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GLOBAL SUPPLY OF TRITIUM FOR FUSION R&D FROM HEAVY WATER REACTORS

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Abstract

Heavy water (D₂O) reactors are presently the only commercial source of tritium. CANDU reactor tritium production in Ontario, Canada, will supply ITER's tritium demand but, following the delay in the ITER schedule, may only be able to supply 7.4 kg for a DEMO fusion reactor in 2055. The required tritium start-up inventory for a DEMO plant depends on a range of parameters (burnup fraction, fuelling efficiency, etc.), and present estimates of this amount vary widely. Although it is in theory possible to start up a fusion reactor from D-D operation alone, the paper discusses the more commonly accepted scenario of an external amount of tritium being purchased from commercial entities. Three tritium production scenarios are presented, assuming that establishments in Canada, the Republic of Korea, and Romania make their tritium stockpiles available to the fusion community. Real data, compiled by the IAEA, are used to make estimates of the tritium production for each reactor. Depending on the production scenario, and the consumption scenarios (ITER operations, and e.g. CFETR), the amount of commercially available tritium produced in heavy water reactors in 2055 ranges from 0 to 27.7 kg.

1. INTRODUCTION

Many authors have considered the issue of tritium availability for future fusion reactors [1-4]. We provide here an updated analysis based on heavy water reactor data from the IAEA [5], and a range of production and consumption scenarios, taking into account the delay to the ITER schedule. The paper is a revised, updated (with more recent data and developments), and abridged version of a previous work by the same authors, found in [6].

The tritium start-up inventory required by a tritium self-sufficient DEMO-class fusion reactor is subject to a wide margin of uncertainty, with estimates in the literature varying from less than 1 kg to almost 20 kg for a ~2 GW fusion reactor [7, 4]. If ITER is successful, it is conceivable that multiple DEMO-class devices may be developed in parallel; the European DEMO machine [8], the Chinese Fusion Engineering Test Reactor (CFETR) [9] and others could potentially require several kilograms of tritium each in the 2050s.

It is theoretically possible to start up a fusion reactor with little or no tritium, however such an operation would take years and if one accounts for the interest rate on a large capital investment, it does not appear to be economically sensible (see [6]). Commissioning of a fusion reactor in D-D plasmas will produce some tritium, provided a breeding blanket is installed, and some have argued that ~5 years of D-D commissioning would be required, creating ~3-5 kg of T [10].

2. TRITIUM PRODUCTION IN HEAVY WATER REACTORS

Tritium is inevitably produced in all water-cooled fission reactors due to neutron capture by deuterium in the water. Fission reactors using heavy water as a moderator and/or coolant generate considerably more tritium than light water reactors (where deuterium is naturally present in one in ~7,000 hydrogen atoms). Several countries have heavy water reactors (HWRs) fleet: most notably Canada (with its significant CANDU HWR fleet), but also the Republic of Korea, Argentina, China, India, and Romania. The latter two are actively building and seeking to build new HWRs, respectively.

The rate of tritium production varies from reactor to reactor and is not information published by plant operators. Estimates in the literature for HWR T production range from 210 to 260 g/GWe/fpy [1, 4]. Here it is assumed that each reactor produces tritium at a rate of 228 g/GWe/fpy for all HWRs, regardless of their design (the average of the estimates found in the literature). Owing to the lack of real tritium production data, historical data for net electricity output were used to estimate tritium production. The data were extracted from the IAEA Power Reactor Information System (PRIS) [5]. The net electrical power output of a HWR gives a reasonable estimate of the tritium production, but it is by no means perfect: there are many scenarios in which the reactor might be operating

but not producing electricity, and indeed the thermal efficiency of HWRs is not uniform, or even constant for a given HWR. Yet in the absence of better data, the net electrical power output provides a reasonable guide to the fission rate in a HWR, and therefore tritium production.

The typical lifespan of a HWR before refurbishment is assumed here to be 30 years. A reactor refurbishment is generally intended to extend the operational lifetime by a further 25-30 years [11] – 25 years is assumed here. A shutdown period of 18 months is assumed for reactor refurbishments, during which time no tritium is produced. Some future refurbishments are assumed in Canada, the Republic of Korea, and Romania (see later description of Scenario B for details). In India, Kakrapar-3 and 4 and Rajasthan-7 and 8 are constructed according to present plans [12].

Fig. 1 shows the estimated annual T production by commercial HWRs in all countries with HWRs, and the resulting T inventories. For years beyond 2017, an average of each reactor's historical load factor is calculated (excluding refurbishment periods) and used to estimate future tritium production rates.

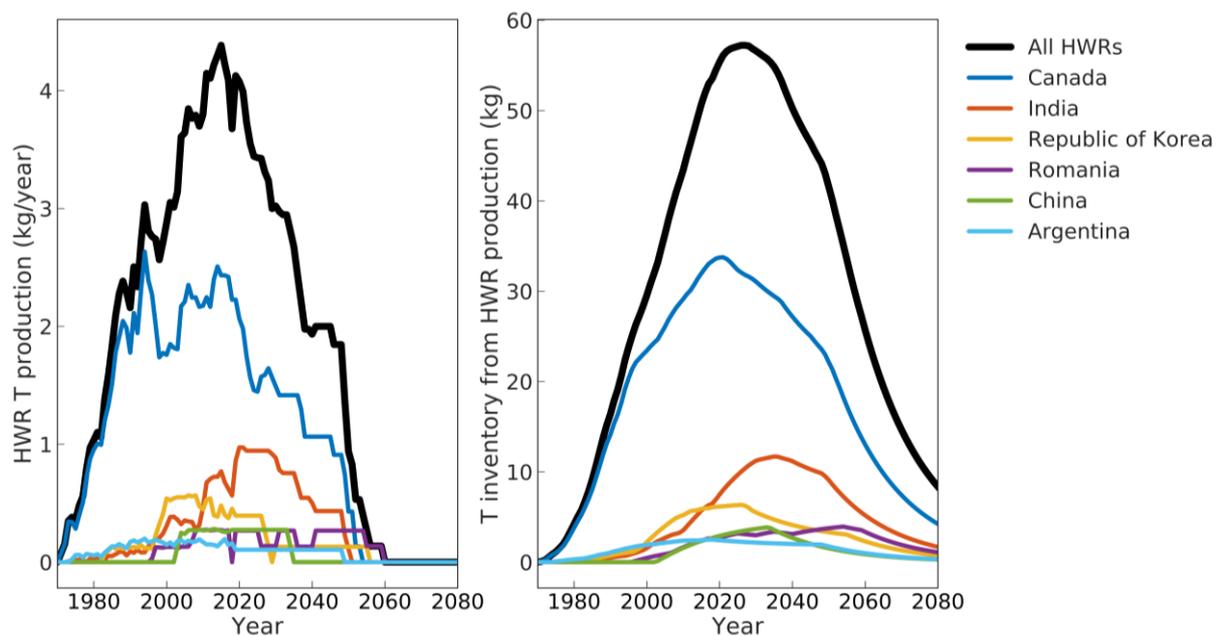


FIG. 1. Tritium production and inventories in all commercial HWRs, grouped by country.

The figure above suggests that a global T stockpile of 30-40 kg from commercial HWR operation will exist in the 2050's.

Despite the many countries in the world with HWRs, at present only two countries are known to actively detritiate the heavy water in their HWRs: Canada and the Republic of Korea, which operate the Darlington Detritiation Facility, and the Wolsong Detritiation Facility, respectively. Romania is presently considering the construction of a detritiation facility at its Cernavoda site. Detritiation of HWRs can be a legal requirement, or it can be economical consideration; e.g. to reduce the cost of maintenance/refurbishment by reducing activation levels. Either way, detritiation facilities are a substantial investment, and it is assumed here that only the three aforementioned countries are able to sell tritium to the fusion programme. Ontario Power Generation (OPG) in Canada sells approximately 100 g/yr of tritium to commercial users [13], at a cost of 25-30 k\$/g [14].

Given that no new HWRs are being considered for construction in Canada and South Korea, it is important to consider the prospects for present HWRs to be refurbished in these countries. Five HWRs in Canada have already been refurbished [11], with Darlington-2 presently being refurbished, and refurbishment plans exist for the Pickering, Darlington, and Bruce sites. In the Republic of Korea, on the other hand, the Korean government recently announced its intent to stop all new build nuclear power plants and life extensions [15]. In Romania, refurbishments for its two existing HWRs are being planned, with two new HWR units are being considered in

the future, along with a new detritiation facility [16]. In all cases, these plans are subject to shifts in governments, political will, and local and global socio-economic circumstances.

In order to estimate how much tritium may be commercially available in the 2050's for fusion research it is useful to define some scenarios of varying optimism:

- Scenario A: Pessimistic
 - Canada: Bruce-6 refurbishment goes ahead, but no other planned refurbishments occur;
 - Republic of Korea: no HWR refurbishments take place;
 - Romania: Cernavoda-1 and 2 are not refurbished, and as such no detritiation facility is built. Romania provides no tritium to the fusion programme;
 - Commercial sales take place at 300 g/yr, in Canada only.
- Scenario B: Moderate
 - Canada: Darlington-1, 3, and 4 and Bruce-3, 5, and 6 are refurbished according to present plans [17, 18];
 - Republic of Korea: Wolsong-2 is refurbished;
 - Romania: a TRF is built, and Cernavoda-1 and 2 are refurbished;
 - Commercial sales take place at 200 g/yr, in Canada only.
- Scenario C: Optimistic
 - Canada: all Bruce and Darlington refurbishments go ahead according to present schedules;
 - Republic of Korea: Wolsong-2, 3, and 4 are refurbishment at their end of life;
 - Romania: a TRF is built, Cernavoda-1 and 2 are refurbished, and Cernavoda-3 and 4 are built and refurbished;
 - Commercial sales take place at 100 g/yr, in Canada only.

Note that in all scenarios all HWRs are assumed to operate for 30 years from the date of their connection to the grid, or 25 years after the date of their restart after a refurbishment. The only exception to this rule is Wolsong-1 in the Republic of Korea, which is assumed to be permanently shut down in 2022 (see e.g. [15] for details). Again, for all scenarios, Gentilly-2 and Point Lepreau in Canada are assumed not to detritiate their moderators (as they are not in Ontario and are not required to by law).

Fig. 2 shows the forecast tritium stockpiles for Canada, the Republic of Korea, and Romania, for all three scenarios.

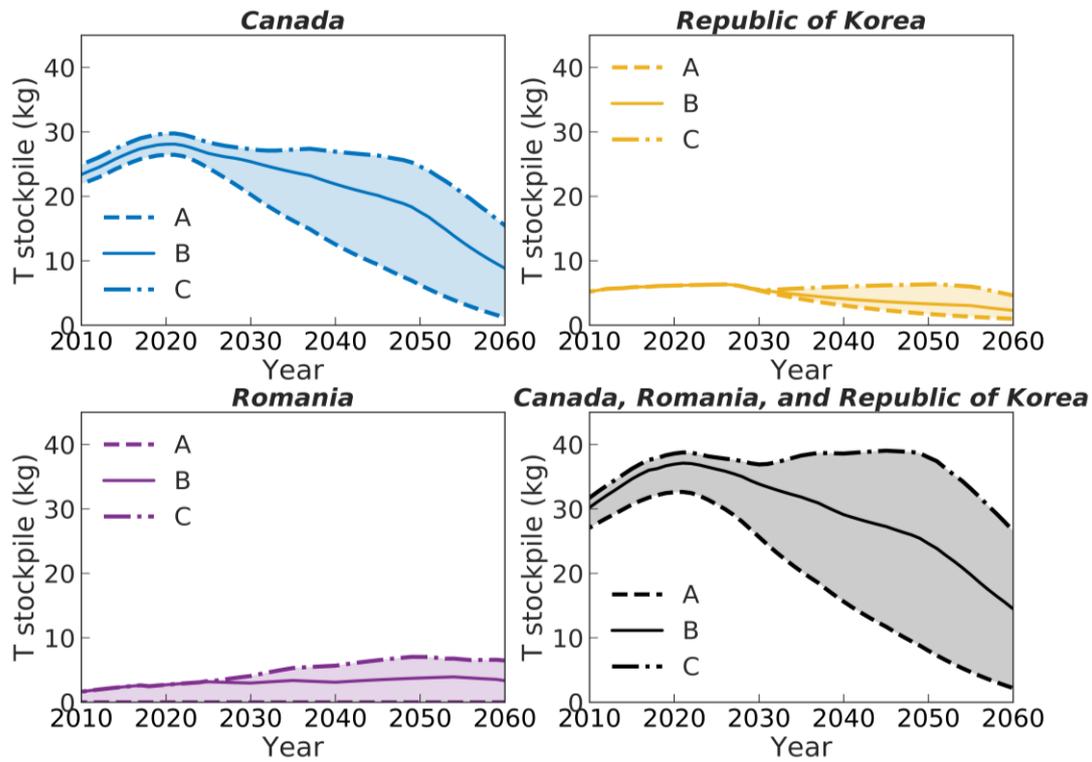


FIG. 2. Commercial tritium stockpiles in Canada, the Republic of Korea, and Romania, for all scenarios, including commercial tritium sales in Canada.

3. FORECASTS OF COMMERCIALY AVAILABLE TRITIUM FOR A DEMO REACTOR

Past, present, and near-future consumption of tritium by fusion R&D is negligible. The National Ignition Facility in the United States of America (USA) has a tritium inventory limit of 0.83 g [19]. JET's planned final tritium campaign (DTE2) is expected to use 55 g of T. The next major consumption of tritium for fusion R&D will be ITER, with tritium operations presently scheduled to start around 2036. Unofficial estimates of tritium consumption by ITER put the figure at a total of 12.3 kg over its operational lifetime. ITER will produce negligible amounts of tritium in the test blanket modules.

Beyond the 2030's, aside from ITER, the demand for tritium from fusion reactors is less clear. Plans for large scale devices such as the Chinese Fusion Engineering Test Reactor (CFETR) in China and the Fusion Nuclear Science Facility (FNSF) in the USA point to the potential of multiple DEMO-class reactors. Furthermore, a host of commercial fusion entities claim to build and operate smaller-scale D-T fusion reactors in the 2030's. Naturally, the existence of any or all these devices is uncertain, as is the amount tritium they require from commercial sources to start operations (if any). In order to represent the potential effect of an additional demand of tritium from fusion sources, a simple approach is adopted: a one-time point-wise purchase of 5 kg of tritium is modelled, five years after the start of ITER D-T operations. This eventuality is denoted as 'CFETR' for convenience.

It is not yet known if or when a DEMO reactor would need to purchase a tritium start-up inventory from commercial entities. Here, it is assumed that a DEMO will be built in the 2040's and will require tritium from commercial sources in 2055.

Fig. 3 shows several forecasts of commercially available tritium from HWR production, accounting for commercial and fusion consumption, for all three scenarios described above, with and without a CFETR-like eventuality.

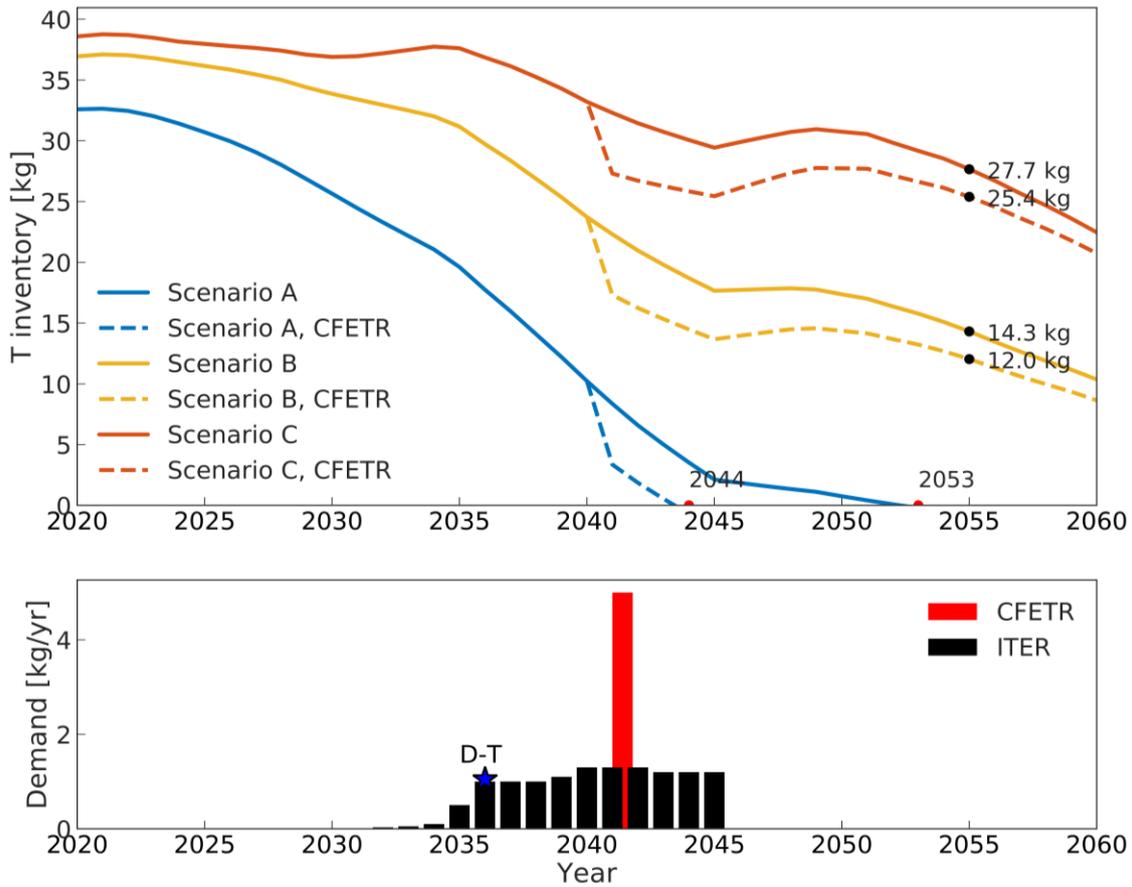


FIG. 3. (above) Stockpiles of commercially available tritium for all scenarios, including commercial and fusion consumption. The amount of tritium available in 2055 or the year in which the tritium runs out is annotated for each scenario. (below) Tritium consumption profile from fusion sources. The start of official ITER D-T operations is denoted with a blue star. Small amounts of tritium will be required beforehand for the commissioning of the tritium plant.

In the most pessimistic tritium production scenario, Scenario A, there is no tritium left for a DEMO reactor in the mid-2050's. Indeed, if there is another fusion reactor which requires an external start-up inventory in the 2040's, it may have to compete with ITER for the commercially available tritium resource. In Scenario B and Scenario C, 12-14.3 kg and 25.4-27.7 kg are available for a DEMO reactor, depending on whether or not a 5 kg "CFETR" eventuality occurs.

Three further aspects are worth highlighting. Firstly, the date of ITER operations has a direct effect on how much tritium is available in the 2050's; if ITER D-T operations are delayed, less tritium is available in 2055, as production tails off beyond 2040 in all but the most optimistic scenario. Secondly, the provenance of the tritium may matter: it could be that entities in the Republic of Korea do not wish or are not allowed to sell tritium to foreign customers, or that OPG in Canada chooses to sell its entire T stockpile to the USA for use in its helium-3 neutron detection programme. Finally, India, China, and Argentina will also have stockpiles of T, which could potentially be made commercially available. These aspects are illustrated in Fig. 4.

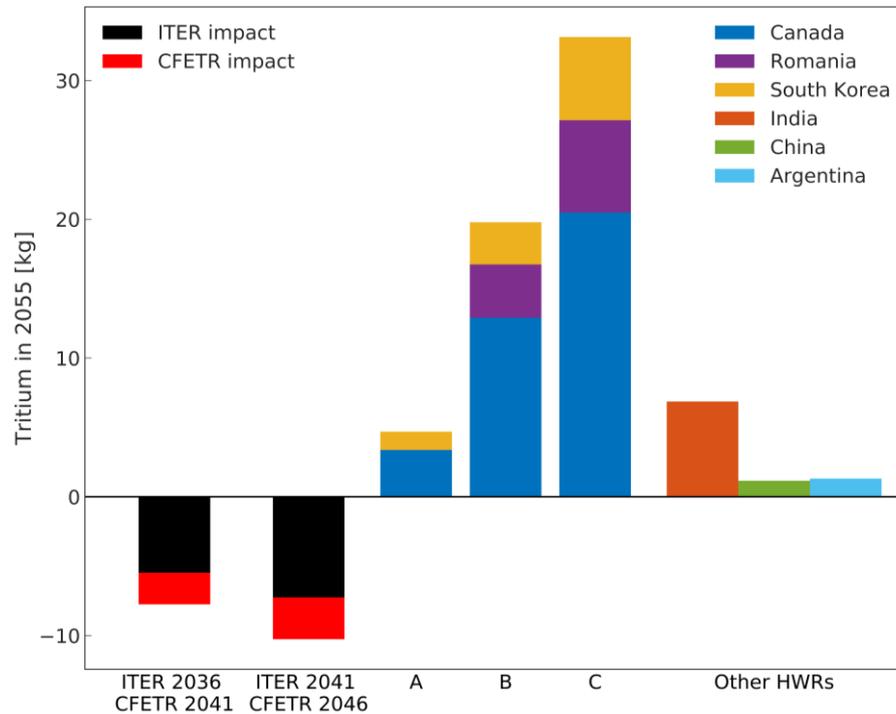


FIG. 4. Tritium amounts in 2055, showing the impact of ITER and CFETR consumption, and associated delays, inventories from each country with present or planned tritium extraction programmes for Scenarios A, B, and C, and potential quantities from India, China, and Argentina.

ITER D-T operations taking place as presently scheduled in 2036 corresponds to 5.47 kg less T in 2055, whereas a five-year delay would result in there being 7.25 kg less tritium in 2055. A similar effect for a delay in a one-off purchase can also be seen in Fig. 4.

China and Argentina would only be able to contribute negligible amounts of T to the fusion programme, as HWRs are not prevalent in these countries. India, on the other hand, could contribute almost 7 kg in 2055 (making only moderate assumptions about future refurbishments and new builds). Given India's prominent HWR programme which aims to substantially increase the size of its fleet in future, India has significant potential to contribute far more tritium. However, there are a number of aspects, some of which are discussed in [20], which admittedly make this eventuality rather unlikely.

4. DISCUSSION AND CONCLUSIONS

As Nils Bohr once commented: "prediction is very difficult, especially if it's about the future". It bears emphasizing that the forecasts presented here are highly speculative, and many events in the near- and long-term future have the potential to disrupt this picture. Fukushima, for instance, had far-reaching effects for the nuclear industry, and saw Germany pledge to shut down all of its nuclear power plants by 2022.

CANDU reactor tritium production in Ontario, Canada, will supply ITER's tritium demand (12.3 kg) but, following the delay in the ITER schedule, may only be able to supply 7.4 kg for a DEMO fusion reactor in 2055 (Scenario B). Depending on the tritium production scenario, and the consumption scenarios (ITER operations, and e.g. CFETR), the amount of commercially available tritium produced in heavy water reactors in 2055 ranges from 0 to 27.7 kg. Given that estimates for the start-up inventory of a DEMO reactor range from 1 to 20 kg, and it is possible that several DEMO-class reactors must compete for the same resource, there are likely to be serious problems with tritium supply for the future fusion R&D programme.

There are other options, still making use of existing nuclear fission reactors, to generate tritium. These are discussed in more length in [6] and are briefly summarized here:

- Modifications to CANDU reactors and other HWRs could theoretically generate additional tritium in a number of ways, such as using adjuster rods containing lithium or doping the moderator with lithium-6.
- Production of tritium in commercial light water reactors using tritium-producing burnable absorber rods is a possibility. Indeed, this is done in the Watts Bar plant in Tennessee, USA, yet the licencing and regulatory arrangements are quite particular to this case, and the estimated cost of tritium production (40-60 k\$/g [21]) is approximately twice as high as for HWR T production.

However, all alternative fission reactor production methods have serious economic and regulatory drawbacks, namely that they would incur loss of electricity production, extensive modifications to existing plants, and would need to be re-licenced for operation.

It is important to note the dependency of the fusion community on events outside its control, most critically the refurbishment of existing HWRs and TEFs, and the construction of new ones in several countries. It is possible that no commercially available tritium remains in the 2050s for use in fusion R&D. D-D start-up or phased D-D/D-T start-up (see e.g. [7, 22]) are potential approaches to mitigate this risk but bring with them a host of design issues which have yet to be earnestly addressed, and are very unlikely to be cheaper than sourcing tritium from HWRs, when accounting for the cost electricity to drive current in a predominantly D-D plasma and the interest rate on a large capital investment.

Regardless of the provenance of any externally sourced tritium, minimizing the tritium start-up inventory should be a design goal for a fusion reactor. Efforts should be made to reduce the present uncertainties in the start-up inventory for fusion reactors, through research into plasma exhaust and tritium processing systems (e.g. [23]), as well as dynamic tritium fuel cycle modelling (e.g. [24]).

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