This is because the blanket inventory never saturates in the reference point (see Fig. 6), and because the inflection point of the inventory occurs well within the first operational phase in all of the randomly generated default timelines.

The doubling time is highly sensitive to more parameters than the start-up inventory, and for TBR values of less than 1.03, the doubling time is infinite; the reactor ends its operational life with less tritium than with which it started.

4.2. Important two-parameter combinations

In this section, we explore parameter couplings, following the same procedure as above, using the default values (as listed in Table 2) except for those varied.

In Fig. 11, the values of t_d and $m_{T_{start}}$ are plotted for important parameter combinations. The black and white lines with arrows showing where ($m_{T_{start}} \leq 8$ kg and $t_d \leq 20$ years) and ($m_{T_{start}} \leq 5$ kg and $t_d \leq 15$ years), respectively, are predominantly for illustrative purposes. They do, however, serve to indicate which portions of the design space would be prohibited should such values of $m_{T_{start}}$ and t_d be adopted as requirements.

For all parameter combinations (with the exception of some noise, discussed later), $m_{T_{start}}$ and t_d are positively correlated, i.e. there are no trade-offs to be found between $m_{T_{start}}$ and t_d. Improving the TFV system in any way results in better performance in both parameters, as would be expected. However, with the exception of combinations of f_b and f_{DIR} (see Fig. 11a), the fuel cycle's response to parameter variations in terms of $m_{T_{start}}$ and t_d is not the same, and can differ significantly. In Fig. 11c, for example, we see that around the reference design point ($\Lambda = 1.05$, $f_{DIR} = 0.8$), $m_{T_{start}}$ is almost constant across the full range of TBR values, and yet the doubling time varies by a factor of 3 in the same range.

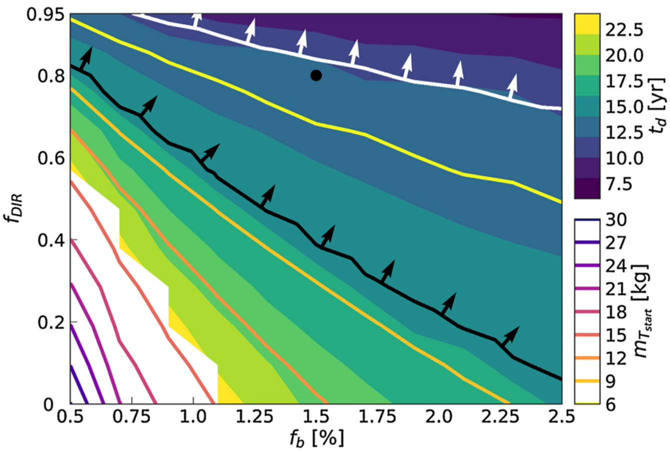
Figs. 11b and 11c show that the start-up inventory is fairly insensitive to Λ, except for extremely low values ($\Lambda \leq 1.03$), confirming the earlier result seen in Fig. 9. Instead, if one sought to reduce $m_{T_{start}}$ by design, improvements in f_b and f_{DIR} should be strived for. Further to this, we see in Figs. 11c and 11e that for values of f_{DIR} above ∼ 0.6, improvements in $m_{T_{start}}$ are modest, and that above this threshold, the sensitivity of $m_{T_{start}}$ to variations in Λ and A_{glob} is almost eradicated. For example, in Fig. 11e, at $f_{DIR} = 0$, a factor 2 increase in $m_{T_{start}}$ can be seen when moving from $A_{glob} = 0.3$ to $A_{glob} = 0.15$, whereas for $f_{DIR} \geq 0.6$, $m_{T_{start}}$ is almost constant across the explored range of A_{glob}. This indicates that DIR is extremely useful in insulating the TFV system from the negative effects of low reactor load factors and, to a lesser extent, low TBR values (see Fig. 11c).

In Figs. 11d, 11e, and 11f, we see that the doubling time is very sensitive to A_{glob}, as we first saw in Fig. 10. Note that this effect is partly due to the increase in the overall life of the reactor when reducing the load factor, as the reactor lifetime is effectively dictated by a neutron fluence target.

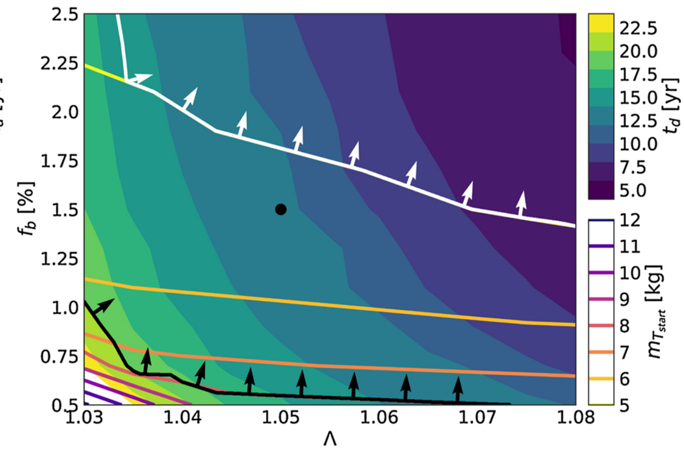
Similarly to Λ, A_{glob} has relatively little effect on $m_{T_{start}}$. This is clearly visible in Fig. 11d, where $m_{T_{start}}$ varies very little over the range (except for very low load factors), and where some noise from the Monte Carlo procedure (and the selection of a maximum from a range of values) can be seen in the contour lines for $m_{T_{start}}$.

5. Discussion and future work

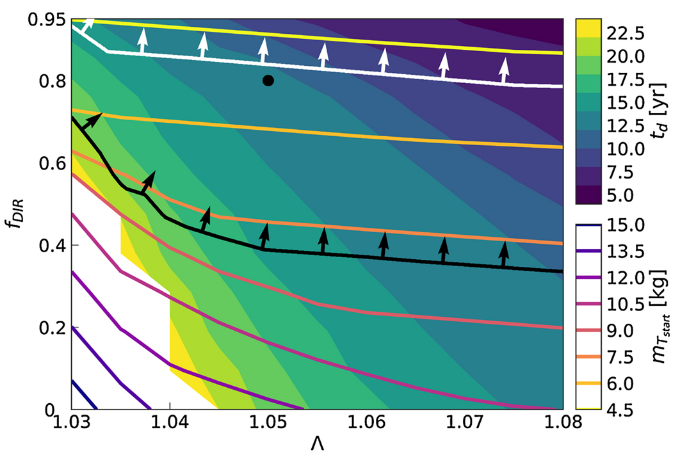
A DEMO reactor's initial start-up inventory will probably need to be purchased from civilian stockpiles, which are likely to be relatively



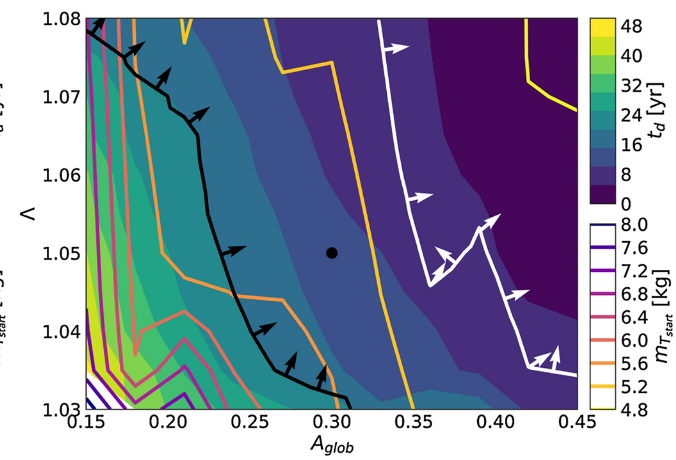
(a) f_b-f_{DIR} parameter space



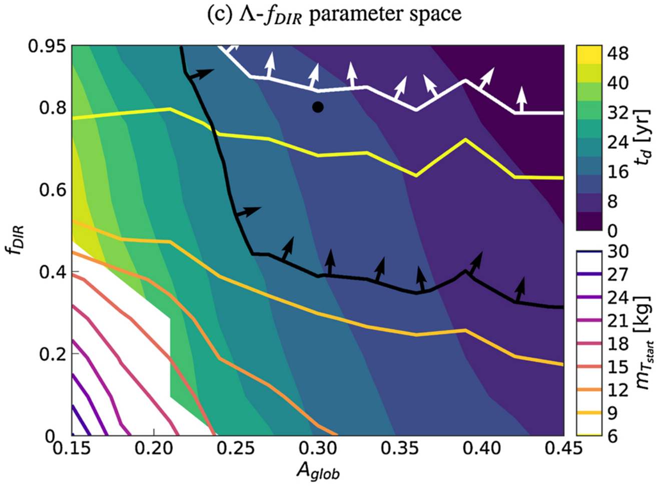
(b) Λ-f_b parameter space



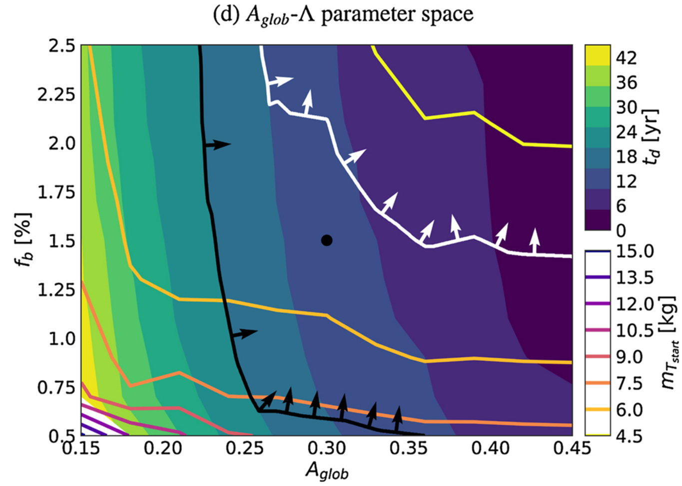
(c) Λ-f_{DIR} parameter space



(d) A_{glob}-Λ parameter space



(e) A_{glob}-f_{DIR} parameter space



(f) A_{glob}-f_b parameter space

Fig. 11. Contour plots of $m_{T_{start}}$ and t_d (filled) for different parameter combinations. The black dot represents the reference set of assumptions, and the black and white lines with arrows demarcate the portions of the parameter space which meet the constraints of ($m_{T_{start}} \leq 8$ kg and $t_d \leq 20$ years) and ($m_{T_{start}} \leq 5$ kg and $t_d \leq 15$ years), respectively. The white space in the t_d contour plots denotes the region of parameter space where the doubling time is infinite.

limited in the 2050's, see [26]. Other reseachers make the case that a DEMO reactor will be able to start up thanks to the tritium it produces during a D-D commissioning phase [5].

Regardless of the provenance of the tritium, it stands to reason that the reactor designer must understand what initial starting inventory would be required for full tritium self-sufficiency, and when a reactor might be able to release a start-up inventory to a future reactor, and indeed what design parameters or aspects influence these criteria. The default values listed in Table 2 are clearly initial guesses and subject to opinion. Furthermore, in many cases the parameters are in fact not even physical, but relate instead to simplified behaviour of more complex phenomena, which should ideally be derived from more detailed modelling or (preferably) experimentation. Others are simply lumped parameters, which should similarly be obtained from detailed analysis of the TFV systems. We note that many of the technologies for each of the different systems have yet to be selected, and that modelling these systems in terms of their crudest performance is probably wise at this pre-conceptual design stage.

Whilst we consider that our methodology for estimating $m_{T_{\rm start}}$ and t_d is appropriate, the assumptions we have made for the various TFV parameter values are likely to be flawed. As such, the results presented herein should be treated with caution.

However, our intent here is to demonstrate the relative impacts of various high-level fuel cycle and reactor parameters and highlight that the low load factors considered for EU-DEMO (and the relative unpredictability of the operation due to RAMI issues) play a role in determining the performance of the fuel cycle. In terms of the fuel cycle performance, a lower load factor drives up the requirements for the fuel cycle components, and, conversely, achieving higher load factors relaxes these requirements.

The reactor load factor and the TBR are the two most important parameters in dictating the reactor doubling time in the parameter space explored for the EU-DEMO. Neither, however, has a particularly important effect on $m_{T_{\rm start}}$. Although the load factor has parametrically less influence on the start-up inventory, randomly occurring failures (particularly in the first few years of operation) often drive the inventory inflection point, which introduces a non-negligible variability in both the start-up inventory and the doubling time.

For TBR values of less than 1.04, the fuel cycle is very sensitive to poor performance in other parameters, as the level of tritium production is so low that even relatively short unplanned outages can disrupt the fuel cycle. It is therefore advisable that the actual required TBR, Λ_r, (ignoring all uncertainties) be above 1.05, much as originally recommended in [9], although we would not characterise this as being “very conservative”. TBR values greater than 1.05 improve the overall performance of the fuel cycle, but less so than improvements in other parameters.

Direct Internal Recycling is an important aspect of the EU-DEMO design which has the potential to relax key design requirements (such as the TBR) or mitigate poor performance. However, care must be taken not to push challenging requirements onto the exhaust processing and detritiation loops by solely maximising f_{DIR}, which *could* make achieving high detritiation factors in the various subsequent tritium separation systems harder. Whether or not this is the case will no doubt emerge from more detailed investigations into the design and technologies of the various sub-systems.

Although DIR can to some extent insulate the fuel cycle from the effects of low load factors (see Fig. 11e), very low load factors ($A_{glob} \leq 0.3$) can still have a strong effect on $m_{T_{\rm start}}$ and t_d, requiring higher performance in other parameters to maintain the same fuel cycle performance (see Figs. 11d and 11f). For the parameter set assumed, and the parameterisation of the load factor (see Section 2.3), we recommend aiming for $A_{glob} \geq 0.2$.

Clearly, achieving $A_{glob} \geq 0.2$, $f_{DIR} \geq 0.6$, or even $\Lambda_r \geq 1.05$ may simply not be possible. Yet from the perspective of the fuel cycle, these parameters are indelibly linked, and poor performance in any one of them will engender more stringent requirements in the others. With precious little knowledge on the relative difficulties of meeting each one of these constraints individually, we cannot comment on what might constitute a reasonable trade-off between them. The recommendations above are derived purely from the response of the design space explored, with the rationale that regions of the design space where the fuel cycle performance degenerates rapidly should be avoided.

A full parameter exploration would be required to better inform the reactor designer of the relative importances of the various TFV and reactor performance parameters, from which one could build a reduced-order model (e.g. neural network, or power law) for the system. The motivation to build reduced-order models of the tritium fuel cycle is to further inform design and R&D priorities.

Unfortunately, the large number of variables (20 sub-system variables, and two reactor variables: A_{glob} and r_{learn}), the iterations required to converge $m_{T_{\rm start}}$ accurately, and the number of Monte Carlo runs needed to reach a statistically representative result mean that a reasonably comprehensive parameter space exploration would be computationally expensive. This remains the subject of future work, but will undoubtedly involve further simplifications of the problem, or variables held constant. Prior to this step, however, we hope to ground more of the parameters in the present simplified models in foundations derived from more detailed models.

6. Conclusions

A simplified dynamic tritium fuel cycle model capable of estimating key fuel cycle performance parameters: start-up inventory, doubling time, and tritium release rate has been built. The irregular and unpredictable nature of a first-of-a-kind fusion reactor's power output has an important effect on the fuel cycle performance, introducing a stochastic element to the problem. The fuel cycle model was run in a Monte Carlo approach across a range of randomly generated timelines, to account for the low reactor load factors without resorting to time-averaged approximations.

The fuel cycle design space has been explored in sub-system performance parameters, independent of technological solutions. The relative importance of some reactor and TFV system design parameters has been illustrated, about a relatively arbitrary default design point. The performance of the fuel cycle in terms of $m_{T_{\rm start}}$ and t_d is sensitive to variations in a broad range of parameters.

The reactor load factor and the TBR are two of the most important parameters in dictating the reactor doubling time in the parameter space explored for the EU-DEMO. Neither, however, has a particularly important effect on $m_{T_{\rm start}}$.

For the parameter ranges explored, the start-up inventory is most heavily affected by the amount of tritium required to operate the tritium plant in steady state (a value which we cannot calculate with our model), f_{DIR}, and f_b.

Direct Internal Recycling has the potential to relax key design requirements for the EU-DEMO (such as the TBR) or mitigate poor performance (such as with f_b or A_{glob}). Based on the performance response of the fuel cycle in the explored design space, we recommend the following minimum values be adopted as requirements/targets: $f_{DIR} \geq 0.6$, $\Lambda_r \geq 1.05$ (ignoring all uncertainties), and $A_{glob} \geq 0.2$, ignoring the relative feasibility of achieving each individual value (on which we cannot comment).

For the default assumptions made for the EU-DEMO reactor, a start-up inventory of 5.78 kg would be needed in the worst-case scenario. The doubling time of the EU-DEMO in the worst-case scenario, for the same default assumptions, is 13.14 years, comfortably after the start of the second operational phase. For the same assumptions *without* DIR, the EU-DEMO start-up inventory would be 16.07 kg, and the reactor would only be able to release the same amount of tritium to another reactor at the very end of its life.

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