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Tritium supply and use: a key issue for the development of nuclear fusion energy

Richard J. Pearson[a,*], Armando B. Antoniazzi[b], William J. Nuttall[a]

[a] School of Engineering & Innovation, The Open University, Milton Keynes, United Kingdom
[b] Kinectrics Inc., 800 Kipling Ave, Unit 2, Toronto, Ontario, Canada

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ABSTRACT

Full power operation of the International Thermonuclear Experimental Reactor (ITER) has been delayed and will now begin in 2035. Delays to the ITER schedule may affect the availability of tritium for subsequent fusion devices, as the global CANDU-type fission reactor fleet begins to phase out over the coming decades. This study provides an up to date account of future tritium availability by incorporating recent uncertainties over the life extension of the global CANDU fleet, as well as considering the potential impact of tritium demand by other fusion efforts. Despite the delays, our projections suggest that CANDU tritium remains sufficient to support the full operation of ITER. However, whether there is tritium available for a DEMO reactor following ITER is largely uncertain, and is subject to numerous uncontrollable externalities. Further tritium demand may come from any number of private sector "compact fusion" start-ups which have emerged in recent years, all of which aim to accelerate the development of fusion energy. If the associated technical challenges can be overcome, compact fusion programmes have the opportunity to use tritium over the next two decades whilst it is readily available, and before full power DT operation on ITER starts in 2035. Assuming a similar level of performance is achievable, a compact fusion development programme, using smaller reactors operating at lower fusion power, would require smaller quantities of tritium than the ITER programme, leaving sufficient tritium available for multiple concepts to be developed concurrently. The development of concurrent fusion concepts increases the chances of success, as it spreads the risk of failure. Additionally, if full tritium breeding capability is not expected to be demonstrated in DEMO until after 2050, an opportunity exists for compact fusion programmes to incorporate tritium breeding technology in nearer-term devices. DD start-up, which avoids the need for external tritium for reactor start-up, is dependent upon full tritium breeding capability, and may be essential for large-scale commercial roll-out of fusion energy. As such, from the standpoint of availability and use of external tritium, a compact route to fusion energy may be more advantageous, as it avoids longer-term complications and uncertainties in the future supply of tritium.

1. Introduction

Recently announced delays to the International Thermonuclear Experimental Reactor (ITER) programme have seen the start date for Deuterium-Tritium (D-T) operations pushed back, with full power operation now scheduled for 2035. This delay, or any further delay, to the ITER schedule may affect the quantity of tritium available for its own operation as well as for operation of parallel fusion efforts, and for DEMO, as the current tritium inventory decays and the landscape of conventional nuclear power generation changes. Previous ideas on the future supply of tritium for nuclear fusion now need to be revisited [1–3].

Tritium is generated in CANDU-type fission reactors through the interaction of fission neutrons with the heavy water moderator and coolant, producing approximately 130 g tritium per year for a typical CANDU reactor [1,4]. Tritium can only be extracted from the heavy water moderator by means of a Tritium Removal Facility (TRF), of which only two are currently in operation, one in Canada and one in South Korea, although there are plans for a third in Romania [5]. There is significant uncertainty over future CANDU supplies of tritium as it is unclear what share of the current fleet of ageing reactors will undergo life extension, whether the operating TRFs will continue to detritiate, or whether new TRFs will be commissioned [5].

Recent delays to the ITER schedule [2,6] and uncertainties over the production of CANDU tritium means that there may be only a limited tritium inventory on which to operate future fusion devices. Neither

* Corresponding author.
E-mail address: richard.pearson@open.ac.uk (R.J. Pearson).

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DEMO, nor any future commercial fusion programme can depend on an external supply of tritium in the long-term, as the requirement for fusion is significantly mismatched against production of tritium from CANDU, and thus the development of an efficient tritium breeding programme is essential for DEMO, and any commercial fusion programme beyond [1,3,7]. However, ITER is a research device and its operation will depend entirely on an external tritium supply of roughly 18 kg over the course of its operation [7].

Further tritium demand may come from any number of private sector "compact fusion" start-ups which have emerged in recent years, all of which aim to accelerate the development of fusion technology. Advances in physics and the emergence of new technologies, aided by an injection of private capital, has shifted focus towards compact fusion concepts, not all of which are based on the tokamak. Although ambitious, these programmes follow an alternative innovation and development model to that of the current international ITER fusion programme. Pressure from investors and smaller device size yields quicker innovation cycles, enabling rapid technology development. As such, this opens the possibility of a faster route to fusion. Amongst numerous others, approaches include Tokamak Energy's high field HTS compact spherical tokamak, Massachusetts's Institute of Technology and Commonwealth Fusion Systems' high field HTS compact tokamak, and General Fusion's acoustically-driven fusion device [8–10]. With development programmes spanning over the next two decades, it is possible that significant quantities of tritium may be required. Independent government projects such as the South Korean K-DEMO and the Chinese Fusion Experimental Test Reactor (CFETR) are also expected to require tritium on a timescale similar to that of the current ITER schedule. Unlike ITER, however, both CFETR and K-DEMO expect to demonstrate tritium self-sufficiency and thus have no ongoing requirement for external tritium.

Ultimately, potential competition for tritium may cause complications in operation of the current ITER programme and may also affect the amount of tritium available for start-up of future DEMO devices, and as such is the basis of this study. This work expands on the scope of previous assessments [1–3], using new information to provide an updated account of the availability and use of tritium for ITER, subsequent DEMO devices, and other fusion endeavours, which plan to develop fusion reactors over the next two decades (note that hereafter use of the phrase "near-term" refers to a timescale of two decades).

2. Model description

2.1. Overview

Following submission of the manuscript of this paper, research with a similar scope was published by Kovari et al., see [11]. The research by Kovari et al. explores the same topic on the availability of tritium for fusion, and findings of the two researches broadly agree. The current work is an independent validation of Kovari et al., with the two analyses approaching the topic of tritium supply from different angles. Together the two papers provide a comprehensive overview.

Our model forecasts tritium availability using data collated from sources estimating both the supply and demand of tritium. The forward time horizon is 40 years, but also includes a 10-year history from 2007 coinciding with the start of tritium production in South Korea. The model builds upon estimates from recent ideas by [1–3], and uses alternate methods and new information to provide an updated account of the current landscape. Key changes in the future supply of tritium are in the high-level operational decisions regarding future Canadian CANDU refurbishment, the political decision to phase out nuclear power in South Korea, and the potential impact of Romanian tritium [5,12–14]. On the demand side key changes included are delays to the ITER programme, the tritium needs of alternative fusion approaches, including private-sector start-ups, and tritium required for DEMO start-up.

2.2. Forecast scenarios

The model considers two supply scenarios. Full details of CANDU tritium supply are given in Section 2.3:

- Supply scenario 1: Canadian Production to end of life of Darlington TRF (2055[1]), South Korean production until 2032 (South Korean CANDU reactors cease operation by 2030), zero Romanian production.
- Supply scenario 2: Canadian Production to end of life of Darlington TRF (2055[1]), South Korean production until end of model time horizon, Romanian production from 2024.

The two supply scenarios broadly reflect the lower and upper bounds of tritium production respectively, notwithstanding the possibility of an unlikely surge or drop in the supply of CANDU tritium. At the current time, the uncertainty surrounding both the future of the South Korean nuclear power programme and the commissioning of facilities to harvest Romanian tritium indicates supply scenario 1 as the current supply trajectory [5,12]. However, given the long timescales involved, all tritium supply and demand projections, scenarios, and assumptions herein should be observed with caution.

The supply scenarios are compared against two demand scenarios. Both scenarios consider non-fusion demand, and the full details of fusion tritium demand are given in Section 2.5:

- Demand scenario A: ITER demand only, with full DT operation starting 2035 (but first tritium for tritium system commissioning starting in 2027).
- Demand scenario B: Enhanced demand scenario. Demand from private sector fusion start-ups, as well as independent government fusion projects, in addition to ITER demand exactly as in demand scenario A.

2.3. CANDU tritium supply

It is assumed that no additional CANDU reactors will be built, and thus tritium is supplied by the existing CANDU reactor fleet only, from Canada, South Korea and Romania.[2] Although it is later discussed that future sources of tritium for fusion may exist, the model assumes that no other sources will produce commercial tritium for fusion [1,2,15,16] (for rationale, see Section 2.4).

Where historical real-world data are available, they are used and extrapolated to build projections. It is assumed that the tritium extraction rate is directly proportional to the rated power output (MWe) as well as the online and operating status of individual CANDU reactors over time. The outage schedule for Canada's Darlington TRF (DTRF) details that servicing creates outages on a three-year cycle, with six months outage in year one, three months outage in year two, and zero months outage in year three [17]. This schedule is assumed to apply for all TRFs, and thus outages, planned or unplanned (including refurbishment), are not considered to affect overall tritium supply.

At the start of the time horizon in the model, Canada is the only commercial producer of tritium. The quantity of global tritium available in the year 2006 was thus calculated from historical data to be 21.1 kg[3] [18], which is in line with previous projections [1–3].

2.3.1. Canada

Historical data from the DTRF were used to calculate average

[1] Existing TRFs will also require life extension. Assumes life extension of the DTRF, see 2.3.1

[2] Tritium accumulation in the heavy water coolant of CANDU is negligible compared with accumulation in the heavy water moderator

[3] Accounts for non-fusion demand of 0.2 kg/year from the start of the DTRF (see Section 2.3.1)

production in Canada. Total production of tritium from the start of DTRF operation in 1989–2011 was 42.5 kg (409 MCi),[4] which is assumed to have been extracted at the average rate of 1932 g/year (18.6 MCi/year) [18]. The average tritium extraction rate is considered to be proportional to the total power output of all online Canadian CANDU units in any given year,[5] hence 1932 g (18.6 MCi) is the annual quantity of tritium produced when all Canadian CANDU units are online and operating [18]. Refurbishment and shutdown plans in [13,14,19] were used to determine estimates for the proportion of operational Canadian CANDU reactors for any given year in the model time horizon.

Average production from the DTRF accounts for outages and the resulting reduction in rate of production, and other year-to-year variability [17,18]. Refurbishment of the DTRF is expected in 2025 but it is possible to avoid a long-term outage (in the order of years) by refurbishing the DTRF subsystems in stages, such that each outage is short (in the order of months); thus, eliminating the possibility of a multi-year outage and corresponding decline in tritium production. In line with assumptions listed in Section 2.3, it is therefore assumed that the average TRF tritium extraction rate is unaffected during TRF refurbishment. Refurbishment extends the life of the DTRF by 30 years, and it is therefore considered to shut down in 2055. While the DTRF continues to operate, production of tritium still decreases over time in line with the steady shutdown of the Canadian CANDU fleet [13,14,19]. Given that the full schedule for Canadian CANDU reactor refurbishment has been published, the rate of production from Canada is assumed the same for both supply scenarios 1 and 2.

2.3.2. South Korea

Historical data from the Wolsong TRF (WTRF) shows average tritium production to be 780 g/year (7.5 MCi/year) [20]. As with the Canadian case, tritium production from the WTRF is assumed to be proportional to the number of CANDU units online in any given year, hence 780 g (7.5 MCi/year) is the annual quantity of tritium produced when all South Korean CANDU units are online and operating.

In supply scenario 1, the WTRF is assumed to shut down in line with the phasing out of nuclear power in South Korea, as per the current political environment [12]. CANDU reactors at Wolsong will run until end of their current license, with national nuclear power generation steadily declining from 2022 through 2030 [12,21]. Thereafter, residual heavy water from the final reactor shutdown is processed at a reduced rate until the WTRF is shut down in 2032.

In supply scenario 2, South Korea is instead assumed to continue dependence on nuclear power. In this scenario, the already refurbished Wolsong unit 1 will shut down in 2038, Wolsong CANDU units 2–4 will be refurbished in series between 2022–2030, allowing operation for a further 30 years. As with the DTRF, the WTRF is assumed to undergo online refurbishment before the end of its design lifetime in 2047, and thus will continue servicing the refurbished CANDU reactors at Wolsong. In supply scenario 2 it is therefore assumed that tritium production from South Korea will continue beyond the end of the model time horizon [17,20].

2.3.3. Romania

In supply scenario 1, Romania's Cernavoda TRF (CTRF) is never built, and Romania does not contribute to the global tritium inventory. In supply scenario 2, the CTRF will be commissioned in 2024 with a 40-year design lifetime, and Romania will continue tritium production beyond the end of the model time horizon. Data, timescales and assumptions, including rationale as to why units 3 and 4 at Cernavoda are not expected to produce tritium, are from [5].

[4] Tritium quantities for TRF production in this section are given in grams and Curies, as the current literature uses both. For the remainder of this paper, tritium quantities will be given in grams only, where the conversion is 9620 Curies to 1 g.

[5] Apart from Point Lepreau, which has not been serviced by the DTRF

2.4. Non-CANDU supply and exclusions

The prospect of non-CANDU sources of tritium presents a range of significant issues relating to regulation, economics, proliferation, and political and public acceptance. Even though the future of CANDU tritium is inherently uncertain, commissioning additional means of tritium production whilst CANDU reactors are producing tritium as a by-product is unnecessary at the current time.

Romania's CTRF may suffer further delays before beginning detailed design and construction, but conceptual design of the CTRF has been completed [22]. In contrast, while India also has the capability to produce tritium from its fleet of heavy water reactors, a TRF has not been designed, or seriously considered, for commercial tritium production. Similarly, Pressurised Water Reactor (PWR) and Boiling Water Reactor (BWR) fission reactors are incapable of producing significant quantities of tritium without the addition of Tritium Producing Burnable Absorber Rods (TPBARs). The model explicitly excludes any contribution of tritium from the Indian heavy water reactor programme, and from other potential sources as explored in [1,2,11] for reasons discussed in Section 5.2.

2.5. Demand

As detailed in Section 2.2, the two supply scenarios are modelled against two demand scenarios. The first considers only demand from ITER (full DT operation starting 2035), alongside non-fusion demand of 0.1 kg/year. The second demand scenario accounts for the same ITER demand and non-fusion demand, but also considers tritium requirements of alternative fusion endeavours.

2.5.1. ITER demand

The model uses the nominal tritium quantities for ITER as detailed in [7] but adjusted to reflect the current ITER schedule with tritium system commissioning starting 2027 and full power DT operations starting 2035 [6,23]. An updated schedule for tritium operations on ITER remains in-progress. The schedule at the current time from which a representative tritium schedule can be inferred is shown in [24], and requirements from [7]. The plan remains four-stage in the ramp-up to full DT operation following first plasma in 2025, where "initial tritium" is not expected until 2035, which refers to the first introduction of tritium to the ITER torus, it is assumed there is a smaller requirement for tritium in the period leading up to full power operation. It is assumed that "pre-fusion operation II" in [24] corresponds to the need for tritium to commission the tritium systems, which will be required in small quantities ahead of full DT operation in a way similar to the operation of JET in the 1990s, and as originally suggested in [7]. As such, the model assumes a 100 g delivery of tritium in 2027 to be used for initial commissioning tests of the tritium systems, followed by a 200 g delivery of tritium in 2030 for tritium system commissioning. Thereafter, tritium will be supplied from 2031 to 2034 in yearly batches of 800 g as it assumed necessary to procure and build up an operating inventory of tritium ahead of full DT operation in 2035, where around 1100 g is then required annually for a 12-year operation period [7].

Scenarios for the ITER schedule, but with a hypothetical further 5-year slip from 2035 to 2040 for the start of full DT operation, were also modelled to capture any later start of DT operations in ITER thereby accounting for any future schedule change. The table in Section 3 also shows the first proposed ITER tritium schedule, originally due to start in 2017 (from [7]), to show the effect on the level of tritium available given the deviation from the original plan to the current one. The modelling and inclusion of multiple ITER schedules is useful, as if an update of the ITER tritium plans is subsequently released, the findings and ideas herein will remain relevant. Assumptions surrounding tritium supply to ITER are different to those made by [11], but both sets of information should be viewed concurrently for completeness.

2.5.2. Additional fusion demand

It is assumed in Demand Scenario B that two to three of the number of competing private sector compact fusion start-ups succeed in progressing towards full-scale fusion testing by 2030. It is estimated that these initiatives will require 0.5 kg of tritium over a 5-year research and development period from 2025 prior to full scale testing starting in 2030 [25]. The tritium requirement for full scale testing is assumed to be analogous to that required for the fusion module described in [26], but for deployment over a shorter testing period. It is assumed that all three compact fusion start-ups will include tritium breeding technology with a Tritium Breeding Ratio (TBR) of less than unity, as per the reactor concept detailed in Menard et al., which specifies that tritium required for a full-scale test reactor will be between 0.4 and 0.55 kg per year, for 6 years at full power operation [26]. The model here accounts for the three compact fusion start-ups all operating concurrently at a capacity factor of ~0.33 each, with a collective demand for external tritium of 0.475 kg per year for a 6-year commercial development period from 2030 [25,26].

Further considered is the tritium demand from independent government projects scheduled to run in parallel to ITER. The Chinese Fusion Experimental Test Reactor (CFETR) is expected to demonstrate full breeding capability but will still require a start-up inventory of 2–3 kg when it begins operation in 2035 [27]. Similar quantities of tritium are expected to be required for the Korean K-DEMO reactor, which will begin operation two years later in 2037 [28]. A nominal one-off value of 2.5 kg was used for both CFETR and K-DEMO demands.

Much smaller quantities of tritium required for scientific experiments taking place over the next decade were also considered to contribute to demand for tritium and have been included in both supply scenarios. The Princeton PTOLEMY experiment is expected to require 0.1 kg [29]; Karlsruhe Institute of Technology's KATRIN received 40 g of tritium in 2016, and may require further quantities in the near future [30]; JET DTE-2 will run with 60 g of tritium in 2018 [31]; and US production of Molybdenum-99 may require a one-off quantity of 100 g of tritium in the 2020 s [32]. Although the tritium needs of such experiments is negligible, collating all demand expected over the next decade is useful for informational purposes, and for completeness of the model.

3. Results

The results in Fig. 1 show the effects of modelling supply scenarios 1 and 2 against demand scenarios A and B. Fig. 2 separates the total annual tritium production from the tritium consumption to better demonstrate the impact of both the supply and demand scenarios being modelled.

The information presented in Table 1 gives further insight into the availability of tritium for DEMO based on three ITER schedules: the original (now superseded) start date with ITER full DT operation starting 2025, and DEMO starting 2042 [1,7,33]; the current schedule with ITER full DT operation starting 2035, and DEMO starting 2054 [6,34]; and a hypothetical further delay whereby ITER begins operation in 2040 (as considered in [2]), and DEMO starts in 2057 (the end of the time horizon on the model).

4. Tritium available for future fusion reactors

4.1. Tritium for ITER

Table 1 shows that despite the 10-year delay from the original ITER schedule from 2025 to 2035, on the current schedule the quantity of tritium available for the operation of ITER remains largely unchanged, due to the rate of supply in both supply scenarios. Tritium supply and demand rates as shown in Fig. 2 suggest that even in the worst-case scenario, Canada is still capable of directly supplying all tritium for the operation of ITER. However, net tritium production from Canada during the period in which it will supply ITER is close to zero (see supply scenario 1 in Fig. 2), and thus the Canadian contribution to the global tritium inventory during this period will be minimal, meaning no additional tritium is diverted to storage, which may have knock-on effects for DEMO (see Section 5.1). South Korea and Romania are thus deemed to be critical drivers in replenishing the global tritium inventory, as they are crucial for building up an inventory for DEMO or subsequent fusion devices.

4.2. Tritium for DEMO

Fig. 1 and Table 1 show that as the ITER schedule slips and, correspondingly, the start of the subsequent DEMO is delayed, the quantity of tritium available for DEMO start-up declines. On the current ITER schedule, there is expected to be between 12.2 kg and 27.6 kg tritium left available for DEMO, dependent on the rate of supply and demand. While the consequences of a further 5-year slip to ITER's schedule (DT operation starting 2040) would not likely affect the ITER mission itself, it may mean only as little as 7.6 kg of tritium is left available for a DEMO in 2057. Therefore, any further slip to ITER is unacceptable from a tritium supply perspective, if the ITER-DEMO pathway to fusion energy is to be realised, as the largest possible quantity of tritium should be made available to secure DEMO start-up.

Estimates for future DEMO tritium start-up requirements must be viewed as approximations, and figures are wide-ranging. It is difficult to estimate the quantities of tritium needed for start-up, as values are heavily dependent on the advances in technology allowing for improved performance parameters in tritium burn-up fraction, recycling

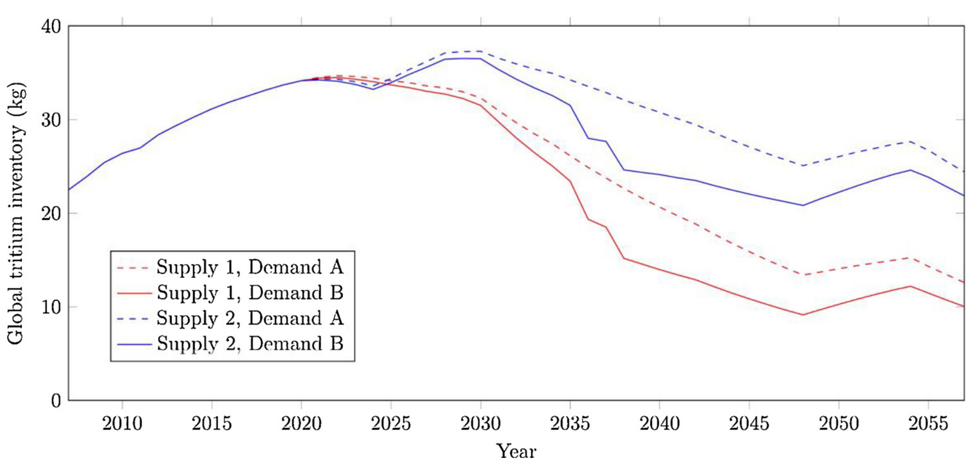

Fig. 1. Available global tritium inventory adjusted for fusion demands.

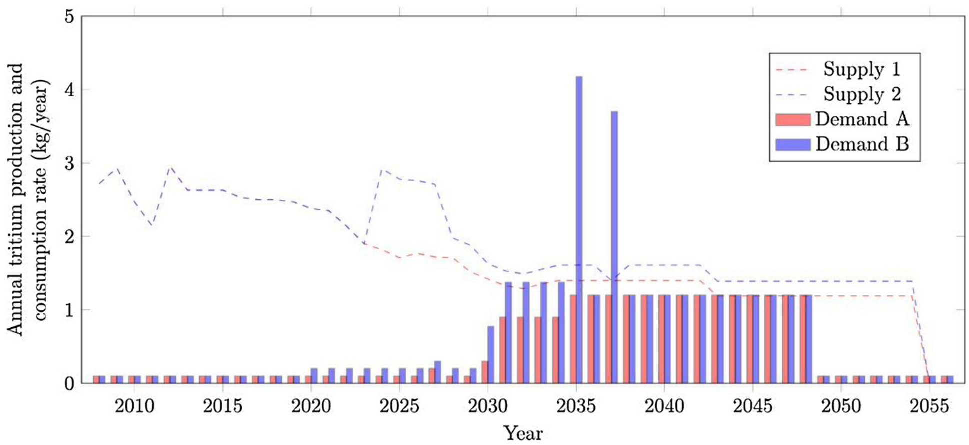

Fig. 2. Available global tritium production and consumption rates for all scenarios.

Table 1
Available global tritium inventory for DEMO based on ITER starting full DT operation in 2025 (original schedule), ITER starting full DT operation in 2035 (current schedule), and ITER starting full DT operation in 2040 (further delayed schedule).

	Demand Scenarios	Tritium for DEMO Supply Scenario 1	Tritium for DEMO Supply Scenario 2
Original Schedule (ITER full DT start 2025, DEMO start 2042)	ITER only	18.2 kg	28.8 kg
	Additional Demand	12.9 kg	23.5 kg
Current Schedule (ITER full DT start 2035, DEMO start 2054)	ITER only	15.3 kg	27.6 kg
	Additional Demand	12.2 kg	24.6 kg
Delay Schedule (ITER full DT start 2040, DEMO start 2057)	ITER only	10.1 kg	22 kg
	Additional Demand	7.6 kg	19.4 kg

time (of the tritium systems), fuelling efficiency, and Tritium Breeding Ratio (TBR). With technical advancements to the point where one such DEMO concept reactor would operate at 2.4 GWth, with a 5% burn-up fraction, a 1-h tritium processing time, and a net TBR of above unity, the tritium required for full power start-up is still expected to be around 8 kg [35,36]. Alternatively, if little technological progression is made then tritium required for a single DEMO start-up may be as much as 50 kg [36].

For the tritium inventory remaining after ITER, perhaps more of an issue is the prospect that several nations are now considering the possibility of pursuing independent, non-collaborative DEMO projects. Taking just two of the current DEMO concepts in the Chinese FDS-II and the European DEMO, even in the best-case the tritium available to supply both DEMO start-ups is barely sufficient, as between 23.1 and 28.1 kg is required for start-up of both such devices, although exact quantities are, as explained, uncertain [1,37]. If start-up requirements are of the order of tens of kilograms, or if multiple DEMOs are commissioned, then the external supply of CANDU tritium for start-up is likely to be insufficient. Further to consider in this context is that the international trade of tritium may be restricted, with independent nations reserving inventories to support domestic DEMO missions [38]. For South Korea to secure K-DEMO, it may restrict sales of tritium from the WTRF [28], and similarly a future European DEMO may ultimately depend solely on the commissioning of the Romanian CTRF [5].

To ensure the success of DEMO it is recognised that technological solutions, particularly tritium breeding technology, should be developed. Beyond the quantities required for reactor start-up, no external source of tritium would be sufficient to fully support a DEMO programme. Even if technology advancements are made during the ITER timeframe, it is expected that availability of fusion-bred tritium prior to DEMO will be zero, unless projects such as CFETR, KDEMO, or other fusion endeavours are successful in developing breeding technology enough to support start-up of further reactors. In which case, current DEMO proposals could become obsolete, and efforts would shift to whichever technology is successful in reaching the point of self-sufficiency with suitable performance. In any case, however, development of tritium breeding may only be enough to achieve self-sufficiency in first-step devices, not for breeding tritium for the start-up of new devices, thus CANDU tritium may still be relied upon.

Without considering the potential for low tritium or DD start-up regimes as a potential route to significantly reduce tritium requirements of future fusion reactors, as discussed in Section 5, the prospect of supplying tritium for future DEMO reactors is both a current and future issue, as dependence on uncertain future externalities dictates the need for a well thought out strategy on tritium supply and related R&D.

4.3. Tritium for other fusion endeavours

The demand spikes for start-up quantities of tritium for CFETR and KDEMO are clearly seen in Figs. 1 and 2, whereas compact fusion demand has a steadier impact on available tritium from 2025. Even so, the results show that until around the time that ITER begins full DT operation in 2035, CANDU tritium is plentiful and available for use by government or private sector compact fusion programmes. Any use of tritium in this period should be seen an efficient use of resource, as what is unused prior to ITER is otherwise diverted to storage only to decay, which is seen as a loss of resource from the perspective of fusion development and a loss in sales for those supplying tritium (although this loss can be mitigated by the opportunity for tritium producers to sell helium-3, the decay product of tritium and a commodity of similarly high value, which has been explored in [5]).

Due to delays to ITER, many of the prospective timescales for compact fusion demonstrations are now planned to happen before ITER starts full DT operation. From a supply perspective, the timescales are near-term enough to say with more certainty that global CANDU plants will remain online until this time, and TRFs will continue to maintain the currently plentiful stockpile of tritium. As such, if the associated technical challenges can be overcome [9,26,39], compact fusion programmes have the opportunity to acquire and use tritium near-term while it is readily available. Furthermore, given that tritium requirement for fusion is directly proportional to fusion power [26,40], assuming that reactor performance parameters and operational programmes can be the same, compact fusion reactors operating at lower power will require smaller quantities of tritium than ITER. One compact fusion reactor using lower quantities of tritium in its efforts also leaves sufficient tritium available for multiple compact fusion reactors to be developed concurrently. The development of concurrent fusion reactor concepts increases the chances of success, as it spreads the risk of failure. Furthermore, as alluded to in Section 4.2, if full tritium breeding capability is not expected to be demonstrated in DEMO until after 2050, an opportunity also exists for accelerated compact fusion programmes to incorporate tritium breeding technology in nearer-term devices, to avoid the associated longer-term issues. As such, from the standpoint of availability and use of external tritium, an accelerated compact route to fusion energy may be more advantageous.

It should be noted that in the case that any compact fusion programme is unable to achieve the required levels of performance for a fusion reactor, it may still offer a unique test bed for fusion technology development. The idea of a compact reactor acting as a Fusion Nuclear Science Facility (FNSF) or Component Test Facility (CTF) is not new, but remains a worthwhile development, and provides rationale for the support of any compact fusion programme from both a tritium supply and use perspective, as discussed here, and in the context of the overall development of fusion energy.

5. Challenges and opportunities

5.1. Tritium accessibility, transport and delivery

Previously, the results of the model were analysed to assess quantities of tritium that may be available at future dates when fusion requires it, and more specifically the quantity that will remain for the start-up of DEMO. However, availability of supply is not the same as access to supply. In reality, there are a number of factors affecting accessibility to the quantities expected to be available as shown in the model herein: extraction from the existing storage vessels, transportation and transportation packages, and the geopolitics surrounding trade.

At the Darlington and Wolsong TRFs, tritium is stored as titanium tritide in tritium immobilization containers (ITC), each capable of storing 52 g of tritium [18,20,41]. Titanium was chosen as the most suitable long-term storage medium because titanium tritide is stable in air and requires high temperatures for extraction [42]. Tritium ITCs were not designed with ease of extraction in mind, and thus extraction of tritium from titanium will likely require special purpose facilities and extraction temperatures of around 600°C [42]. In addition, the older tritium storage vessels will have significant He-3 that will require separation from the tritium, which, as mentioned in Section 4.3, may itself be of value as a commodity [5]. Once heated to elevated temperatures to extract tritium the ITCs will most likely not be reused by the DTRF or WTRF as they will now have tritium permeated into, and possibly through, the container wall, and the containers will have been heated close to, or beyond, the design temperature. Hence the ITCs will now become tritiated waste that must be disposed of at a cost. Thus, if the tritium stored in the ITCs is needed, there will be additional efforts required impacting cost and potentially schedule. In addition, the following questions would need addressing:

i Will an ITC be shipped to ITER/DEMO for tritium extraction at site?
ii Or, will tritium from an ITC be extracted at the tritium removal facility and fed into an appropriate transport container?

Canadian tritium alone is sufficient to supply ITER, and as such tritium at the DTRF can be extracted as it is being generated, placed into appropriate containers using depleted uranium or ZrCo as the storage medium, and made ready for immediate use [41]. It is recognised that any TRF outage, as detailed in assumptions made in Section 2.3, would mean that direct supply of any significant quantity of tritium for any fusion reactor, including ITER, would not be possible. If a TRF is offline for any significant period, it would affect the direct supply of tritium, and thus extracting stored tritium from an ITC from the TRF storage vault would be necessary. Although this is seen as an issue that impacts DEMO, solutions may be needed sooner for ITER, too. Fig. 2 suggests that much of the required tritium start-up inventory for DEMO will need to be extracted from the ITCs in the TRF storage vault, as such a large requirement excludes the option of direct TRF supply like that envisaged for ITER. A similar issue may affect start-up quantities of tritium required for CFETR and K-DEMO during the 2030s. However, for K-DEMO tritium from the WTRF could be diverted into appropriate storage containers in the years leading up to operational start.

It can be expected that significant quantities of tritium (in the order of 1 kg/yr) will be shipped to the ITER site in multiple shipments. Availability of transportation packages meeting the requirements of the competent authorities in Europe and tritium supply countries will be needed. The tritium shipments will require a type B(U) package [7,43]. At present, international shipment of tritium from Canada, requiring a type B(U) package, utilizes an existing transport package, the GE Healthcare Type B(U) 3605D [44]. However, it is limited to ~5 g per shipment. Shipment of larger tritium quantities (50 or 100 g) requires a transport package which presently is not available. KAERI has been commissioned by ITER to develop a tritium storage and shipping package for the international shipment of tritium [45,46]. Some countries have approved transportation packages for domestic use [47]. At present, the US NNSA (National Nuclear Security Administration) has a transportation package, the BTSP (bulk tritium shipping package) which is capable of transporting up to 150 g of tritium as gas, or solid on hydride beds within the USA [48]. Additional work is required to utilize the package for international shipments such as certification in the relevant countries and, in the case of the BTSP, support from the US government, to ensure that tritium shown to be available is accessible to fusion programmes around the globe.

The model assumes a hypothetical global tritium stockpile that is available for all activities. As posited in Section 4.2, tritium-producing nations may look to preserve domestic tritium resource and could limit the projected quantities available for international use, as shown in results herein. Movement of tritium from the supply countries to Europe will require nuclear cooperation and trade agreements and must satisfy the import and export controls of the appropriate countries, as well as the International Atomic Energy Agency (IAEA) [43]. Tritium movement from Canada to Europe has already taken place, but not from South Korea [49]. A change in the global political environment, such as the proposed movement away from nuclear power generation in South Korea, has the potential to impact the shipment of large quantities of tritium [12,21]. Additionally, because of fears of radioactive releases or theft, public pressure may also militate against the large scale international shipment of tritium. As such, these issues may present an additional hurdle in future trade of, and access to, the global tritium inventory. Such issues may be particularly difficult for private sector fusion start-ups without government backing.

5.2. Tritium supply from non-CANDU sources

Non-CANDU sources of tritium are excluded from the model to reflect that they are not being considered at the current time, and the results suggests that they will not be needed for the next two to three decades whilst the supply of tritium from CANDU is sufficient enough to support fusion efforts. Despite this, Fig. 1 shows that the global tritium inventory begins to decline from as early as 2025 due to supply not being able to replenish inventory stocks as quickly as demand and decay work to reduce them. As such, non-CANDU tritium production options do exist as to be deployed in the future. However, although non-CANDU sources of tritium may be capable of significantly boosting supply, they come with a number of issues relating to economics, regulation, and political and public acceptance.

South Korea and Romania have the potential to provide a boost to the global CANDU tritium inventory, but China and India may yet also prove to be a long-term solution for supplying tritium for DEMO devices

[2,15,50]. China produces a small quantity of tritium as oxide at Qinshan and is exploring alternate methods of commercial tritium production [1,16], and India produces a significant quantity of tritium in its heavy water reactors, but has no commercial tritium separation facility [2,15,50]. If a need arises and international agreements can be reached, with a 7–10 year lead time, India could commission a tritium removal facility capable of producing commercial tritium on timescales appropriate to, and quantities potentially sufficient for a future international DEMO programme, and certainly for any domestic programme, too. However, on the international scene, whilst India is well placed to produce tritium, possessing a fleet of 18 pressurised heavy water reactors (PHWRs), the country's status as a non-signatory of the nuclear non-proliferation treaty (NPT) raises important difficulties [51]. A key obstacle is that India operates eight PHWR nuclear power plants outside the IAEA safeguards regime [51]. Consequently, it is most unlikely that IAEA NPT signatory nations would enter into commercial arrangements for Indian tritium associated in any way with such facilities. Among the regulatory issues, in Europe at least, could be the need for a formal justification to assess whether expected public benefits outweigh the radiological risks, the cost of the endeavour, and the geopolitical ramifications. Such an assessment could be difficult to achieve sufficient to grant permission.

The cross-section for tritium extraction from the light water used in conventional PWR and BWR fission reactors is so low as to render such systems unsuitable for tritium production, without the addition of TPBARs, however such methods are employed for weapons-related production of tritium and may be unattractive given the association. Tritium must be removed from the heavy water moderator for CANDU reactors to remain in safe operation, and can be considered a by-product [5]. Purpose-built or re-assigned fission reactors to produce tritium for fusion, on the other hand, would not. Kovari et al. proposes the addition of lithium-6 to the moderator of HWRs, including CANDU [11]. This measure, and indeed other competing suggestions for non-CANDU tritium production would represent a significant adjustment to the safety case for such power stations. In Western liberalised electricity markets, it would seem unlikely that plant operators could easily be compelled to embark on tritium production. Given the regulatory hurdles that would need to be overcome, any attractive incentive may have to be so generous as to perhaps render the resulting tritium uneconomic for the fusion energy research community. Any route to fusion whereby fission reactors must be commissioned or modified to supply fusion will raise questions over the viability of fusion in the near-term and may suffer backlash and cause unrest in support of publicly funded fusion programmes. Much of the continued support for fusion depends on the promise that fusion technology has distinct benefits over its fission relative, with weaker links to nuclear proliferation risks.

5.3. DD and low-tritium start-up

Although our results suggest that there will be tritium available for a DEMO reactor following ITER, there is large uncertainty and numerous uncontrollable externalities. Such issues dictate the need to consider alternative strategies for the start-up of fusion reactors without external tritium. By starting a fusion reactor with no tritium introduced to the vessel, instead producing it through DD, and subsequently produced DT, neutrons with a breeding blanket,[6] it is possible to build up a tritium inventory enough for full 50:50 DT operation in the order of months [40,52]. DD start-up does not completely avoid the need for externally sourced tritium, with small quantities still required to commission the isotopic tritium separation systems (in the order of 100 g) [2,40,52–54]. However, provided that effective tritium breeding technology can be developed, future fusion reactors operating on a DD start-up regime could significantly reduce the requirement for external tritium for reactor start-up, so that commissioning of multiple reactor would be possible, as detailed below.

Zheng et al. indicate that DD start-up may prove uneconomical as electricity costs for heating and current drive could be significant.[7] However, it is thought that any energy costs would substitute the cost of externally sourced tritium, which, in the context of discussion here, may be unavailable altogether in the quantities required. In conducting power ascension tests under DD-start-up for the commissioning phase of a fusion power plant as a pre-requisite to the promise of commercial power production, the financial and time expenditure may be acceptable. Equally, a ramp-up to full power is acceptable from a technical standpoint, as power ascension tests are practical and realistic in operation of a fusion reactor commissioning phase, akin to the start-up of a PWR fission reactor [52,54]. To alleviate some of the issues with this, introducing a small quantity of tritium may accelerate the time to 50% DT [40,52,53], reducing overall cost and time of a ramp-up phase and increasing the viability of the approach, whilst using significantly less tritium. Compact fusion reactors may offer an additional advantage in this respect. As discussed in Section 4.3, the quantity of tritium required for a fusion reactor is directly proportional to fusion power, and thus compact concepts with lower absolute fusion power will require even lower quantities of tritium under a DD start-up regime. Again, this allows for other concurrent fusion concepts to continue development, whilst not using up large quantities of tritium resource.

Where it is widely understood that any external tritium source could not support a commercial programme, irrespective of fusion reactor size, it is also important to note here the limitations with regards to the availability of external tritium for the commercial roll-out of fusion energy. To allow for reasonable expansion during commercial roll-out, on commercialisation models as suggested in [55], a DD start-up regime may present the only realistic option. The concurrent start-up of multiple devices and the concept of "doubling time", defined as the time required to produce enough excess tritium for full power start-up of a subsequent reactor [36], would limit the speed of growth of commercial roll-out and could thus also affect the commercial viability of fusion as an energy technology option [52]. Such commercialisation issues are all but removed by a DD start-up regime, although it is again important to note that for commercial roll-out, a small quantity of external tritium will still be required for the commissioning of the tritium systems. However, despite avoiding the need for a doubling time, the level of performance of the tritium breeding systems, recycling systems, and the absolute physics parameters allowing for low tritium start-up to be feasible remain technologically unproven and such issues are critical. Therefore, there remains a need for technological advancements in these areas, particularly in tritium breeding, as detailed in [36].

6. Conclusions

Despite the delay to its schedule, there is a sufficient supply of tritium for the operation of ITER. Although tritium for ITER remains available, there may still only be as little as 12.2 kg remaining for the start-up of subsequent DEMO reactors, provided there are no further delays on the ITER-DEMO pathway. However, as several nations are considering pursuing independent non-collaborative DEMO projects, even in the best-case scenario the global CANDU tritium inventory is unlikely to be able to provide tritium for the start-up of multiple DEMO devices. While countries such as Romania, and even India or China, can

[6] Tritium production from the DD fusion reaction instantly leads to a mix of DD/DT fusion reactions in the reactor. Both DD neutrons and DT neutrons produce tritium, but difference in neutron energies from the reactions means that effective TBR from DD is lower than for DT [52]

[7] The length of time taken, and the energy consumed, for a DD start-up regime is dependent on performance parameters, as well as the TBR, efficiency of heating and current drive systems, and energy prices. It is out of scope to estimate costs without a specific reactor configuration to base estimates on. Refer to [40,52,53] for DD start-up research studies

produce substantial quantities of tritium, owing to the large uncertainty and complex issues surrounding the variety of potential tritium supply sources, there is a possibility that external tritium will be unavailable for start-up of a DEMO fusion reactor around 2050.

The uncertainty over longer term supply of tritium highlights the benefits of any fusion option utilising CANDU tritium in the near-term. If the associated technical challenges can be overcome, compact fusion programmes have the opportunity to use tritium over the next two decades whilst it is readily available, and before full power DT operation on ITER starts in 2035. Assuming a similar level of performance is achievable, a compact fusion development programme, using smaller reactors operating at lower fusion power, would require smaller quantities of tritium than the ITER programme on the road to fusion energy, while leaving sufficient tritium available for multiple concepts to be developed concurrently. The development of concurrent fusion concepts increases the chances of success, as it spreads the risk of failure. Any tritium consumed in the period prior to ITER should be seen as an efficient use of resource, as unused tritium will be diverted to long-term storage, where it will be left to be extracted for future DEMO missions, or to decay. As such, from the standpoint of availability and use of external tritium, an accelerated compact route to fusion energy may be more advantageous, as it avoids longer-term complications and uncertainties in the future supply of tritium. A publication is in preparation on how Technology Roadmapping can be used to support the accelerated development of compact fusion energy programmes.

More broadly, efforts should be made to accelerate development of all fusion programmes, with future issues regarding tritium supply, as detailed here, in mind. If full tritium breeding capability is not expected to be demonstrated in DEMO until after 2050, an opportunity exists for accelerated compact fusion programmes to incorporate tritium breeding technology in nearer-term devices, and to thus avoid the associated longer-term issues. Conversely, if near-term compact fusion development efforts are unsuccessful, then unless ITER and the post-2050 DEMO programme can be accelerated, then long-term supply problems will still exist for the ITER-DEMO route to fusion energy. For any long-term fusion reactor, and certainly a future commercial programme, DD and low-tritium start-up regimes, particularly when deployed for compact fusion reactors, may ultimately avoid issues surrounding external tritium supply and use. Thus, the feasibility of DD start-up should be further explored in the context of future tritium supply, and for supporting the large-scale commercial roll-out of fusion energy.

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