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Analysis of Coolant Purification Strategies for Tritium Control in DEMO Water Primary Coolant

Vincenzo Narcisi [1], Andrea Quartararo [2], Ivo Moscato [3] and Alessia Santucci [1,*]

[1] Fusion and Technology for Nuclear Safety and Security Department, ENEA, Via E. Fermi 45, 00044 Frascati, RM, Italy
[2] Department of Engineering, University of Palermo, Viale delle Scienze, 90128 Palermo, PA, Italy
[3] Fusion Technology Department, EUROfusion Consortium, 85748 Garching, Germany
* Correspondence: alessia.santucci@enea.it; Tel.: +39-0694005405

Abstract: A major objective of the European fusion program is the design of the DEMOnstration power plant named DEMO. Up to now, most fusion experiments have been dedicated to a plasma physics investigation while, in DEMO-oriented activities, large attention is devoted also to other systems necessary to produce tritium and to convert the fusion power to electricity. The blanket region, responsible for tritium breeding, is characterized by high tritium concentrations, high temperature, and large heat transfer metallic surfaces in which tritium can permeate. Therefore, the problem of tritium permeation and the resulting tritium content in the primary coolant are of great relevance for DEMO. For the pre-conceptual design of the Water-Cooled Lead–Lithium variant, the tritium permeation rate from blanket into coolant was assessed and possible mitigation strategies were suggested. Starting from a review of the CANDU tritium experience, a preliminary assessment of the maximum tritium concentration target in the DEMO primary coolant was performed and different strategies (off-line, on-line, and hybrid) for the water coolant purification system coupled with the DEMO operating scenario were analyzed. The intent is to identify suitable solutions to reduce the tritium concentration inside the water coolant, having in mind the complexity of a water detritiation process.

Keywords: coolant purification system; CPS; distillation column; permeation; primary heat transport system; water-cooled lead–lithium; WCLL; breeding blanket; detritiation system; tritium recovery and removal; chronic and acute leakage; fuel cycle

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1. Introduction

Tritium self-sufficiency and net electricity production are key milestones for the European DEMOnstration fusion power plant named DEMO, guiding the design of two important engineering systems such as the Breeding Blanket (BB) and the Primary Heat Transport System (PHTS). The ambitious scope is to demonstrate the possibility to produce at least the amount of tritium needed to sustain fusion reactions while guaranteeing efficient power removal and sustainable and reliable electricity production.

The Breeding Blanket is the system responsible for the tritium production. Here, neutrons generated in the plasma chamber interact with lithium-producing tritium and deposit thermal energy removed by the primary coolant, flowing in specific cooling tubes within the BB. Thus, the Breeding Blanket operates with a high tritium concentration in the breeder, high temperature, and a large metallic surface for efficient heat removal. In such conditions, tritium permeation towards the primary coolant is enhanced, and once permeated into the PHTS, tritium can migrate towards rooms and, eventually, reach the environment due to further permeation and leaks. A steady tritium concentration within the primary coolant is reached when tritium permeation from the blanket is balanced by the tritium escape and recovery. Three safety-related parameters must be kept under control

and thus are usually being monitored: tritium concentration in buildings that house the primary coolant, tritium inventory in a secondary cooling system, and tritium release from the stack. Limiting such parameters could lead to a less stringent design of downstream tritium removal systems (e.g., dryers and the Exhaust Detritiation System—EDS) and a more reliable and economical operation of the machine.

The mitigation strategy foreseen for DEMO relies on the adoption of anti-permeation barriers for BB walls and Steam Generator (SG) tubes [1,2], and on the Coolant Purification System (CPS) [3,4]. The function of the CPS is to ensure a tritium concentration within the primary coolant below the maximum target value, derived from safety considerations.

At the end of the pre-conceptual design phase, in 2020, two concepts were individuated as promising candidates for the DEMO BB [5]: the Helium-Cooled Pebble Bed (HCPB), a helium-cooled design relying on a solid ceramic lithium–beryllide compound as a breeder and neutron-multiplier [6], and the Water-Cooled Lead–Lithium (WCLL), a water-cooled BB with a liquid lead–lithium alloy as breeder and neutron-multiplier [7]. The present paper is focused on the WCLL concept and, in particular, on the assessment of different strategies that could be adopted for the tritium control in the water primary coolant.

During the pre-conceptual design phase, two strategies were individuated for the water CPS, namely the on-line and the off-line schemes [3]. The former relies on a continuous bypass of a certain fraction of the primary flow rate, which is redirected within the CPS. Once treated, the primary water with a reduced tritium content is returned to the PHTS. The two parameters that characterize such strategy are the fraction of primary flow to be routed into the CPS and its efficiency. On the other hand, the off-line strategy does not treat continuously the primary coolant. In this scheme, the PHTS is supposed to be operated without purification until a certain target tritium concentration in the primary coolant is reached. After that, the whole coolant inventory is discharged and substituted with virgin water. Tritiated water discharged from the PHTS must be treated with a dedicated water detritiation facility. It is worth noticing that in this case, a high tritium removal efficiency must be guaranteed because the water is not recirculated in a closed loop. The characteristic parameters for the off-line strategy are the CPS efficiency and the time before reaching target tritium concentration in the PHTS.

A fundamental parameter that leads the CPS design is the maximum target tritium concentration in the primary coolant. A preliminary assessment of the effect of such a parameter on the CPS size was presented by Narcisi and Santucci [8]. In that study Water Distillation (WD) was selected as reference technology for the water CPS, and the effect of some relevant parameters on the size of the column (CLM) was investigated. Among them, the PHTS target tritium concentration was recognized as a key matter for the CPS design. It is worth emphasizing that such a parameter is still an open issue, and safety considerations and calculations are ongoing.

Starting from the experience on CANDU reactors, the present paper derives considerations on the maximum allowable tritium concentration in the DEMO WCLL BB primary coolant and investigates multiple solutions for a Coolant Purification System able to meet the identified tritium concentration values.

2. Target Tritium Concentration in PHTS

2.1. CANDU Experience

A wide experience in tritium recovery from water derives from the operation of CANDU reactors. In such Nuclear Power Plants (NPPs), most of the tritium inventory is produced by neutron activation of deuterium contained in the heavy water (D_2O) adopted as a coolant and moderator [9], responsible for the production of around 2.4 kCi MWe^{-1} y^{-1} of tritium [10,11]. In these systems, tritium concentration continues to increase towards an equilibrium determined by the tritium production, the tritium decay, and the tritiated heavy water loss. Depending on the reactor and its operation, the theoretical equilibrium tritium activity was evaluated in the range of 65 ÷ 90 Ci kg^{-1} in the moderator and 2 ÷ 3 Ci kg^{-1}

in the coolant [9,11–14], where the difference in tritium concentration is due to the higher residence time for the moderator under neutron flux.

The high pressure (around 8.9 MPa) and high temperature (around 270 °C) of the primary cooling system are the principal contributors to the tritiated heavy water escape in a CANDU reactor (small chronic leakages and occasional spills), accounting for 80 ÷ 90 percent of total loss [9,13]. Nevertheless, considering the different tritium concentrations, the moderator is expected to contribute to 70 ÷ 80 percent of the total tritium emission (airborne and waterborne). On the other hand, the tritium release from the primary cooling system is the most relevant contributor to internal occupational exposures (around 80%), responsible for the increase of the overall maintenance cost due to the requirement for personnel protective equipment and procedures [13].

Over the seven decades of CANDU reactor experience, measures to control tritium escapes have been developed and adopted to reduce both tritium emissions and the dose to workers and the public. The tritium control strategy relies on multiple barriers: tritium recovery, leak tightness, vapor recovery, confinement and local ventilation control, and purge ventilation. While the first three barriers contribute to minimizing both occupational exposures and environmental emissions, the two ventilation systems reduce occupational exposures but do not provide protection against environmental emissions [9].

Despite the high cost, tritium recovery is the most fundamental system available to remove tritium from heavy water and, thus, to reduce consequences of heavy water escapes. For this reason, all the countries involved in the operation of CANDU reactors promoted the construction of Tritium Removal Facilities (TRF) with the aim to minimize tritium inventory within heavy water: Darlington TRF in Canada [15], Wolsong TRF in South Korea [16], and Cernavoda TRF in Romania [17]. Among these, Darlington is the biggest TRF, processing heavy water coming from all the Canadian CANDU with a continuous rate of 360 kg h^{-1} [14].

A maximum tritium concentration target for the primary cooling system is considered 2 Ci kg^{-1} for CANDU [9]. Thus, a consolidated tritium control strategy must rely on the TRF and the vapor recovery dryers. Bonnett et al. investigated the relationship between tritium concentration in the reactor vault, dryer performance, and tritium concentration in primary cooling system. Their work highlights the need to keep tritium concentration below 0.3 Ci kg^{-1} in the coolant to ensure in both chronic and acute release scenarios a tritium concentration in the rector vault lower than 100 MPC(a) (Maximum Permissible Concentration airborne—1 MPC(a) = 10 μCi m^{-3}). Such a threshold is linked to the adoption of cumbersome air-suits during outage activities (concentrations below 100 MPC(a) allow operation with respirators, reducing the overall duration of a planned outage and the consequent occupational dose). The case of 1 Ci kg^{-1} was also studied, showing the possibility to stay below 100 MPC(a) during chronic release but highlighting a tritium vault concentration of around 280 MPC(a) under the acute release scenario [18].

2.2. The Case of DEMO WCLL BB Primary Heat Transport System

The tritium generation rate in DEMO breeding material is around 320 g d^{-1} [3]. Even a small tritium escape (less than 0.1% of blanket production) from lead–lithium toward the primary coolant due to permeation through the BB cooling tubes and channels might lead to very high tritium concentration in the heat transport system. As a yardstick, the tritium production rate in the heat transport system of a typical CANDU 6 is usually less than 40 kCi y^{-1} (i.e., less than 12 mg d^{-1}) and might lead to tritium equilibrium specific activity as high as 3 Ci kg^{-1} [9]. Therefore, considering the operative conditions of DEMO WCLL BB PHTS (15.5 MPa and 295–328 °C, [19]), a CPS appears to be necessary for tritium control in the primary coolant, along with the adoption of anti-permeation barriers [3].

As presented by Narcisi and Santucci [8], the maximum tritium concentration target in the primary coolant is a key parameter for the dimensioning of the CPS main technologies. On the other hand, the evaluation of a consolidated value for the DEMO PHTS is ongoing. Based on the CANDU experience, a target of 2 Ci kg^{-1} was adopted for many years of

operation [9], although the current trend is to reduce it below 1 Ci kg^{-1} [18]. Regarding Fusion Power Plants (FPPs), a large spread of values is found in the literature. For example, 1 TBq kg^{-1} (corresponding to around 27 Ci kg^{-1}) is currently adopted as a reference for Japan's fusion demonstration plant [20], whereas 5 Ci kg^{-1} was used for the pre-conceptual design of the DEMO water CPS [3]. Moreover, the value of 0.015 g m^{-3} (corresponding to around 0.21 Ci kg^{-1}, assuming the average water density of 697.135 kg m^{-3}) was adopted for the estimation of the tritium inventory in the WCLL Breeding Zone (BZ) PHTS [21] during the pre-conceptual design phase of DEMO. Table 1 collects the most relevant values of tritium concentration in the PHTS found in the literature from CANDU experience and Demonstrating FPPs.

Table 1. Tritium concentration values in PHTS.

CANDU Reactor			Demonstrating FPP		
T Generation Rate	T Concentration in PHTS		T Generation Rate	T Concentration in PHTS	
	Actual	Trend		JA-DEMO	EU-DEMO
~0.57 g d^{-1} [18]	2 Ci kg^{-1} taken from [8]	<1 Ci kg^{-1} taken from [17]	~320 g d^{-1} [3]	27 Ci kg^{-1} taken from [19]	5 Ci kg^{-1} taken from [3]

Another crucial aspect for tritium control in the WCLL BB concept is represented by the water leakage because tritium permeated from BB to the PHTS is mainly oxidized into HTO. Thus, the primary coolant acts as a sink for tritium, avoiding further permeation towards buildings. Nevertheless, primary coolant leakages represent a significant contribution to the tritium escape. Leakages are classified as chronic and acute: chronic leakages are those which are normally expected from a particular area of the tokamak building, whereas acute escapes occur with a higher rate than the chronic ones and are less quantifiable than the chronic releases. Acute leakages can be due to equipment failures, spills, etc.

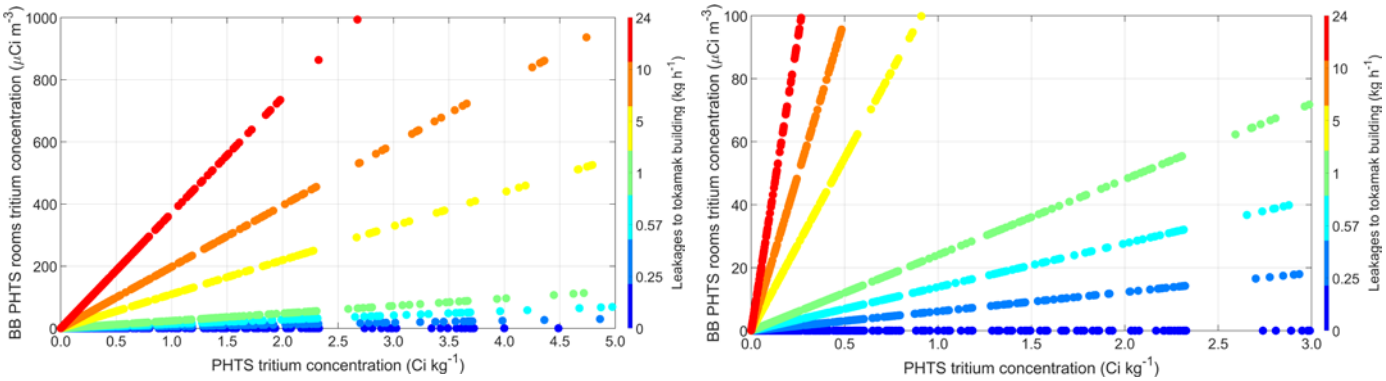
According to the Canadian CANDU experience [9], 14 kg h^{-1} is the expected water escape rate for a reactor unit, combining chronic and acute leakages. Among these, around 80% are related to the primary cooling system. Most of these releases are due to pressure tubes' end fittings, not present in an FPP, whereas only 1% ÷ 4% are related to component leakages (e.g., valves fittings and flanges). Furthermore, 1% ÷ 2% of the total is due to permeation of deuterium through the steam generator tubes into the secondary system. It is estimated that a maximum heavy water loss towards the secondary system is 0.15 kg h^{-1}, including tube leakages [9]. Looking at the operative conditions of DEMO WCLL BB PHTS, it is also convenient considering the PWR experience. Typical leakages of PWRs are in the order of 0.02 gpm (corresponding to 4 ÷ 5 kg h^{-1}) [22], whereas the chronic release from steam generator to secondary system is usually kept below 1 gal d^{-1} (around 0.15 kg h^{-1}). Based on the literature review and on engineering judgments, 0.5 kg h^{-1} could be considered a realistic leakage rate from DEMO WCLL BB PHTS towards classified rooms, considering that pressure tubes' end fittings and refueling operations, responsible for most of the leakages in NPPs [9,22], are not foreseen in future FPPs. Furthermore, according to the CANDU and PWR experience, the value of 0.15 kg h^{-1} is assumed for chronic loss from the primary to the secondary system. It is worth emphasizing that such assumptions do not originate from a quantitative evaluation performed on DEMO WCLL BB PHTS. They are derived from the NPPs experience and are considered only for a preliminary evaluation of the water CPS since the comprehensive analysis for releases in the DEMO WCLL BB PHTS is not yet available [21].

In order to evaluate the relationship between the tritium concentration in the primary coolant, in the PHTS rooms, and in the PCS, a lumped-parameters dynamic tritium model was developed and was implemented in the MATLAB-SIMULINK environment. The model solves the tritium mass balance of all the systems involved in the tritium pathway from the PHTS to the environment (i.e., PHTS, CPS, dryers, tokamak and tritium buildings, and PCS), imposing the following boundary conditions: the tritium permeation rate from the breeding zone, the CPS mass flow rate, the leakages from the PHTS to the PCS, the

leakages towards the BB PHTS rooms, the anti-permeation barriers in the SG, and dryers' efficiency. Except for the latter parameter, all the boundary conditions are varied in the sensitivity analysis, whereas an efficiency of around 100% is assumed for the dryers. The air flow rate routed into dryers is calculated by the model to ensure a fixed dew point into the tokamak and tritium buildings. The results obtained are representative of a steady-state concentration of tritium inside the plant, thus resulting in conservative estimations.

The first figure of merit considered in the analysis is the steady-state tritium concentration in the BB PHTS rooms within the tokamak building, obtained by performing a set of parametric analyses by varying the aforementioned parameters. Each point depicted in the following pictures is representative of a single steady-state solution of the parametric analysis.

In Figure 1, the tritium concentration in the BB PHTS rooms is shown for different leak rates from the PHTS to the tokamak building as a function of the tritium concentration in the primary coolant. The PHTS rooms' concentration is expressed as μCi m^{-3}. For comparison, 1 MPC(a) corresponds to 10 μCi m^{-3} (100 MPC(a) is the threshold for the adoption of cumbersome air-suits during outage activities) and 1 Derived Air Concentration (DAC) of HTO is about 8 μCi m^{-3} (concentrations below 1 DAC allow operations without respiratory protection). Figure 1 shows that, under the assumed tritium concentration in the coolant, tritium inventory in the PHTS rooms is kept well below the threshold of 100 MPC(a), except for the two cases of higher leak rates, allowing operations of qualified personnel with respirators. If the goal is to limit the concentration in the PHTS rooms to below 1 DAC, Figure 1b shows that a concentration lower than 1 Ci kg^{-1} is required in the primary coolant if a realistic leak rate of 0.57 kg h^{-1} is considered from the PHTS to the tokamak building. The target PHTS concentration reduces to 0.3 Ci kg^{-1} assuming a leak rate of 1 kg h^{-1}.



(**a**) (**b**)

Figure 1. Tritium concentration in BB PHTS rooms for different leak rates as function of tritium concentration in primary coolant: (**a**) full range between 0 and 1000 μCi m^{-3}; (**b**) detail for small tritium concentration values.

The second figure of merit considered in the analysis is the steady-state tritium concentration in the PCS, due to leaks and permeation from the primary to secondary system through the SG.

It is worth pointing out that although the parametric analysis is based on the variation of several parameters, the concentration within the BB PHTS rooms is uniquely determined by the leakages from the primary circuit and the tritium concentration in the PHTS. Concerning the tritium concentration in the PCS, it is affected as well by only two variables: the leakages between the primary and the secondary system and the tritium concentration in the PHTS. This latter variable, although not directly imposed in the parametric analyses, is obtained by combining the various leakages and the mass flow rate of the CPS, and it is relevant to the tritium concentration both in PCS and in the BB PHTS rooms due to the particular form of the governing equations.

As for any NPP, the DEMO PCS is mostly located in a non-nuclear building, and it is usually designed as non-nuclear system. Such a requirement poses a limit in terms of radioactive inventory (not only tritium) of the secondary system. As a matter of fact, in accordance with French regulations for nuclear pressure equipment (order of 12 December 2005 replaced by the order of 30 December 2015 concerning nuclear pressure equipment, known as the "ESPN order"), pressurized equipment is classified as nuclear when, following a failure, it releases an activity higher than 370 MBq. In the case of the DEMO PCS, assuming a deaerator of about 400 m^3 (half-filled), a concentration of around 50 μCi kg^{-1} (red dashed line in Figure 2) would lead to nuclear classification (it must be underlined that actual tritium activity is divided by a factor 1000 when performing ESPN classification). As shown in Figure 2, assuming a realistic leak rate from PHTS to PCS of 0.17 kg h^{-1}, a concentration of 2 Ci kg^{-1} is admissible in the primary coolant. The increase in the leak rate has a dramatic effect on the allowable tritium concentration in the PHTS.

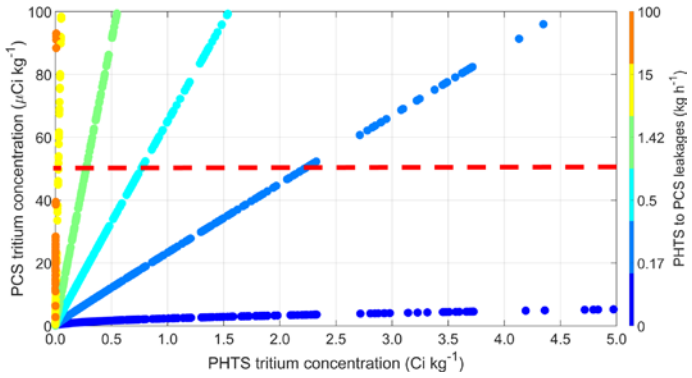


Figure 2. Tritium concentration in PCS for different leak rates from primary to secondary system, as a function of the tritium concentration in primary coolant.

3. The Water Coolant Purification System

This section presents a discussion on the available strategies to cope with the PHTS requirements and the preliminary sizing of the main technologies of the DEMO WCLL BB Coolant Purification System.

The CPS belongs to the Outer Loop (OUTL) of the DEMO Fuel Cycle [23]. Its main interfaces are the Chemical and Volume Control System (CVCS) of the PHTS and the Water Detritiation System (WDS) [8]. A small fraction of the primary coolant flow rate is redirected from the CVCS into the CPS. Once treated, water with a reduced content in tritium is sent back to the CVCS, whereas a small portion of the flow rate, enriched in tritium, is delivered to the WDS.

The parameters that mainly characterize performance and operation of the CPS are the efficiency, expressed as the ratio between the difference of tritium concentration in inlet and outlet CPS streams, the tritium concentration in water feeding the CPS, and the flow rate that must be routed into the CPS to achieve the target tritium concentration in the primary coolant. Once defined, the CPS efficiency and, given a maximum target concentration in the PHTS, the CPS flow rate can be derived from the tritium mass balance [24], in which the source term is the tritium permeation rate from the BB to the PHTS. The study presented in this paper relies on the most recent outcomes of the tritium permeation analysis [2] that updated the boundary conditions assumed in the pre-conceptual design phase [3]. In a reference scenario relying on anti-permeation barriers with a Permeation Reduction Factor (PRF) equal to 100 (PRF is defined as the ratio between the permeation rate with bare walls and the permeation rate with anti-permeation barriers) and on a Tritium Extraction and Removal system (TER) with an efficiency of 80%, the permeation rate from breeder to BZ and First Wall (FW) PHTSs is calculated as 0.42 g d^{-1} and 9.28 mg d^{-1}, respectively. It is worth pointing out that such permeation rates do not depend on the tritium concentration in the primary coolant because, once permeated, most of the tritium is trapped in HTO and

does not contribute significantly to the increase of HT partial pressure within the coolant [3]. Thus, such boundary conditions are valid for each PHTS tritium concentration.

Assuming the aforementioned boundary conditions and a CPS efficiency equal to 100% (the whole tritium content into the CPS feeding stream is recovered), the needed CPS flow rate (F) is expressed as a function of the maximum tritium concentration target in PHTS (x_F) in Figure 3.

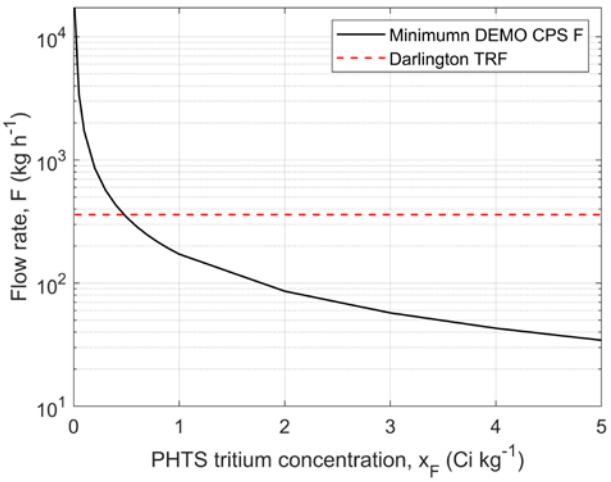


Figure 3. CPS feeding flow rate as a function of the PHTS maximum tritium concentration target for a source term of 0.43 g d^{-1} and a CPS efficiency of 100%.

As shown in Figure 3, the higher the CPS feeding flow rate, the lower is the tritium concentration into the primary coolant. In addition, Figure 3 provides a useful comparison with the throughput of the Darlington TRF (360 kg h^{-1}), expressed by the red dashed line. It is worth emphasizing that a TRF is a highly energy-demanding system and the Darlington TRF is the largest detritiation facility worldwide. Its throughput is considered a maximum limit for the DEMO water CPS, determining a minimum achievable tritium concentration target of 0.5 Ci kg^{-1} (see Figure 3), regardless of the technology adopted for tritium recovery.

The Water Distillation is currently considered the most promising technology for the DEMO water CPS because of its simplicity and safety characteristics [8]. The main drawback is a relatively low efficiency (60% ÷ 70%), although it does not represent a big issue for the on-line strategy. As a matter of fact, the on-line CPS works as a closed loop with PHTS, meaning that not all the tritium content must be recovered but only the amount needed to keep the target concentration in PHTS. On the other hand, the lower the efficiency, the higher is the required CPS flow rate.

A sensitivity analysis was carried out by Narcisi and Santucci [8], fixing some relevant operative conditions of the system (i.e., WD operative pressure of 10 kPa, tritium concentration in a WDS stream of 100 Ci kg^{-1}, and a PRF applied to BB walls of 100). In that study, the authors performed a preliminary sizing of the column considering a full power steady state operation of DEMO, corresponding to an extremely conservative scenario with an availability of 100%. As reported by Federici et al. [25], current DEMO design assumptions consider availability of the plant relatively low for the initial years of operations (first DEMO operating phase), which increases to about 30% or more in the second DEMO operating phase. For this reason, in order to consider a more realistic, but still conservative, operational schedule, the present design activity is based on an ideal sequence of nine 70-day plasma operations, five 7-day ex-vessel maintenance, and three 4-month in-vessel maintenance. From the point of view of the DEMO plant, such a schedule can be considered a best-estimate operation with around 65% availability (unscheduled maintenance is not considered). Referring to the CPS, it will operate continuously regardless of the DEMO operational schedule. Therefore, during maintenance, the CPS will recover tritium from the

primary coolant without (or with a reduced) tritium permeation from BB, since the tritium generation rate is null (or negligible). Thus, the higher the plant availability, the lower is the period in which the PHTS tritium inventory can be reduced.

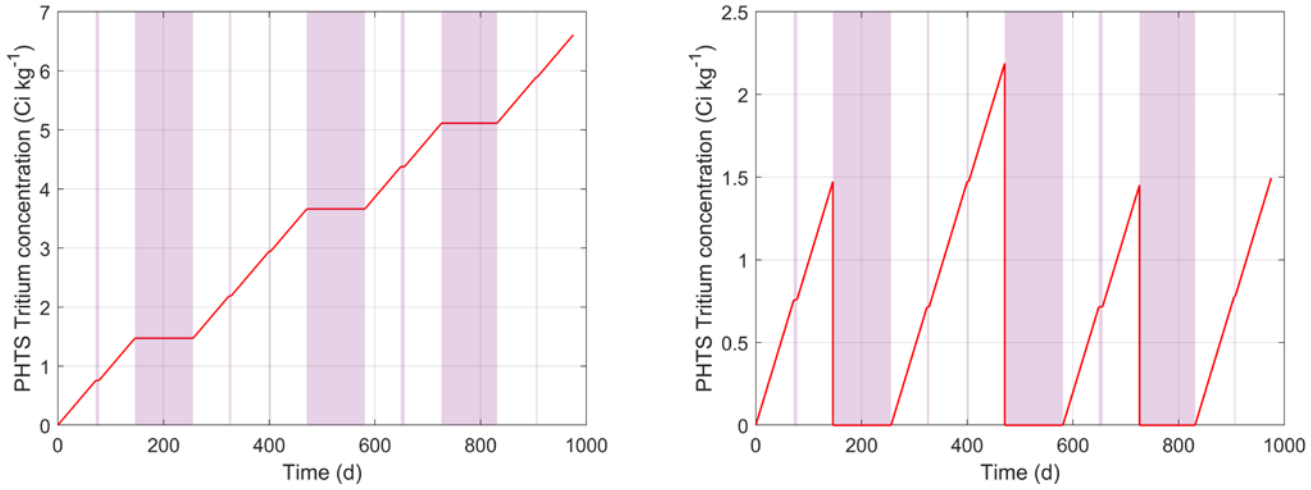
In the following subsections, the impact of the plasma operational schedule on the CPS sizing is analyzed for three relevant configurations: on-line, off-line, and hybrid strategy. For this purpose, a dynamic modeling of the WD CLM has been developed in the MATLAB environment. The model solves the material balance equations in all the stages of the column, assuming the vapor–liquid equilibrium of the binary mixture involved in the process. A detailed description of the model is presented in [8]. Furthermore, the interface between CPS and PHTS was modeled, assuming the following main boundary conditions: the BB permeation rate is equal to 0.43 g d^{-1} during plasma operations and null during maintenance, and the PHTS tritium losses for leakages and permeation are neglected. Simulations start with virgin water in which tritium concentration increases as a result of the unbalance between the source term (i.e., the BB tritium permeation) and sink term (i.e., the CPS tritium removal) that tends to zero as the target tritium concentration in coolant is approached. Dynamic modeling of the column allows a more realistic simulation evaluating the CPS efficiency per each time step, depending on the feeding conditions [8].

3.1. Off-Line Strategy

In the off-line strategy, the PHTS does not relies on a continuous treatment of the primary water and tritium inventory within the coolant increases until the maximum target tritium concentration is reached. Then, the whole water inventory of the PHTS is discharged and substituted with virgin water. The drained tritiated water is treated in a dedicated facility to reduce the tritium content and to allow the reuse as virgin water.

Figure 4a shows the case in which the PHTS is operated without the CPS over the whole plasma operative sequence (around 2.8 years). Maintenance periods are highlighted with purple background (please refer to the online version of the paper for colored figures). Such a solution could be convenient if it is guaranteed a certain period of operation before the water discharge. In the pre-conceptual design, a period of one year was supposed satisfactory [3]. Furthermore, it could be convenient to foresee the water discharge during an in-vessel maintenance to not affect the plant availability. Based on the considered plant operative schedule, the off-line strategy is unsuitable for a target concentration below 2 Ci kg^{-1}. Indeed, a concentration of around 2.2 Ci kg^{-1} is reached in the PHTS after 324 days from the beginning of the operations, just before the second ex-vessel maintenance. Increasing the limit up to 4 and 5 Ci kg^{-1} would allow the water discharge during the second and the third in-vessel maintenance, respectively, allowing only a single water discharge for the first DEMO operating phase. It is worth emphasizing that the throughput of the off-line CPS must ensure the reuse of the treated water before the following water discharge. This means that a single water discharge would considerably relax the CPS requirements and, thus, the size.

In Figure 4b, an example of the off-line methodology is presented, considering three water discharges during the three in-vessel maintenance. The maximum tritium concentration in the primary coolant is kept below 2.5 Ci kg^{-1} over the whole first operative phase. To accomplish this with such an operation, a detritiation facility with high separation efficiency (e.g., the Combined Electrolysis and Catalytic Exchange—CECE) working with a throughput of 30 kg h^{-1} is needed, along with a water reservoir system for the whole primary coolant inventory (722 m^3 at 15.5 MPa and 295 ÷ 328 °C, [19]). Such a big water reservoir represents the main drawback of the off-line strategy.



(**a**) (**b**)

Figure 4. Increase of tritium concentration within primary coolant under assumed plasma operative sequence: (**a**) without CPS; (**b**) CPS off-line strategy, the whole PHTS water inventory is replaced with virgin water during in-vessel maintenance.

3.2. On-Line Strategy

In the on-line strategy, a portion of the primary coolant is continuously routed into the CPS and the feeding flow rate depends on the efficiency of the detritiation system and on the maximum tritium concentration target (Target x_F in Table 2) in the PHTS. This latter parameter guides the sizing procedure of the WD CLM [8], based on the assumption to ensure the limit of concentration in the primary coolant under the full power steady state operation. Once the main dimensions of the column are defined, the operation under the assumed plasma sequence is simulated with the dynamic model, providing information about the tritium concentration in the PHTS (Maximum x_F in Table 2), the tritium inventory in the WD column, and the power consumptions of the CPS main components (i.e., reboiler and condenser). Based on the overview presented in Section 2, the analysis was performed for six values of the maximum tritium concentration target (from 0.5 to 5 Ci kg^{-1}) and the main outcomes are summarized in Table 2. In practice, the WD CLM is dimensioned for the given target x_F, but it is operated with a maximum x_F resulting from the considered plasma scenario operation. Per each case, the interface with WDS was fixed to 1.72 kg h^{-1} at 100 Ci kg^{-1}, balancing the BB tritium permeation rate.

Table 2. Main features of CPS components for different tritium concentration targets.

Target x_F	F	Number of CLMs	H_{CLM}	D_{CLM}	Maximum x_F	T Inventory	RBL Power	CND Power
Ci kg^{-1}	kg h^{-1}	–	m	m	Ci kg^{-1}	g	MW	MW
5	45	1	11.55	0.96	3.1	0.825	0.613	0.616
4	65	1	10.25	1.16	2.7	1.161	0.884	0.889
3	80	1	11.77	1.29	2.1	1.43	1.09	1.1
2	110	1	14.17	1.51	1.5	1.975	1.5	1.51
1	200	2	18.64	1.45	0.9	3.529	2.75	2.78
0.5	360	3	30.42	1.6	0.5	6.481	5.02	5.09

Per each target x_F, the selection of the feeding flow rate (F) derives from an optimum between the height (H_{CLM}) and the diameter (D_{CLM}) of the WD CLM: the increase of F allows reducing column height for a certain detritiation target, while requiring larger diameters to cope with pressure drop specifications of the packing. Thus, an optimum in terms of packed volume exists and the design approach relies on the minimization of this parameter, except for the 0.5 Ci kg^{-1} case, whose optimum falls on a flow rate higher than

the Darlington TRF limit. For this target x_F, 360 kg h^{-1} was considered, involving much higher columns.

The selected packing for the WD CLM is the CY Gauze Packing by Sulzer [26], widely used for WD technology [27–29]. In order to cope with the maximum diameter supplied by Sulzer for this packing (i.e., 1.8 m), more parallel columns are needed for higher F (i.e., 200 and 360 kg h^{-1}, see Table 2). The size of the column affects not only the encumbrance and the cost of the unit but also the tritium inventory in the column. It is worth mentioning that such inventory is mainly located at the bottom of the column, where highly tritium concentrated water (100 Ci kg^{-1}) is collected. Thus, the height of the column has less effect than the diameter.

A fundamental figure of merit is the power consumption of the system. The OUTL is the highest energy-demanding system of the DEMO fuel cycle and, in the BB WCLL variant, the CPS is one of the most energy-demanding technologies of the OUTL. In this view, reduction of the CPS power consumption could lead to an appreciable benefit in terms of thermodynamic efficiency of the machine. The CPS power consumption is mainly due to the reboiler (RBL) and the condenser (CND). It is worth emphasizing that energy consumption is not a relevant issue for the RBL because its low operative temperature (saturation temperature for water at 10 kPa is 45.81 °C) allows the recovery of waste heat from other systems (e.g., the CVCS, see [8]). Nevertheless, the size of the reboiler could be an issue in terms of tritium inventory since the bottom stream exits the column at 100 Ci kg^{-1}. A small fraction of this stream is sent to the WDS (1.72 kg h^{-1}), whereas the rest of the flow rate is boiled and sent back to the column. Thus, the reboiler works continuously with a tritium concentration equal to 100 Ci kg^{-1} affecting the whole inventory of the CPS. For example, for the case of x_F equal to 5 Ci kg^{-1}, it is estimated that the reboiler contains around 1.25 g of tritium [8], which is higher than the inventory of the WD CLM.

Table 2 also reports the maximum x_F achievable during the considered DEMO operating schedule. As mentioned, the CPS is supposed to work also during maintenance, when tritium permeation decreases considerably, allowing the reduction of PHTS tritium inventory.

For the cases between 5 and 2 Ci kg^{-1}, it leads to a final concentration lower than the maximum target within the PHTS. An example of the evolution of PHTS tritium concentration is presented in Figure 5a for the target case of 5 Ci kg^{-1}, where the tritium removal capability is appreciable by the comparison between x_F (red line) and the tritium concentration in the distillate stream x_D (black line), sent back to PHTS. On the other hand, when the maximum target is lower (i.e., 1 and 0.5 Ci kg^{-1}), the tritium concentration approaches the design value before the in-vessel maintenance, as shown in Figure 5b for the target case of 1 Ci kg^{-1}.

A partial hybrid solution was assessed combining the on-line strategy with the off-line methodology presented in Figure 4b. In this configuration, primary water is continuously routed and treated in the CPS, but after each in-vessel maintenance the whole PHTS water inventory is discharged and substituted with virgin water. As shown in Figure 5a (dashed lines for partial hybrid strategy), the partial hybrid configuration allows reduction of the maximum x_F reached during the first DEMO operative phase from 3.1 to 1.8 Ci kg^{-1}, operating the same on-line WD column. The drawback of such a solution is the need for a water reservoir for the whole PHTS water inventory and the need for an additional highly efficient detritiation facility processing 30 kg h^{-1} of medium tritiated water (below 5 Ci kg^{-1}). Furthermore, such a solution results are less efficient when the maximum target is lower than 2 Ci kg^{-1}, as shown in Figure 5b, where the difference between the on-line and partial hybrid strategies is negligible.

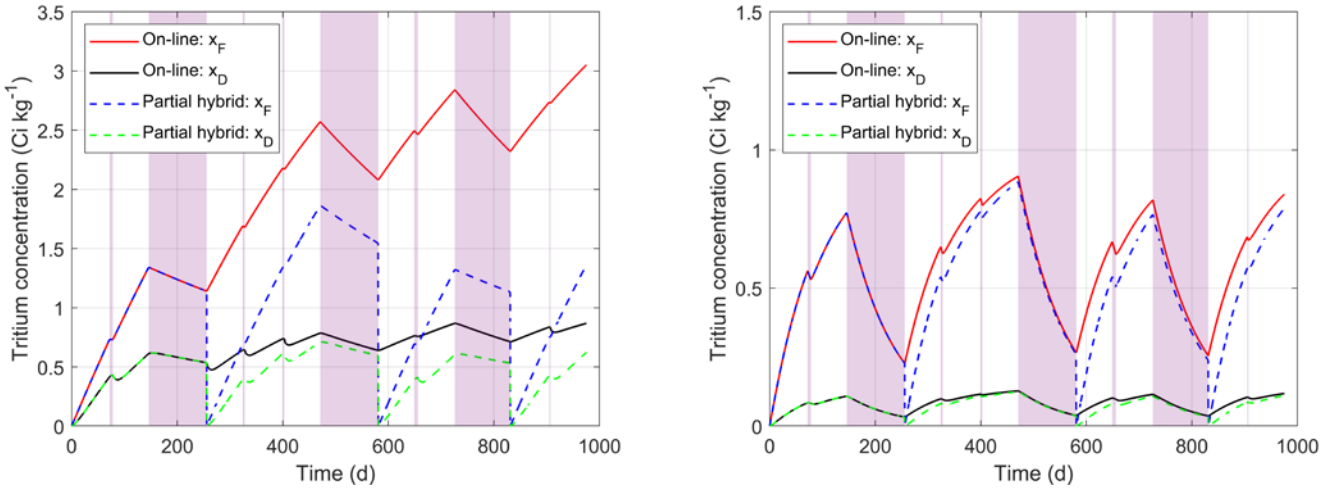


Figure 5. Increase of tritium concentration in primary coolant (x_F) and in the distillate stream (x_D) under assumed plasma operative sequence for the on-line (solid lines) and the partial hybrid strategy (dashed lines): (**a**) maximum target tritium concentration in PHTS of 5 Ci kg^{-1}; (**b**) maximum target tritium concentration in PHTS of 1 Ci kg^{-1}.

3.3. Full Hybrid Strategy

Aiming at reducing the CPS energy consumption and at allowing the possibility to decrease tritium concentration in the primary coolant below 0.5 Ci kg^{-1}, a full hybrid solution between on-line and off-line strategies was considered. The flow diagram of this configuration is presented in Figure 6.

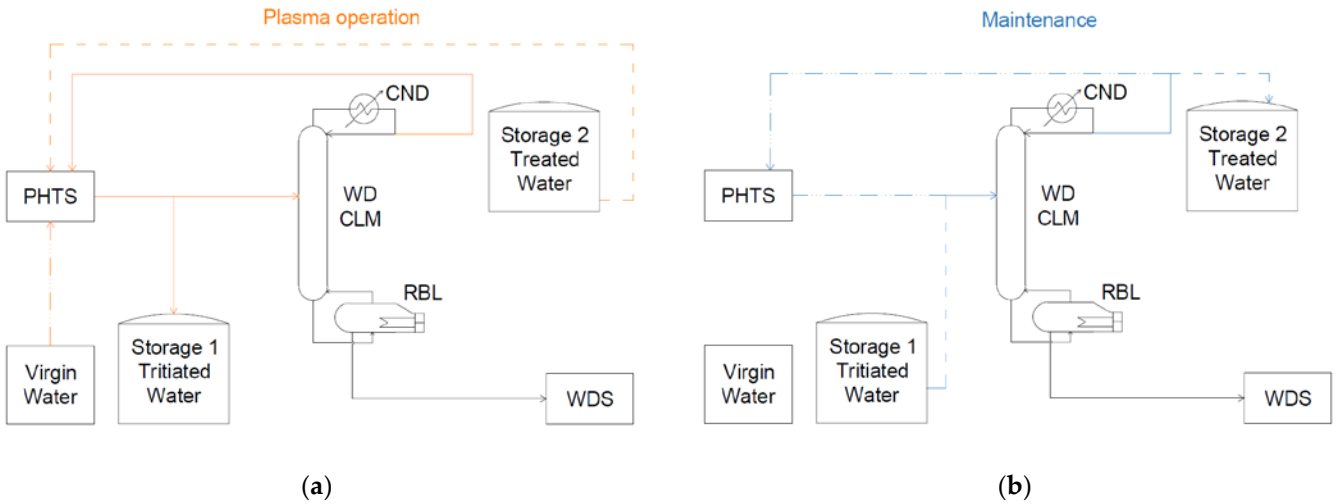


Figure 6. The water CPS full hybrid strategy: (**a**) flow diagram during plasma operation; (**b**) flow diagram during maintenance.

The CPS consists of a WD column, sized for a fixed feeding flow rate (of 45 to 360 kg h^{-1}, see Table 2), and of two storage systems: one for tritiated water coming from the PHTS (Storage 1 in Figure 6) and one for treated water from the WD CLM (Storage 2 in Figure 6). During plasma operation (see Figure 6a), a certain portion of the primary coolant flow rate, higher than the WD design value, is taken from the PHTS and split in two streams: one, corresponding to the WD design feeding flow rate, is sent directly to the column for detritiation, whereas the rest is sent to Storage 1. Once treated in the column, the distillate flow rate is sent back to the PHTS with a reduced amount of tritium, whereas

the flow rate sent to Storage 1 is balanced with the treated water from Storage 2, if available, or with virgin water from the network. During maintenance (see Figure 6b), the CPS is decoupled from the PHTS, tritiated water from Storage 1 is treated in the column, and the distillate is collected in Storage 2 for reuse in the following plasma operation. Depending on the inventory of Storage 1 and on the WD throughput, the whole tritiated water contained in Storage 1 could be treated before the end of an in-vessel maintenance. In this case, the PHTS is coupled again with the CPS and a throughput equal to the WD design point is withdrawn and treated in the column, reducing the PHTS tritium inventory until the end of the maintenance.

Such a system ensures a higher tritium removal rate than the homologous on-line strategy (with the same column and, thus, the same power consumption), and in fact it is equal to the amount of the tritium removed in the bottom stream (to WDS) plus the amount sent to Storage 1. The WDS requirement is also fulfilled with a continuous throughput of 1.72 kg h^{-1} at around 100 Ci kg^{-1}. The main drawback is the presence of two storage systems with the consequent higher tritium inventory of the whole CPS. The volume of the two storages is evaluated assuming water at 0.1 MPa and 25 °C.

Table 3 summarizes the main outcomes of the analysis. The design procedure starts by fixing a target tritium concentration in the primary coolant, ranging between 0.2 and 2 Ci kg^{-1} (on-line strategy results more suitable for higher x_F). The size of the WD column is selected from the ones dimensioned for the on-line strategy, considering a design x_F higher than the maximum tritium concentration target and keeping in mind that lower design x_F value leads to higher energy consumption. Thus, the WD feeding flow rate (F) is fixed and the rest of the flow withdrawn from the PHTS is sent to Storage 1 (see Table 3). Therefore, the amount of coolant entering the CPS is given by the one that feeds the WD CLM plus the one that goes to Storage 1.

Table 3. Sizing and operation of full hybrid strategy for the water CPS.

Target x_F	WD x_F Design	F	Storage 1 Feeding	RBL Power Saving	CND Power Saving	Storage 1 Volume	Storage 2 Volume	Storage 1 Max Tritium	Storage 2 Max Tritium
Ci kg^{-1}	Ci kg^{-1}	kg h^{-1}	kg h^{-1}	MW	MW	m^3	m^3	g	g
2	5	45	65	0.887	0.894	605	118	98	6.5
2	4	65	45	0.616	0.621	213	194	35	17.4
2	3	80	30	0.41	0.41	136	135	19.3	7.4
1	2	110	90	1.25	1.27	450	300	47	9
0.5	2	110	250	3.52	3.58	3000	300	160	7
0.5	1	200	160	2.27	2.31	800	550	42	5.5
0.3	0.5	360	214	–	–	1000	1000	30	1.3
0.2	0.5	360	500	–	–	4500	1000	95	0.9

As presented in Table 3, the full hybrid strategy allows a conspicuous power saving, evaluated as the difference between the power consumption of the on-line and full-hybrid strategies for the same target tritium concentration: lower is the maximum allowable tritium concentration in the primary coolant, and higher is the power saving. On the other hand, the lower target x_F needs a larger reservoir because of the higher Storage 1 feeding flow rate. The full hybrid strategy also allows reaching maximum tritium concentration in the primary coolant lower than 0.5 Ci kg^{-1}, while keeping the WD throughput within the limit of 360 kg h^{-1}. Nevertheless, such a requirement implicates a high power consumption (around 5 MW for both the RBL and CND) and very large storage systems, although the tritium inventory is not highly influenced due to the low concentration in the streams.

It is worth emphasizing that the values summarized in Table 3 represent the maximum for the water and tritium inventory in the storage systems, which work under alternative filling and draining. An example of such operations is shown in Figure 7, for the case of target x_F equal to 1 5 Ci kg^{-1} and WD design point of 2 Ci kg^{-1}. In general, water inventory, and thus tritium content, increases in Storage 1 during the plasma operation, with tritiated water coming from the CVCS, whereas treated water from Storage 2 is used to balance the PHTS water discharge.

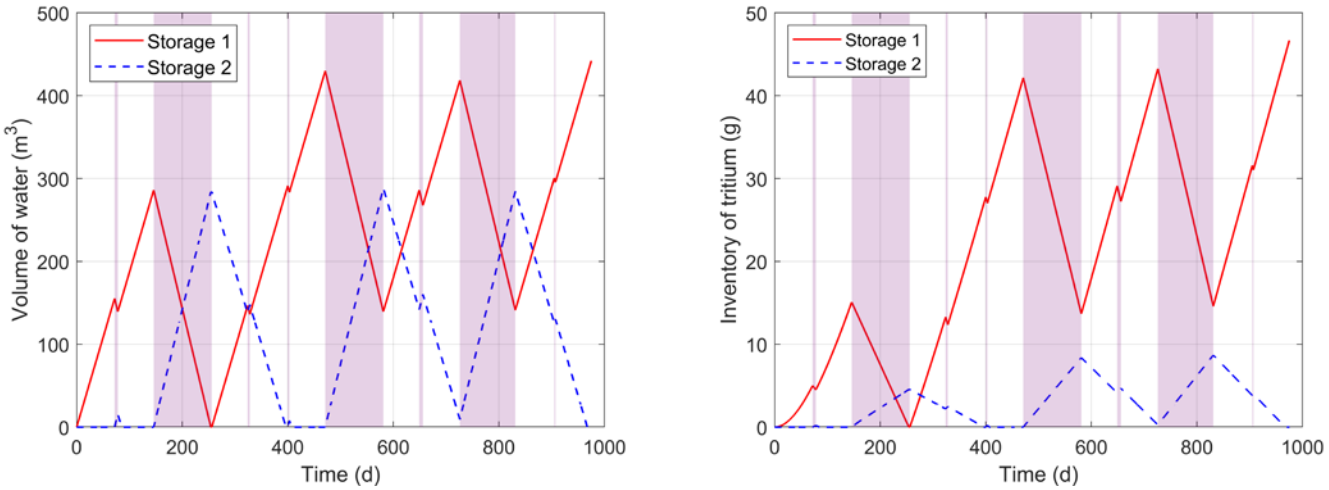


Figure 7. Operation of full hybrid water CPS under the assumed plasma operative sequence: (**a**) trend of water inventory into Storage 1 and Storage 2; (**b**) trend of tritium inventory into Storage 1 and Storage 2.

For the sake of comparison, it is worth considering that the complete drainage of the PHTS in the off-line strategy would require a tritiated storage system of around 510 m^3 under the same storage conditions (i.e., 0.1 MPa and 25 °C) with a maximum tritium inventory of 115 g, assuming the procedure shown in Figure 4b. Furthermore, a storage for the treated water is also needed, with a capacity of 510 m^3 and a negligible tritium content, considering a TRF with around 100% efficiency.

4. Conclusions

At the end of the European DEMO pre-conceptual design, tritium removal from the primary coolant was recognized as a key concern for the WCLL BB concept [2]. Two approaches were individuated for the CPS: the on-line and the off-line strategies [3]. In this work, the possibility to use such strategies was further investigated, coupling the methodologies with the WD technology and with a proposed DEMO operative sequence.

The work started with a literature review of the CANDU experience in the management and treatment of tritium, focusing on the maximum tritium concentration target in primary coolant and on the water leak rates, relevant for tritium emissions and the dose to workers and the public. Then, a first evaluation of the maximum tritium concentration target for DEMO PHTS was performed, posing emphasis on the derived tritium concentration in the tokamak building and in the PCS. A preliminary range for the PHTS tritium concentration was identified in 0.2 ÷ 2 Ci kg^{-1}, depending on the leak rate and on the admissible limit of tritium inventory in the tokamak building.

Based on these outcomes, a design procedure for the water CPS was proposed, relying on a dynamic modeling of the WD column and on the assumption of a DEMO operative sequence. Although providing considerable simplification in the tritiated water management, the off-line strategy highlighted some limitations in keeping tritium concentration in the PHTS below 2 Ci kg^{-1}, together with the concern of tritiated water storage. On the other hand, the on-line strategy allows lower tritium concentration targets, although the high energy consumption could be an issue. With the purpose to reduce the energy consumption and to allow the possibility to reach a lower tritium concentration in the primary coolant (until 0.2 Ci kg^{-1}), a hybrid solution was proposed and assessed as the most viable strategy if a tritium concentration lower than 1 Ci kg^{-1} must be ensured. However, this choice implies a non-negligible amount of tritiated water to be stored in dedicated areas. Further assessments and safety evaluations are, thus, encouraged to check the full viability of this strategy.

The present activity has provided useful information in the definition of the main parameters affecting the water CPS sizing. The finalization of the CPS conceptual design will benefit from the consolidation of interfaces and requirements concerning, especially, the information related to the maximum tritium concentration inside the primary coolant as well as the target tritium concentration in the PHTS rooms.

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