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Operational Tritium Inventories in the EU-DEMO Fuel Cycle

J. C. Schwenzer,[a]* C. Day,[a] T. Giegerich,[a] and A. Santucci[b]

[a]*Karlsruhe Institute of Technology (KIT), Institute for Technical Physics, Karlsruhe, Germany*
[b]*ENEA, Fusion and Technology for Nuclear Safety and Security Department, Frascati, Italy*

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Abstract — *The European Demonstration Fusion Power Reactor (EU-DEMO) has to operate in a completely tritium self-sufficient mode after initial start-up, which includes producing excess tritium to allow the start-up of other reactors. The initial start-up inventory is mainly dictated by operational inventories in the fuel cycle (FC). Advances in FC technologies and immediate recycling of a large fraction of the torus exhaust gas in the direct internal recycling loop are expected to contribute greatly to an overall low operational inventory. The remainder of the torus exhaust gas, as well as tritium from the blankets, nevertheless requires treatment in the tritium plant in order to perform the necessary purification and isotope rebalancing. Here, the employed systems still feature significant operational inventories and predominantly require steady-state operation in order to maximize their performance. In this paper the operational tritium inventories in the major FC systems are reported based on the pre-concept FC design. Additionally, major dependencies of these inventories on key design drivers of the FC are discussed. It is predicted that the EU-DEMO FC will be able to operate with an overall tritium inventory of less than 2 kg.*

Keywords — *EU-DEMO, fuel cycle, tritium inventory.*

Note — *Some figures may be in color only in the electronic version.*

I. PREFACE AND INTRODUCTION

The European Demonstration Fusion Power Reactor (EU-DEMO) transitioned from the pre-concept phase to the concept design phase in 2021. For the work package Tritium – Matter Injection – Vacuum (TFV), this implied a first formulation of an integral design of the fuel cycle (FC) that follows a novel, three-loop architecture, as outlined in Ref. 1. This paper builds on this design point and is thought to be complementary.

*E-mail: jonas.caspar.schwenzer@kit.edu
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When looking at a DT demonstration fusion power plant, there are several types of tritium inventories present on-site. First, there are all inventories that are required for nominal operation of the plant. These include, e.g., tritium in the burning plasma, holdups in the processing systems of the FC, or holdups in the free volumes of the piping between systems. We call these operational inventories, and they are always present by design. Second, parasitic inventories can also accumulate in materials or mediums that are exposed to tritium, especially in plasma-facing components and breeding blankets. In a first approximation, these can be considered "lost" from a FC perspective, as laborious recovery is required to make the tritium therein available for reuse. These not easily recoverable inventories, and we refer to them as sequestered inventories. Last, there is also tritium held back in storage, either to be exported for the start-up

of another plant or as reserve for on-site use, which we call storage inventories. The start-up inventory, meaning the amount of tritium that is required to reach sustainable full-power operation, also bears significant importance for plant designers as it can severely limit the attractiveness of a Demonstration Fusion Power Reactor (DEMO) plant if it is excessively high. Under the assumption that tritium from breeding is available only in significant quantities if all systems of the torus and the FC operate at their designated full-power design point, this start-up inventory of the plant is at least as high as all operational inventories of the plant, plus any sequestered inventories that build up in the period leading up to this point.

Furthermore, additional buffer inventories may also be required to compensate for tritium decay in phases with lower availability or to provide fueling reserves. The quantification of such buffer inventories (and in turn the start-up inventories) therefore has to take into account other constraints, such as expected plant availabilities, scheduled maintenance phases, and global parameters such as the tritium breeding ratio (TBR). Such analyses have in the past been performed by Coleman et al. and more recently by Abdou et al. but have not been applied to the pre-concept design of the EU-DEMO (Refs. 2 and 3).

As it has recently been shown that DD start-up is not an attractive option for the EU-DEMO (Ref. 4), the start-up inventory has to be provided from rapidly fading stockpiles at significant cost.[5] Furthermore, from a safety perspective, operational inventories can be equivalent to releasable tritium inventories. Their minimization is therefore not only desirable from an economical perspective but also of utmost priority to promote the passive safety of the plant and thus imposes stringent requirements for the design of the FC. This has driven the development of the novel direct internal recycling (DIR) concept and the continuous KALPUREX pumping process for the EU-DEMO FC and is one of the major design drivers leading to the pre-concept architecture as presented in Refs. 1, 6, and 7.

Section II provides an overview of what kind of operational tritium inventories are expected in the systems of the FC, as well as a first quantification thereof for the pre-concept design point. All inventories given refer to steady-state or flattop burn phase values. Section III then highlights major dependencies of these inventories with regard to upcoming design decisions and technology choices.

II. TRITIUM INVENTORIES IN THE EU-DEMO FC

The architecture and associated primary technology choices of the FC are given in Ref. 1. Figure 1 is a block diagram of the FC, comprising the direct internal recycling loop (DIRL), tasked with directly recycling a majority of the exhausted hydrogen isotopologues; the inner tritium plant loop (INTL), where the remaining hydrogen isotopologues are recovered and the fuel composition is rebalanced; and the outer tritium plant loop (OUTL), tasked with processing tritium extracted from the breeding blankets and recovered tritium from detritiation. As no detailed engineering design exists for many of these systems, the primary goal here is to provide an upper estimate or achievable maximum design target. This is done either with the help of process modeling, using the FC simulator developed in TFV, or via scale-up of comparable systems from, e.g., ITER, where applicable. For each system, the key assumptions as well as employed boundary conditions are summarized, and tritium inventories are then derived therefrom.

Especially many systems of the OUTL still feature significant uncertainties in their inputs, requirements, design, and optimization. Estimation of their tritium inventories is therefore challenging at this early stage and prone to still feature significant uncertainties. Here, nevertheless, an attempt is made using conservative assumptions wherever input data are lacking or requirements are not yet fully established.

Next to the systems themselves, some operational inventory is also present in piping between systems and infrastructure elements, such as heat exchangers, blowers, filters, etc. At this stage, these components cannot be quantified correctly. While no detailed quantification of these contributions can be given at the moment, we estimate that their overall contribution is small when compared to the sum of the operational inventories of all systems. This is due to a number of reasons. First, minimization of free volumes in areas of high tritium concentrations (especially the DIRL and INTL) is a primary design goal. Second, tritium of high enrichment is only transmitted between systems in the gas phase below ambient pressure. Third, technologies resulting in large systems with many ancillary components are used only in the OUTL, where tritium concentrations are significantly lower. Fourth, piping lengths between systems carrying large tritium streams are minimized by the building layout of the tritium plant. While the presented inventories are in all cases conservative, it is emphasized that they do not quantify any and all inventories of the FC or the plant but rather serve to give an initial estimate of major FC systems and to point out further optimization potential or development needs for the upcoming concept design phase as well as the impact that some upcoming decisions might have.

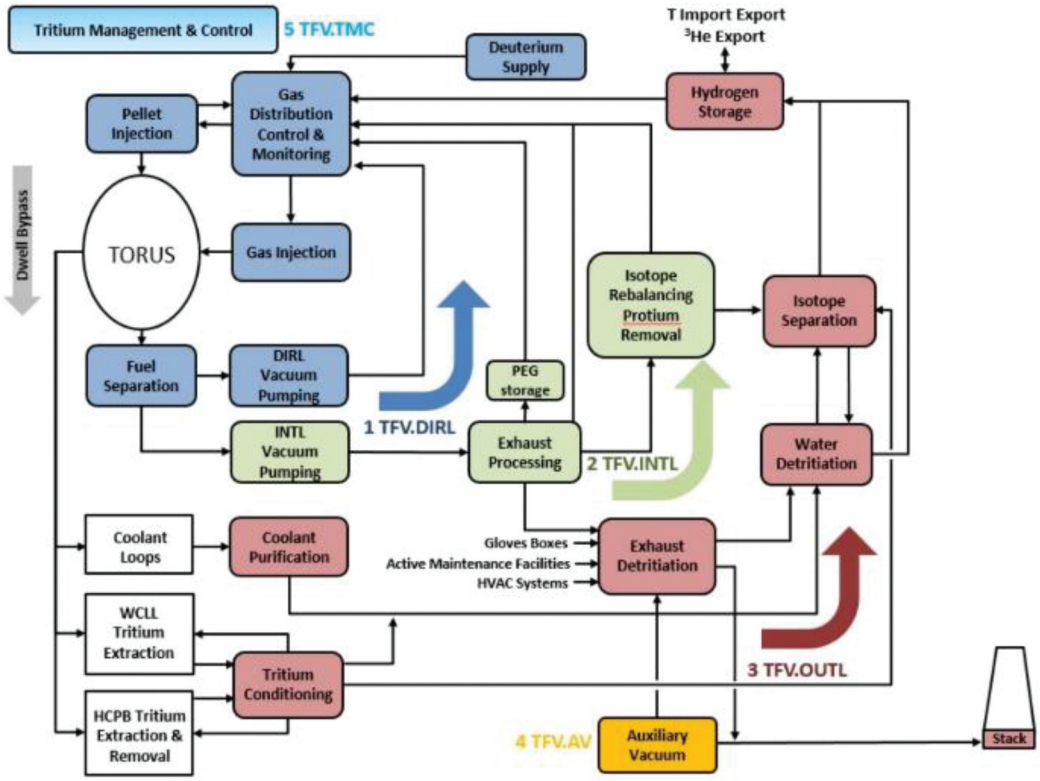

Fig. 1. System block architecture of the DEMO FC pre-concept design point.

II.A. Pellet and Gas Injection

Matter injection provides tritium-containing gases via two systems, namely, for fueling of the plasma and for plasma control (detachment control and edge density shoulder control): (1) a pellet launching system comprising a pellet source and acceleration system and (2) a gas puffing system. The pellet launching system can reach significant tritium inventories as liquid and solid tritium is present in the pellet source at nonnegligible processing times. Accurate determination thereof would require the physical dimensions of the employed systems, which are not yet available. An estimate can nevertheless be made when looking at comparable systems. Gouge et al. report a tritium inventory limit for the ITER pellet fueling system that utilizes an extruder as the pellet source and a gas gun for acceleration.[8] The tritium inventory is given as 150 g, of which 100 g are allocated to the accelerant gas of the gas gun, which we consider as not applicable here assuming that EU-DEMO will use centrifuges. The remaining 50 g are then distributed across two alternating extruders and vacuum pumping systems as well as pellet waste. The described system offers a continuous design throughput of 75 mol/h of DT to the torus. Linear upscaling to the EU-DEMO pellet fueling throughput of 380 Pa·m^3/s[a] of DT (=602 mol/h[b]) (Ref. 1) yields a system tritium inventory of approximately 401 g. We would like to highlight that this is thought to be a very conservative estimation, especially considering the use of alternating pellet sources that will be replaced by fully continuous extruders, as well as further technological advancements or optimizations in fueling efficiency, vacuum pumping, and pellet production.

Next to fuel injection via pellets, gas puffing of DT is also foreseen, currently at 80 mol/h of DT (=50 Pa m^3/s) (Ref. 1). Here, tritium inventories are present only as gas in the available volumes for pipes and vessels. Assuming a target fuel reserve time of 5 min, an additional inventory of 20 g of tritium is present in the system.

II.B. Fuel Separation, DIRL, and INTL Vacuum Pumping

The metal foil pump (MFP) employed in the fuel separation system offers gaseous inventories in its upstream and downstream volumes as well as dissolved

[a] Throughout this paper, we use 273.15 K as reference temperature for volumetric gas flowrates.

[b] Throughout this paper, we use the atomic mass of 3.0160 g/mol for one triton when converting between molar and mass quantities.

tritium in the foil. A single MFP can be regarded as a cylinder with a length of 2 m and a diameter of 0.45 m, of which 10% of the inner volume is occupied by the plasma line. For an updated configuration based on the one described in Ref. 9, we have assumed 54 MFPs, giving a total volume of 15.5 m^3 at an assumed upstream pressure of 3 Pa. The MFPs are housed in nine rectangular casks of (2 × 2 × 1.5) m^3 each, totaling 36.8 m^3 after the volume of the MFPs is subtracted.

With an assumed gas temperature of 500 K on both sides and a downstream pressure of 105 Pa, 2.8 g of tritium are present as gaseous inventory in all MFPs. Next to the gaseous inventories, the MFP also contains hydrogen dissolved in the foil (made of vanadium or niobium). As permeation occurs here in a surface-limited regime, the hydrogen concentration across the foil can be assumed as constant and bounded by the maximum concentration at the high-pressure side. Using Sieverts law, it is given by $c_T = K \cdot p_{T2}^{0.5}$, where c_T is the concentration of atomic tritium in the material and K is the Sieverts constant. Solubility data of tritium in niobium ($K_{Nb} = 19.39\ \text{mol m}^{-3}\text{Pa}^{-0.5}$) and vanadium ($K_V = 13.78\ \text{mol m}^{-3}\text{Pa}^{-0.5}$) as given in Ref. 10 at 1000 K are used. With a tritium partial pressure on the downstream side of 53 Pa and a foil volume of 2.83×10^{-4} m^3 ($A = 2.83$ m^2 and $d = 0.1$ mm), this yields a maximum tritium content of 4.6 g or 6.4 g for vanadium and niobium, respectively, in the foil of all MFPs.

All pumps employed in the vacuum systems offer large volumes where gaseous tritium inventory is present at pressure levels ranging from the sub-divertor pressure to close to ambient pressures. The technology selections of the pumping systems used here are based on the Karlsruhe liquid metal–based pumping process for reactor exhaust gases[1,7] (KALPUREX), with an assumed configuration based on preliminary performance data evaluated from a KALPUREX test stand.[11] The configuration features a cascade of linear diffusion pumps (LDP) (only in the INTL), booster pumps (BP), and six stages of liquid ring pumps (LRP). Table I gives the number of employed pumps in each stage, their assumed volumes, and inlet and outlet pressures. The volume-averaged pressure p_{avg} in each pump is assumed to be $0.5(p_{in} + p_{out})$, and the molar tritium fraction in the pumped gas is assumed to be $x_{T2} = 0.49$, matching the composition at the divertor output. As the total quantities of plasma enhancement gases (PEGs) and impurities in the exhaust stream do not change in the pumping systems (only completely directed toward the INTL in the fuel separation system) and all pumps are distributed proportional to the gas load of the DIRL and INTL, the total average tritium concentration across both loops remains constant. As the KALPUREX process employs liquid mercury as the working fluid, active cooling is used to prevent the propagation of mercury vapor to upstream systems. All pumps (except the MFP) are therefore assumed to operate at 300 K. Similarly, the heat of compression is also assumed to be removed by the cooling system, and the same constant gas temperature is used in the calculations.

TABLE I

Tritium Inventories in the Torus Vacuum Pumps

Pump	p_{in} (Pa)	p_{out} (Pa)	V_{pump} (m^3)	n	m_T (g)
LDP	3	105	0.86	18	1.0
BP	105	280	0.1	54	1.2
LRP stage 1	280	1 000	0.1	13	1.0
LRP stage 2	1 000	2 700	0.1	9	2.0
LRP stage 3	2 700	8 000	0.1	9	5.7
LRP stage 4	8 000	22 000	0.1	6	10.7
LRP stage 5	22 000	75 000	0.1	3	17.2
LRP stage 6	75 000	95 000	0.1	3	30.2

A total overall operational tritium inventory of 76.4 g of tritium for the vanadium MFP or 78.2 g for the Nb MFP is found for all torus vacuum pumps, excluding piping between different pump stages.

II.C. Exhaust Processing

For the exhaust processing system (EPS), a system of tube-in-tube permeators is used. Here, the geometries, materials, and operating conditions as in Ref. 12 are used (also given in Table II). For such a configuration, the following operational tritium inventories are present: (1) gaseous inventory in the upstream volume (lumen side), (2) gaseous inventory in the downstream volume (shell side), and (3) dissolved tritium in the foil. With a torus gas throughput of 430 Pa·m^3/s of DT and an assumed DIR ratio of 80%, 31 permeator tubes are required for the first stage and 4 for the second stage to achieve a hydrogen separation fraction of >95% per stage.[1]

An upper bound of the gaseous inventories is given when using the inlet tritium concentration over the complete length of the tube on both sides. Assuming ideal gas behavior, the

TABLE II

Sizing Parameters of the Permeators in the Exhaust Purification System

Sizing Parameters	Stage 1	Stage 2
Number of tubes	31	4
Feed pressure (Pa)	2×10^5	
Permeate pressure (Pa)	1×10^3	
Inner diameter (cm)	1	
Outer diameter (cm)	2.5	
Foil thickness (μm)	125	
Tube length (m)	0.5	
Feed T content (mol %)	45.4	33.8
Retentate T content (mol %)	49.5	
Total T inventory (g)	1.46×10^{-1}	

molar inventory of the diatomic gas is then evaluated via the ideal gas law at the conditions given in Table II. In a steady-state diffusion-limited permeation regime, the concentration profile in a one-dimensional slab (as first approximation of the foil, neglecting its curvature) establishes linearly between the surface concentrations on both sides of the foil. The molar inventory of monatomic tritium is then $N_T = V_{foil} \cdot (c_{lum} + c_{perm}) \cdot 0.5$, with N_T the molar amount of atomic tritium in units of mol; V_{foil} the volume of the foil in units of m^3; and c_{lum} and c_{perm} the concentration of monatomic tritium in units of mol m^{-3} in the foil on the lumen side and the permeate side, respectively. This surface concentration is given by Sieverts law as $c_{T2,s} = K \cdot (p_{T2})^{0.5}$, with K the Sieverts constant and p_{T2} the partial pressure of T_2 above the foil. In a first approximation, this solubility is independent of the isotopologue.[13] Serra et al. report $K = 0.567$ mol m^{-3} $Pa^{-0.5}$ for D_2 in $Pd_{25}Ag$ at 450°C, which is also used for tritium here.[14]

The process also foresees the use of catalytic crackers to liberate compound hydrogens. Their inventory is dependent on the required residence time to achieve sufficient conversion ratios. As these impurity amounts in the torus exhaust are not quantified yet, the tritium inventory of this system cannot be further detailed at present. Only a relative tritium inventory proportional to its throughput (0.34 g/min of tritium) can be given. Experimental time constants for a similar process in the ITER impurity processing stage have been reported as $\tau = 1.6 \pm 0.15$ min (Ref. 15). Allowing for a total residence time equal to ten times the upper bound (=17.5 min) in order to achieve sufficiently high conversion fractions, this contribution amounts to 6 g of additional gaseous tritium inventory.

II.D. Isotope Rebalancing and Protium Removal

As the membrane coupled temperature swing absorption process (MC-TSA) foreseen for the isotope rebalancing and protium removal (IRPR) system operates semicontinuously, the total tritium inventory can be evaluated from a global material balance around the system. With the configuration as described in Ref. 1, the system processes a superficial steady-state flow rate of 11.1 Pa·m^3/s. Typical cycle times for similar absorption-based systems range from 30 to 60 min (Ref. 16). Here, we assume a slightly shorter cycle time of 2380 s, as no cooling to LN_2 temperatures is required. Additionally, only a fraction of 8% of the total column inventory is fed and extracted during one cycle to not disturb the concentration profile in the column, resulting in a total residence time of 29 750 s. With a feed tritium molar fraction of $x_{T2} = 0.495$, this yields a total tritium inventory of 433.7 g for the columns. In order to integrate the process into the continuous working environment of the FC, buffer tanks upstream and downstream the process are used that also hold a tritium inventory. The feed tank continuously accumulates at least the same molar amount as is fed in the uptake phase, and the downstream tanks hold the same molar amount distributed between them that is then continuously discharged to downstream systems. All tanks also hold a baseline inventory that is given by the volume and base pressure of the tank as they can feed only into systems of lower pressure. The IRPR column take-up pressure is assumed to be 2 bars while the downstream systems are assumed to require feed streams at a minimum of 1 bar. Limiting the maximum pressure of all tanks to 4 bars (at 273.15 K), the required tank volumes and tritium inventories as in Table III result. In total, the operational tritium inventory in the IRPR system block amounts to 556 g.

TABLE III

Sizing Parameters and Tritium Inventories of Buffer Tanks Used in the IRPR

Buffer Tanks	V (m^3)	p_{min} (bar)	x_{T2} (mol %)	m_{T2} (g)
Feed tank	0.15	2	0.495	74.1
Heavy tank	0.075	1	0.55	43.7
Light tank	0.015	1	0.35	5.1

II.E. Exhaust Detritiation

As given in Ref. 1, it is here assumed that the system block is expected to process a gas load of 12 000 Nm^3/h containing 150 kg/h of water as humidity as well as a tritium content of 1 g/h. In reality, there will be a number of different subsystems processing streams from different sources and also depending on the present gas species (e.g., air versus process gases). Here, one superficial exhaust detritiation system (EDS) based on wet scrubber technology is assumed. As the molar density ratio of water in the liquid to the gaseous phase at normal conditions exceeds 1200 and tritium concentrations are expected to be generally very low, gaseous inventories are assumed negligible in this first approximation.

From process simulation, it is estimated that a wet scrubber column with specifications as given in Table IV, with packing data taken from Ref. 17, achieves the required purification to discharge the gas stream to the stack. At these conditions, up to 30 m^3 of liquid water is present in the wet scrubber column. The maximum tritium molar fraction in the liquid water leaving the EDS reaches $x_{HTO} = 2.1 \times 10^{-6}$ (approximately 1.25×10^{14} Bq/m^3) at the bottom of the column. Using the pure H_2O liquid density of 54 924 mol/m^3 at 320 K (Ref. 18), this yields a tritium inventory in the form of liquid water of 11 g.

We would like to stress that this of course marks a significant overestimation as the tritium concentration decreases over the length of the column. Furthermore, this does not constitute the final design status of the system, and additional measures to minimize the tritium inventory (and subsequently potential discharges) are being pursued in accordance with the as-low-as-reasonably-achievable (ALARA) principle. Additionally, a column of this size is of course not feasible. Instead, multiple smaller columns over different subsystems achieving the same required cross section will be used.

TABLE IV

Operating Parameters of a Single Superficial Wet Scrubber Column

Parameter	Value
Cross section (m^2)	8
Height equivalent of theoretical plate (m)	0.4
Number of stages	30
Liquid holdup fraction (vol %)	30
Column temperature (K)	320
Drain liquid level (m)	0.1
Liquid vapor ratio (mol/mol)	1.2

II.F. Water Detritiation

The liquid phase catalytic exchange (LPCE) column of the water detritiation system (WDS) is evaluated similarly to the wet scrubber column. The WDS receives different inputs depending on the breeding blanket employed [helium-cooled pebble-bed (HCPB) concept or water-cooled lithium-lead (WCLL) concept] and the associated technologies for tritium extraction and coolant purification. The operating conditions for both cases are given in Table V; packing parameters used in the process model are chosen to agree with Ref. 19. Next to the LPCE column, the electrolyzer employed as the bottom reflux stage also features significant liquid holdups at the highest tritium concentration in the system. Iwai et al. report on the design of the WDS foreseen for ITER including the electrolyzer unit, which was taken as the design basis for the process model.[20] As the system consists of multiple modules with multiple cells per module, linear scale-up is applicable. One module is reported to produce 30 Nm^3/h of gaseous hydrogen with a liquid holdup of 0.038 m^3 resulting in a specific liquid holdup of 1.27×10^{-4} $m^3/Nm^3 \cdot h^{-1}$. Table VI also gives the gas output produced as well as the resulting tritium inventory for both cases. As with the EDS, this is a substantial overestimation and thus thought to be an upper bound for the present configuration.

TABLE V

Sizing Parameters and Tritium Inventories of the WDS System for Both Blanket Systems

Sizing Parameters	WCLL	HCPB
LPCE Column		
Cross section (m^2)	10.9	10.75
HETP (m)	0.35	
Number of stages	23	22
Liquid holdup fraction (vol %)	5	
Liquid molar tritium fraction x_{HTO}	2.3×10^{-5}	2.2×10^{-5}
Liquid tritium inventory (g)	33.1	29.9
Electrolyzer		
Gas stream output (Nm^3/h)	3427	3387
Liquid inventory (m^3)	0.435	0.430
Tritium inventory (g)	1.65	1.55

TABLE VI

Packing Parameters for Different CD Systems as well as Values Adopted for this Work

Packing Parameters	ITER (Ref. 23)	JET (Ref. 25)	TSTA (Ref. 24)	Value Used
HETP (cm)	5.5	6	5	5
v_{gas} (m/s)	0.125	0.05 to 0.1	0.089	0.1
h_l (vol %)	10	14.5	10 to 15	15

II.G. Isotope Separation

As the cryogenic distillation (CD) columns of the isotope separation system (ISS) can feature large holdups of liquid hydrogen at high tritium concentrations, the upper bound estimations as done for the EDS and WDS would lead to significant overestimations. Additionally, gaseous inventories are not negligible as gas densities are much higher due to the cryogenic temperatures. The tritium inventory is therefore evaluated with the aid of an equilibrium stage ISS model as implemented in the TFV FC simulator. The model features inventories as (1) liquid holdup on the packing, (2) liquid holdup in the reboiler, and (3) gaseous inventories in the remaining column volume including the condenser. Because of the absence of packing, liquid inventories in the condenser are assumed negligible, and its volume is assumed to be that of one empty stage. For a packed column of n theoretical equilibrium stages, the total tritium inventory is then given by

$$m_{\mathrm{T2},tot} = \left(\sum_{n=1}^{n-1} \left(I_{liq,n} \cdot x_{n,\mathrm{T2}} + I_{gas,n,\mathrm{T2}} \cdot y_{n,\mathrm{T2}} \right) + I_{liq,reb} \cdot x_{bot,\mathrm{T2}} + I_{gas,cond} \cdot y_{cond,\mathrm{T2}} \right) \cdot MW_{\mathrm{T2}} \ , \quad (1)$$

where MW_{T2} is the molar weight of T_2, I_n is the gas or liquid molar holdup on each stage, and x_{T2} and y_{T2} are the superficial tritium molar fractions in the liquid phase or gas phase respectively. The (fixed) stage holdup is given by $I_{liq} = V_{liq} \cdot \rho_{liq,av}$, with $\rho_{liq,av}$ the average liquid density, which is evaluated over all species and stages with pure component data taken from Ref. 21. The liquid volume is given by $V_{liq} = V_n \cdot h_l$, where h_l is the liquid holdup fraction and V_n is the total stage volume given by $V_n = \mathrm{HETP} \cdot A$ with the cross-section area of the column and HETP the height equivalent of a theoretical plate (assuming high porosity packing and omitting the volume taken up by the package itself). The HETP values and holdup fractions are generally determined experimentally and closely dependent on the operating conditions of the column. As no detailed design or experimental campaign for the DEMO ISS system exists as of yet, these data are taken from literature for similar applications, most notably the ITER ISS system,[22,23] the Tritium Systems Test Assembly (TSTA) CD system,[23] and the CD system of the JET active gas handling system.[24]

The cross section of the column is then adapted so that the maximum superficial gas velocity is not exceeded in order to achieve the same flow conditions as for the experimentally determined HETP values. Table VI gives an overview of the relevant design parameters.

The liquid and gaseous concentration profiles are then evaluated from the ISS model of the FC simulator. Figures 2a and 2b show the liquid composition for the three columns for the described setup of parameters for the HCPB and WCLL, respectively. Next to the liquid inventory on packing, the reboiler also features significant molar inventories. Yamanishi et al. report on the stable operation of a CD system at reboiler liquid levels down to 7 cm (Ref. 25). For this evaluation 10 cm is used for all columns. Table VII summarizes the conditions used for all three columns and resulting T inventories in both blanket scenarios.

As can be seen from the difference between the WCLL and HCPB setups, slight shifts in the concentration profile can already significantly alter the tritium inventory of a column. While this offers large potential for optimization (not exploited here), rigorous process monitoring and control will have to be used in order to ensure operation at the designated operation point. For the presented study, these differences lay well within the remaining optimization potential and are not distinct enough to point to an advantage between one of the blanket systems with regard to their incurred tritium inventory. As can be concluded from Table VIII, the present separation task is thought to be achievable with an inventory design limit of less than 1 kg of tritium in the ISS while also accounting for infrastructure elements such as heat exchangers and liquefiers.

II.H. Coolant Purification System

Water-cooled lithium-lead CPS: The coolant purification system (CPS) for the WCLL breeding blanket mainly

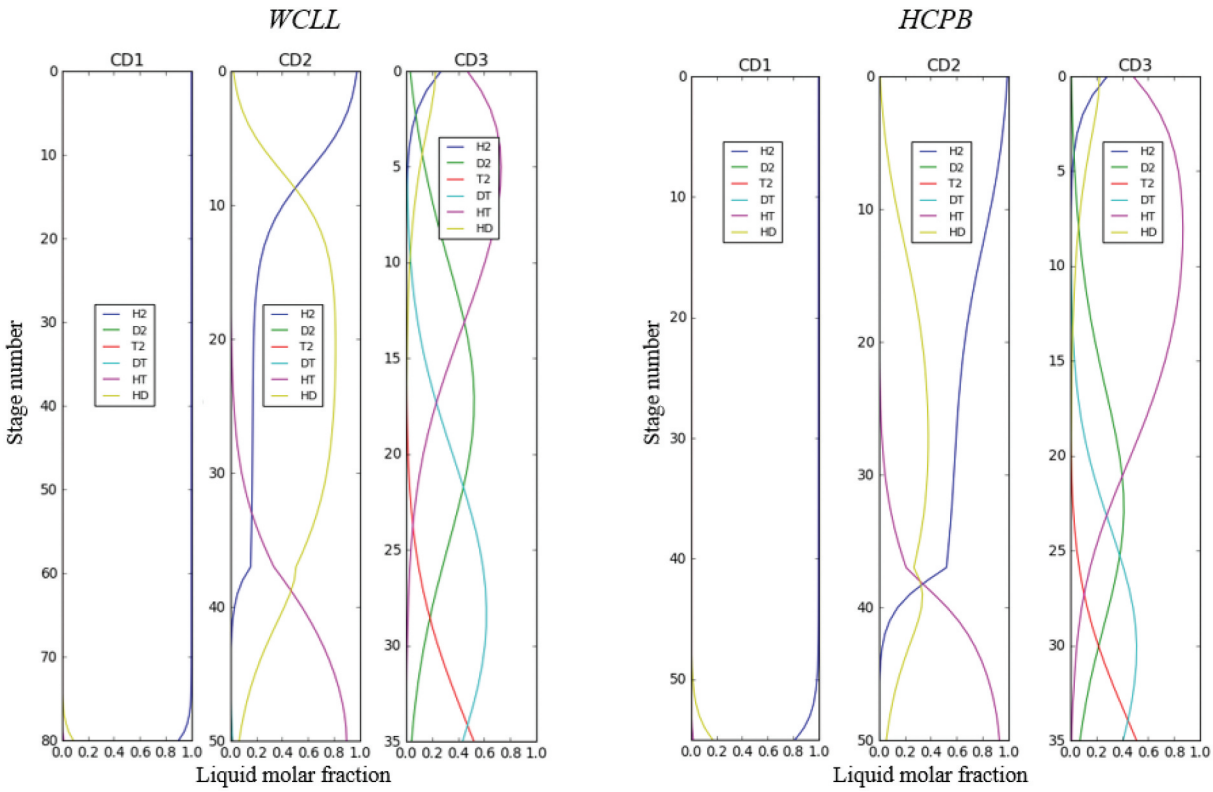

Fig. 2. Liquid molar fraction profiles of hydrogen isotopologues in the CD columns of the ISS as used for the calculation of the system tritium inventory: (a) WCLL case and (b) HCPB case.

TABLE VII

Sizing Parameters and Tritium Inventories for the Three CD Columns Employed in the ISS for Both Blanket Systems

Sizing Parameters and Tritium Inventories	HCPB			WCLL		
	CD1	CD2	CD3	CD1	CD2	CD3
Cross section (m^2)	0.082	0.01	0.0078	0.081	0.0083	0.0094
Stage liquid holdup (mol)	22	2.8	2.4	21.4	2.3	2.8
Stage gas holdup (mol)	2.1	0.25	0.17	2.1	0.2	0.2
Reboiler liquid holdup (mol)	294	40.0	33.2	287	32.2	39.6
Liquid tritium inventory (g)	16.7	202	351	13.4	171	406
Gas tritium inventory (g)	0.1	7.0	15.2	0.1	6.1	15.9
Total tritium inventory (g)	592			613		

consists of water detritiation and is integrated with the WDS and is not separately accounted for here.

Helium-cooled pebble-bed CPS: The HCPB CPS consists of two cyclic processes converting any Q_2 in the helium coolant into Q_2O and then absorbing it on zeolite molecular sieve (ZMS) beds. No tritium buildup in the oxidation beds is foreseen (albeit some may be trapped contributing to a sequestered inventory). The bulk of the systems tritium inventory therefore resides on the molecular sieve beds. In steady-state operation, the CPS removes 0.7 g/day of tritium from the coolant to counteract buildup.[26] When operating the CPS ZMS beds with a design cycle time of 4 days, 2.8 g of tritium are present in the system at the edge case of one fully saturated bed and one completely regenerated bed.

TABLE VIII

Summary of All FC System Blocks Operational Tritium Inventory

System Block	Tritium Inventory (g)	
	WCLL	HCPB
Matter injection	421	
Torus vacuum (DIRL + INTL)	78	
Exhaust processing	6.1	
Isotope rebalancing and protium removal	556	
Exhaust detritiation	11	
Water detritiation	35	31.5
Coolant purification		2.8
Isotope separation	613	592
Tritium conditioning	<1	67
Tritium extraction and removal	67	
Total	1788	1765

II.I. Tritium Extraction and Removal, Tritium Conditioning

The tritium extraction and removal system (TERS) for the HCPB as well as the tritium extraction system (TES) of the WCLL are described in Ref. 26. Next to these, the FC pre-concept design point foresees a tritium conditioning system (TCS) to process extracted tritium before it can be sent for isotope separation

Helium-cooled pebble-bed TERS: To remove hydrogens and water vapor from the helium stream used to purge the blankets, a set of reactive and cryogenic molecular sieve beds is employed in the HCPB TERS. As these continuously accumulate inventory, their cycle time is a trade-off between limiting its tritium inventory while still allowing for efficient heating and cooling. With a TBR of 1.05, approximately 320 g/day of tritium are extracted from the blanket. With a cycle time of 5 h (Ref. 27), the system holds a tritium inventory of 67 g.

To remove any remaining helium in the stream before entering isotope separation, a set of Pd-Ag permeators is foreseen in the TCS. As the system processes only less than 5% of the tritium flow rate as the EPS while employing the same technology, its inventory can be assumed to be proportional and generally to be <1 g.

Water-cooled lithium-lead TES: The current primary technology choice for tritium extraction from lithium lead is by counterflow purging with a helium stream doped with protium [gas liquid contacting (GLC)]. The purge gas is then sent to the TCS where the hydrogens are absorbed on metallic getter beds. Using two alternating beds (one active and one being regenerated) and assuming the same cycle time and tritium extraction rate as for the HCPB TERS, the system holds a tritium inventory of 67 g.

III. DEPENDENCIES AND INTERACTIONS

III.A. Torus Gas Throughput

For the design point reported above a flattop torus, fueling of 430 Pa·m^3/s of DT was used, with 50 Pa·m^3/s via gas puffing and 380 Pa·m^3/s via pellet injection. This fueling requirement is determined via the product of burnup fraction f_b (referring to the integral burnup fraction, see Ref. 3) and fueling efficiency η_{fuel}, with $f_b\eta_{fuel} \approx 0.006$ (corresponding to an exhaust helium fraction of 0.6 mol %) for the case discussed. If improvements can be made here, e.g., by increasing the fueling efficiency by optimization of the pellet injection location (see Ref. 28), the load on the matter injection system, torus vacuum system, and EPS decreases. As all of these systems continuously process the fuel in modular units, their size and tritium inventory scale linearly with the achievable $f_b\eta_{fuel}$.

III.B. Protium Removal Load

The removal of protium from the fuel is one of the main tasks of the IRPR system. In order to avoid the buildup of protium in the fuel, the same amount of protium that enters the FC has to be removed continuously. The amount that can be removed continuously depends on its concentration in the feed stream of the system. Reducing the protium source terms (e.g., from outgassing of metal surfaces in vacuum) in the FC or increasing the allowable concentration in the fuel subsequently reduces the load on the system. As the IRPR system also comprises multiple smaller units, linear scaling of the IRPR then results when changing these factors. As the IRPR also discharges a waste stream containing the extracted protium and some tritium to the ISS, its inventory is also affected.

III.C. TES Effluent Composition

As has been laid out, one of the major inventory contributions to the FC is the CD system in the ISS. The biggest load in terms of tritium is the effluent of the TES, sending approximately 320 g/day of tritium in a mixed hydrogen stream requiring isotope separation

including the treatment of HT to provide tritium in fuel quality. There also exist some technology candidates that do not require the use of hydrogen as a purge medium, for example, permeation against vacuum, or vacuum sieve trays for tritium extraction from PbLi (Ref. 29). These technologies are able to extract nearly pure tritium, requiring only minor purification effort. These or similar technologies, as well as the conscious use of purge media in the tritium extraction, could help to significantly reduce the tritium inventories in the ISS, leaving it only with a primary task of processing trace tritium streams as they arise from IRPR and WDS.

IV. SUMMARY, CONCLUSIONS, AND OUTLOOK

Table VIII and Fig. 3 summarize the evaluated system operational tritium inventories of each system block of the DEMO FC pre-conceptual design configuration.

The inner FC (comprising DIRL and INTL) accounts for an inventory 1072 g, which is independent of the selected breeding blanket. The bulk of this inventory herein stems from the IRPR system and the pellet fueling system where high tritium concentrations are present and the largest improvements can be achieved by technological advancements. The outer FC then accounts for the remaining 693 g if using a HCPB blanket, or 716 g if using a WCLL blank. In both cases the OUTL inventory is heavily dominated by the ISS. As the technology selections for tritium extraction and removal (GLC for WCLL, cryogenic molecular sieves for HCPB) assumed here produce similar stream compositions to be sent for isotope separation, the same FC architecture is used in both cases, and only minor differences (<25 g) in tritium inventories arise that are thought to be well within the remaining optimization potential.

There still exists major optimization potential in almost all areas of the tritium plant and especially in systems providing an isotope separation functionality. Therefore, these are areas with a strong research and development focus in TFV and the fusion community in general. New active materials with improved characteristics for MC-TSA are under investigation at Karlsruhe Institute of Technology; packing material performance for packed columns has significantly improved since the operation of the early CD setups used as reference here; and experience in the design and operation of these processes is continuously increasing, with valuable large-

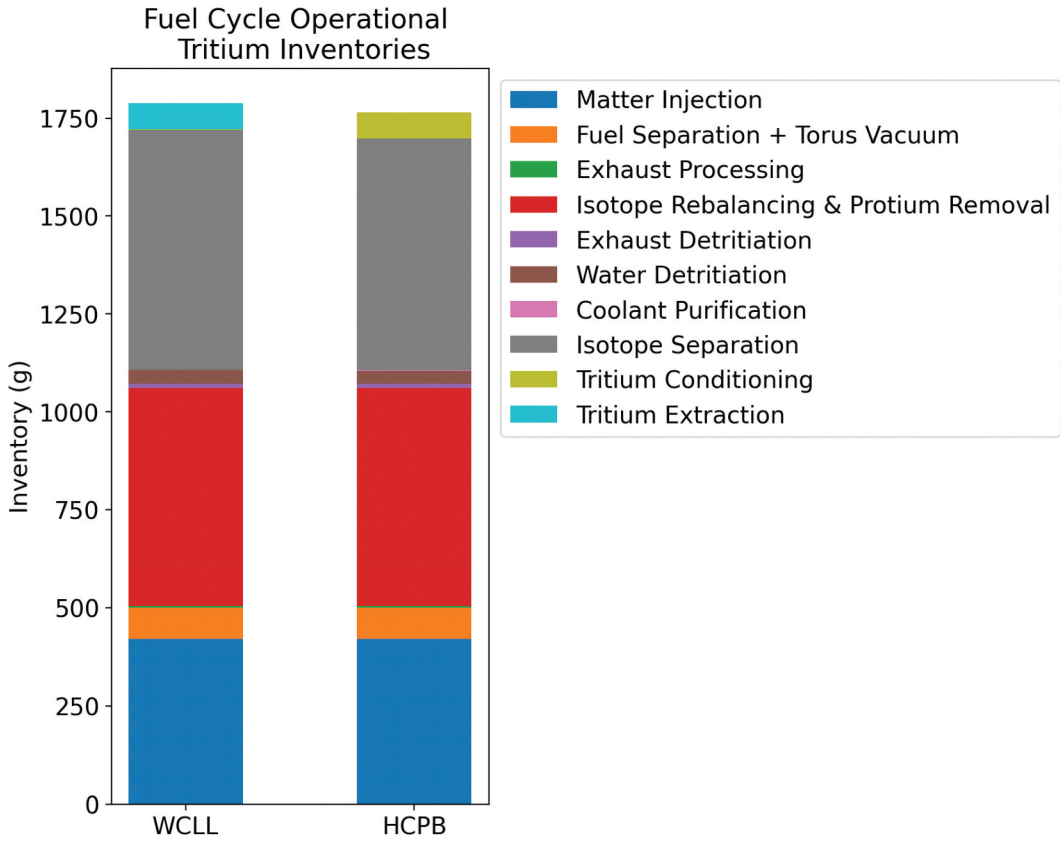

Fig. 3. Tritium inventories in the systems of the EU-DEMO FC for both blanket concepts.

scale performance data expected to arise from the ITER FC and accompanying experimental setups in the H3AT Research Centre.[30]

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ORCID

J. C. Schwenzer http://orcid.org/0000-0001-6064-4332

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