Activation characteristics of the fusion power plant coolants He, water, Pb-Li and aspects of tritium extraction techniques

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Abstract. This paper presents the activation characteristics of the helium, water and Pb-Li coolants when employed in the HCPB, DCLL and WCLL DEMO power plants. Related activation analyses were performed on the basis of coupled MCNP transport and FISPACT inventory calculations using 3D DEMO models developed within the PPPT programme. The He coolant shows a very low activity level with no emission of gamma radiation. The water coolant shows a very high activity and gamma radiation level during plant operation and shortly after shut-down due to the radionuclide ^{16}N generated from ^{16}O. This results in a permanent γ-radiation source in the entire water loop during plant operation. The Pb-Li coolant acts also as breeder material and thus shows a high activity level due to the tritium generated. Without considering tritium, the activation level is significantly lower and is dominated by Pb activation products. The generation (and potential release) of ^{210}Po is of serious concern requiring possibly the continuous extraction of the Bi produced from the irradiated Pb-Li. Furthermore some aspects of the tritium extraction from the considered coolants are presented. Tritium will be produced in large amounts in the Pb-Li coolant which serves also as tritium breeding material. Small quantities may be present in the helium or the water coolant due to permeation processes. A preliminary evaluation as far as tritium permeation in the WCLL, HCLL, HCPB and DCLL is concerned is introduced. A critical review of the technologies that have the potential for the industrialization at DEMO conditions and the features of the implementation in the coolant systems is presented as well.

1. Introduction

Helium gas, water and the liquid metal Pb-Li are the primary coolants considered for the heat extraction in future Fusion Power Plants (FPP). Within the European Power Plant Physics and Technology (PPPT) programme of the EUROfusion Consortium [1], four blanket concepts utilizing these coolants are under development for a DEMOnstration power plant: the Water-Cooled Lithium Lead (WCLL), the Helium Cooled Pebble Bed (HCPB), the Helium Cooled Lithium Lead (HCLL) and the Dual Coolant Lithium Lead (DCLL) [2].

The activation of the coolants by neutron induced activation reactions on coolant constituents, impurities and possible corrosion products affects the safety during operation and maintenance of the plant as well as the processing and management of the activated materials including a possible re-use or the final disposal in a repository. It is thus required to have an assessment of the activation inventories produced in the FPP as well as the resulting radiation hazard potential.

The first part of the paper is devoted to the activation characteristics of the helium, water and Pb-Li coolants when employed in the HCPB, HCLL, DCLL and WCLL DEMO power plants. The related activation analyses were performed on the basis of coupled MCNP transport and FISPACT inventory calculations using 3D DEMO models developed for the blanket design and optimisation analyses within the PPPT programme. Activation results are reported and discussed including possible measures to reduce the radiation hazard.

The second part of the paper addresses aspects of the tritium extraction from the considered coolants. Tritium will be produced in large amounts in the Pb-Li coolant which serves also as tritium breeding material. In the helium or the water coolant, small amounts of tritium may be present, mainly due to permeation processes. A preliminary evaluation of the extraction techniques is provided as far as tritium permeation in the WCLL, HCLL, HCPB and DCLL is concerned. The paper concludes with a critical review of the technologies which show the potential for the industrialization at DEMO conditions and the features of the implementation in the coolant systems.

2. Coolant activation characteristics

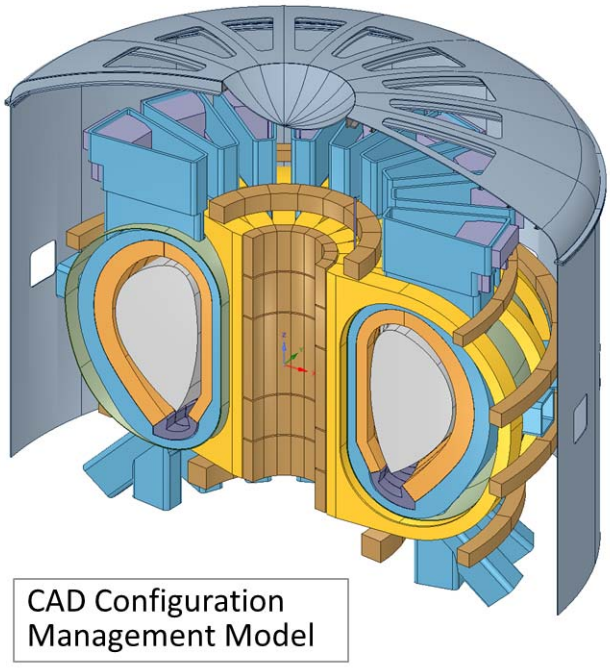
The activation characteristics are assessed for the coolants helium gas, water and the liquid metal eutectic alloy Pb-15.7Li as employed in the designs of the HCPB, WCLL and DCL DEMO fusion power plants developed within the PPPT programme.

2.1 DEMO blanket concepts

The development of the EU breeder blanket concepts for DEMO is conducted within the PPPT programme of EUROfusion. The considered blanket concepts include three liquid metal based blankets, utilizing the eutectic alloy Pb-15.8Li as breeder material (HCLL, WCLL, DCLL) and a solid breeder blanket (HCPB) with Li_4SiO_4 pebbles as breeder and beryllium as neutron multiplier. The HCPB and HCLL blankets employ high pressure helium gas (8 MPa) as coolant, the WCLL blanket utilizes water at 15.5 MPa for the cooling. The DCLL blanket concept, on the other hand, employs helium (8 MPa) for the cooling of the blanket steel structures, including the highly loaded first wall, while the Pb-Li breeder is directly cooled by circulating the Pb-Li liquid metal to the heat exchanger. In this work, we consider the HCPB, the WCLL and the DCLL for the activation analyses of the helium, water and Pb-Li coolants, respectively.

Fig. 1 shows a CAD model of DEMO, along with the main reactor parameters, used as basis for the blanket design and the activation analyses. To this end, specific models of the blanket modules, derived from the engineering CAD models of the HCPB, HCLL, DCLL and WCLL blanket concepts, are inserted into the empty spaces reserved for the blanket [3]. This process is detailed on the example of the HCPB DEMO in the next section.

The DEMO blanket design is based on the Multi Module Segmentation (MMS) scheme with typically 6 to 8 modules arranged in poloidal direction in a torus segment on either side of the plasma chamber. The modules are attached to a Back Supporting Structure (BSS) that acts as mechanical support and hosts the main manifolds for the coolant and the Tritium carrier. The space available in radial direction for the breeder blanket, including first wall (FW), breeder zone, manifold and blanket support structure, is about 80 cm and 130 cm, inboard and outboard, respectively. As a common design feature of the FW, a 2 mm thick tungsten armor is assumed. Fig. 2 shows the modules designed for the HCPB, DCLL and WCLL breeder blankets.

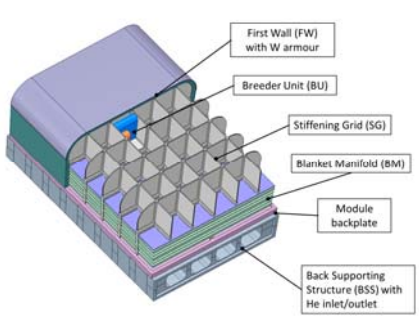


"EU DEMO1 2015"

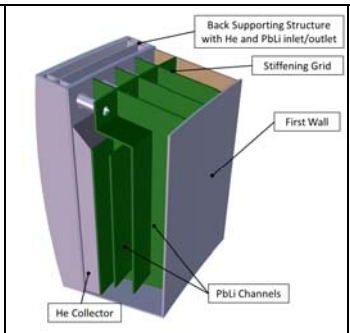
Main reactor parameters	
No. of TF coils	18
Major radius [m]	9.072
Minor radius [m]	2.927
Aspect ratio	3.1
Plasma elongation, κ_{95}	1.59
Plasma triangularitry, δ_{95}	0.33
Average neutron wall loading [MW/m^2]	1.05
Fusion power [MW]	2037
Net electric power [MW]	500

$\Rightarrow$ *18 torus sectors of 20°*

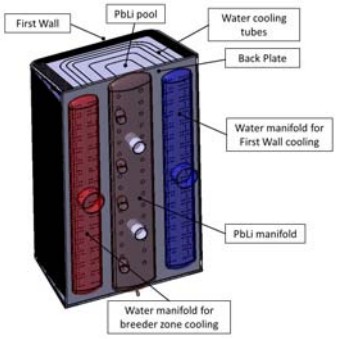
Fig. 1: EU DEMO Baseline model and parameters



HCPB



DCLL



WCLL

Fig. 2: HCPB, DCLL and WCLL breeder blanket modules developed for DEMO (2015).

2.2 Computational approach

Coupled neutron transport – activation calculations are performed to provide the activity inventories of the considered coolants at the specified locations in DEMO and decay times after shut-down. KIT's computational scheme linking the MCNP Monte Carlo code [4] and the FISPACT inventory code [5] through automated interfaces (see Fig. 3) is used for these calculations. This approach enables the use of full and detailed 3D models of DEMO as developed for the design analyses of the blanket concepts (see Fig. 4 for HCPB model). JEFF-3.1 nuclear data are used in the MCNP transport calculations, and EAF-2010 activation cross-section data in the FISPACT inventory calculations.

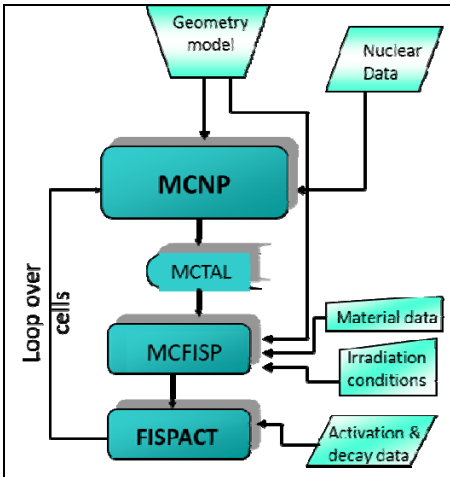


Fig. 3: Computation scheme for coupled MCNP transport – FISPACT inventory calculations

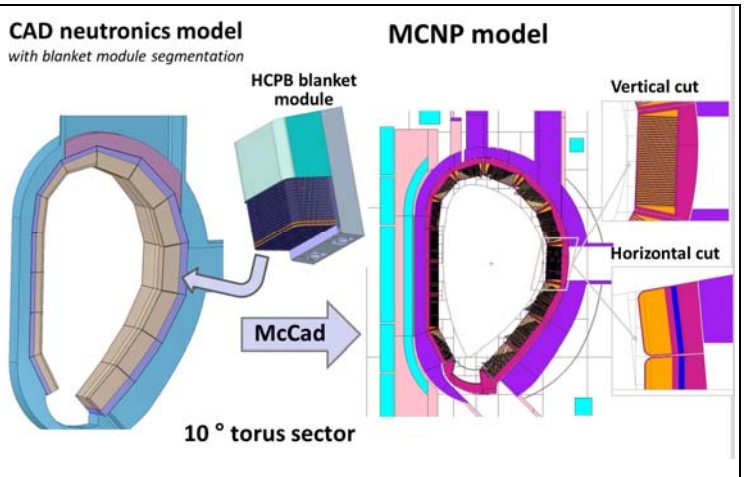


Fig. 4: MCNP model of the HCPB DEMO as generated from underlying CAD models and used with the coupled MCNP-FISPACT calculations.

The first computation step provides the neutron flux spectra, calculated with MCNP in 175 energy groups at the specified locations (geometry/material cells). In this work, we consider the central outboard blanket module (BM) which is subjected to the highest neutron wall loading, approximately 1.3 MW/m2. For the He gas and the water coolants in the HCPB and the WCLL blankets, respectively, the first wall (FW) of the BM is selected where the coolants are irradiated at the highest neutron flux levels. For the DCLL with the Pb-Li coolant, the selected location is the front channel of the BM. Here the neutron flux is averaged over the poloidal height of the BM and a radial depth of 5 cm.

The second computation step consists of a series of nuclide inventory calculations with the FISPACT code using the neutron flux spectra provided by the preceding MCNP calculation. In this work the inventory calculations are limited in each case (HCPB, WCLL, DCLL) to one location (geometry cell) and material (He, water and Pb-Li, respectively) as described above. Thus no loop over the geometry cells and materials is required as indicated in Fig. 3.

The inventory calculations require as input the elemental material composition and the irradiation history. For the He coolant, pure helium is considered with its natural isotopic abundancies (1.38 appm ^{3}He, 99.999862 at% ^{4}He). Potential impurities are at extremely low levels and are considered not significant with regard to activation issues. For the water coolant, pure water is considered with a conservatively estimated amount of steel corrosion products of 20 g in 200 tons of water [6] and the elemental composition shown in Table 1. For the Pb-Li eutectic alloy, the material specification shown in Table 2, provided by F4E for the procurement of Pb-Li [7], is used.

Table 1: Elemental composition of the corrosion products assumed in the water coolant [6]

Element	wt%
Fe	75.8078
Ni	7.6774
Co	0.0351
Cr	14.8827
Mn	1.4281
Cu	0.1689

Table 2: Elemental composition of the Pb-17.8Li eutectic alloy, including impurities and tramp elements [7]

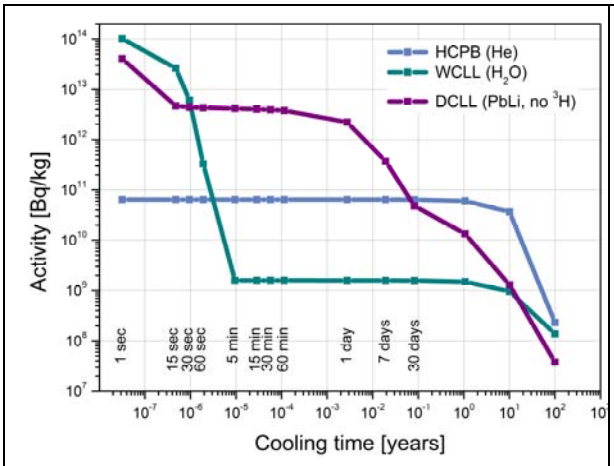
Element	wt% [10^{-2}g/g]	Element	wt% [10^{-2}g/g]
Li	0.62	Mo	0.005
Ag	0.001	Ni	0.005
Cu	0.001	V	0.005
Nb	0.001	Si	0.01
Pd	0.001	Al	0.01
Zn	0.001	Bi	0.02
Fe	0.005	Sn	0.02
Cr	0.005	W	0.02
Mn	0.005	Pb	Balance

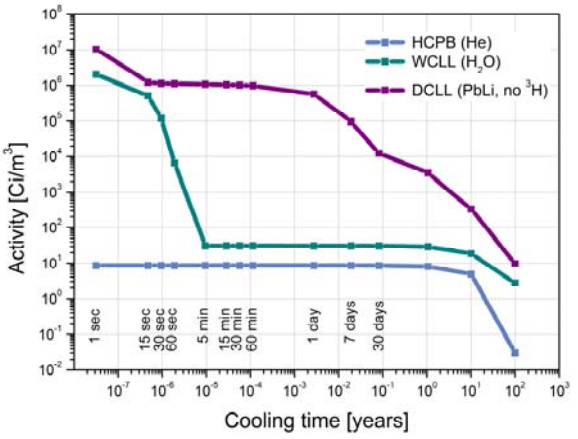
The irradiation scenario assumed for the activation calculations is based on the operation scheme specified for DEMO. The scheduled operation runs over 20 calendar years (CY) at an average availability of 30%. This results in a total DEMO plant lifetime of 6 full power years (FPY). Two operation phases are assumed: The first phase will run over 5.2 CY and reach 1.57 FPY. This phase assumes the deployment of a so-called starter blanket with a maximum displacement damage accumulation of 20 dpa in the steel of the first wall. (The second phase will last 14.8 CY (4.43 FPY) and employ another blanket that can withstand at least 50 dpa).

The irradiation scheme used in this work represents the first DEMO operation phase with a continuous operation over 5.2 years (CY) minus 10 days at 30% of the nominal fusion power followed by 10 days pulsed operation with 48 pulses of 4 hours at full power and 1 hour dwell time in between.

2.3 Results presentation and discussion

Fig. 5 compares the specific activities calculated for the He, water and Pb-Li coolants when irradiated in the HCPB, WCLL and DCLL DEMO, respectively, as specified above. Fig. 5a shows the specific activities in units of Bq/kg. The mass densities of the coolants at the given operation conditions amount to 4.92 kg/m3, 725 kg/m3, and 9540 kg/m3, respectively. The specific activities, accordingly converted into units of Ci/m^3, are shown in Fig. 5b. It is revealed that Pb-Li shows the highest activation level, even without considering tritium generated in the Pb-Li breeding material. The He activation level is lowest and only due to the tritium produced on the minor ^{3}He isotope. The activation level of water is high at the short term, and thus during plant operation, and very low afterwards. A more detailed discussion of the observed behaviour is given in the following sub-sections.





a): Specific activity [Bq/kg]	b): Specific activity [Ci/m3]
Fig. 5: Specific activity of the He, water and Pb-Li coolants as function of the cooling time	

2.3.1 Helium gas in the HCPB DEMO

The activity of the He coolant is only due to tritium generated through the $^{3}He(n,p)^{3}H$ reaction from the minor ^{3}He isotope (1.38 appm natural abundancy). The resulting activity level for the HCPB DEMO is at 6.4 10^{10} Bq/kg (see Fig. 6) which translates into a specific activity of 0.35 Ci/m^3. Tritium decays to ^{3}He via β^- decay ($T_{1/2}$=12.3 y) with no emission of γ-radiation.

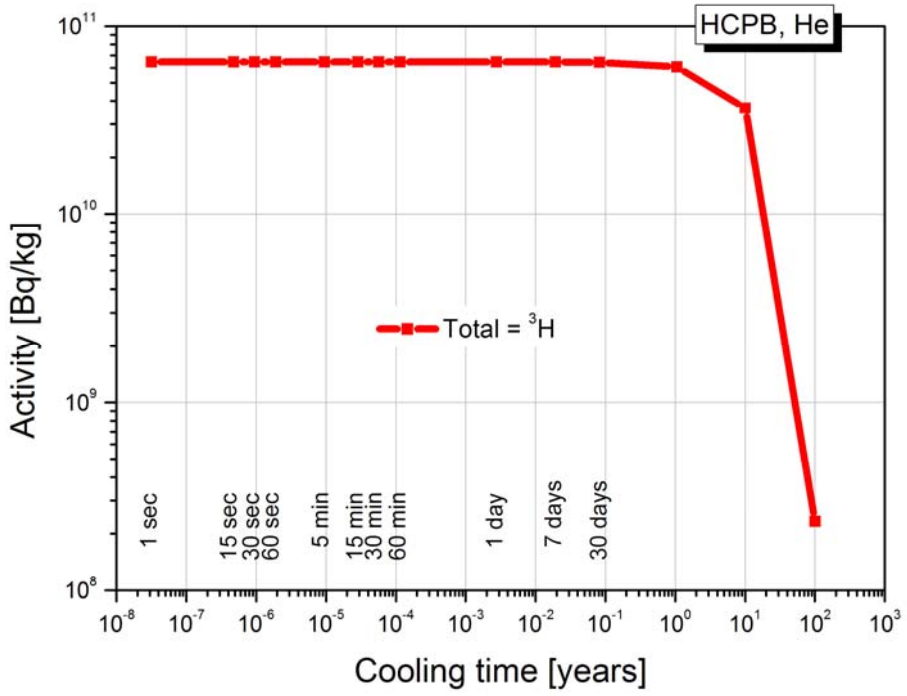
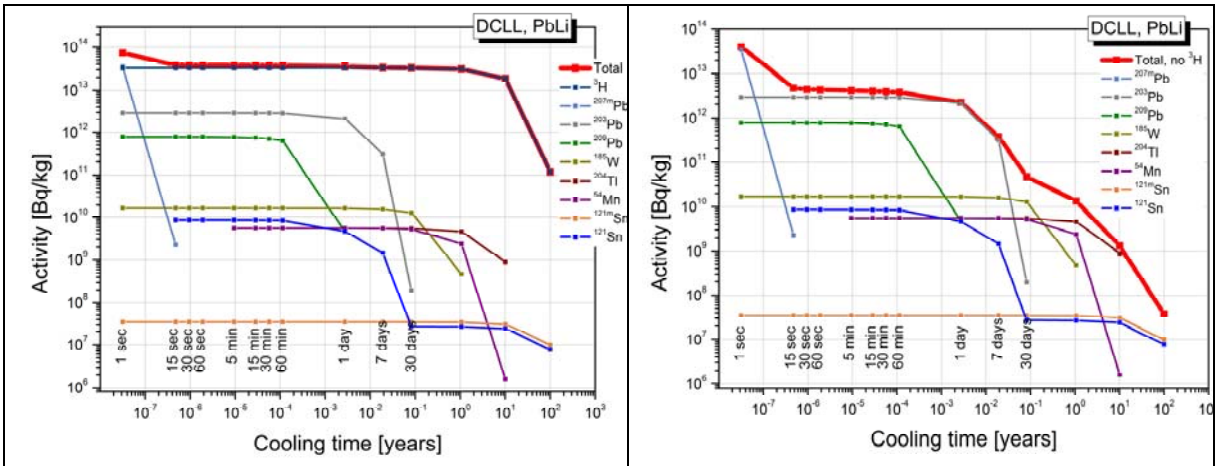


Fig. 6: Specific activity [Bq/kg] of the He coolant in the HCPB DEMO as function of the cooling time.

2.3.2 Pb-Li in the DCLL DEMO

Pb-Li serves both as breeder material and coolant in the DCLL DEMO. The activity is thus dominated by the tritium generated in the $^{6}Li(n,\alpha)t$ breeding reaction in Pb-Li (Fig. 7a).

Tritium is externally extracted from the Pb-Li for the refuelling of the (d,t) plasma. Suitable extraction techniques are discussed in section 3.3 below. We thus consider the activation characteristics of the Pb-Li coolant without tritium, as shown in Fig. 7b. The activity level is significantly lower (several orders of magnitude) and is dominated by Pb activation products, notably ^{207m}Pb ($T_{1/2}$= 0.8 s) and ^{203}Pb ($T_{1/2}$=51.9 h) at short times, and ^{204}Tl ($T_{1/2}$=3.78 y) at longer times, see Fig. 7b.



a): Specific activity [Bq/kg] with tritium

b): Specific activity [Bq/kg] without tritium

Fig. 7: Specific activity of Pb-Li in the DCLL DEMO as function of the cooling time

2.3.3 Water in the WCLL DEMO

The activity level in the water coolant, shown in Fig. 8, is very high at short times due to the generation of the short-lived β^--active radionuclide ^{16}N ($T_{1/2}$= 7.13 s) via the reaction ^{16}O(n,p)^{16}N. This applies accordingly during plant operation times and results in a permanent γ-radiation source of the circulating water inside and outside the irradiation zone. (As a consequence, the water pipes need to be properly shielded in the entire water loop). After the decay of ^{16}N, the activity drops to a very low level (around 10^9 Bq/kg) due to small amounts of ^{3}H and ^{14}C produced form ^{2}H and ^{16,17}O, respectively.

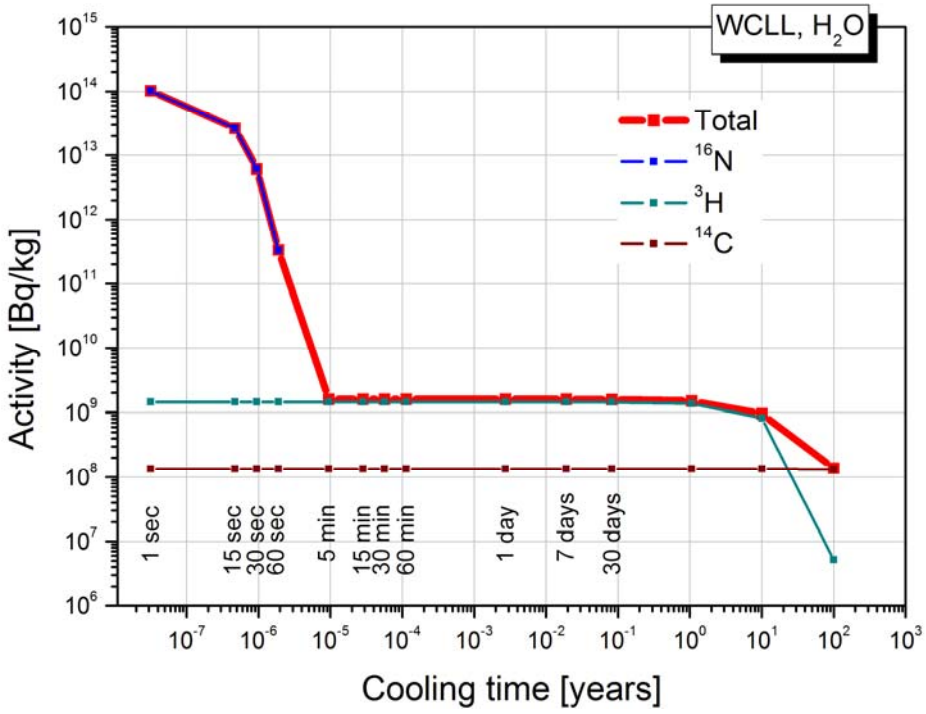


Fig. 8: Specific activity [Bq/kg] of the water coolant in the WCLL DEMO as function of the cooling time.

2.3.4 Contact gamma dose rates

The contact gamma dose rate is provided with the FISPACT calculation for the approximation of a semi-infinite slab arrangement of the activated material. Thus this approximation does not take into account the real geometry, as employed in the coupled transport-activation calculation, nor the transport of the emitted decay photons through the actual material configuration.

Fig. 9 shows this contact gamma dose rate for the water and the Pb-Li, activated in the WCLL and the DCLL DEMO, respectively. Figs. 10 a and b show the breakdown into individual radionuclide contributions for the Pb-Li and the water coolant. (It is recalled that the activation of the He coolant in the HCPB DEMO does not result in gamma radiation due to the fact that the activity is only due to the tritium which decays without emission of gammas).

The dose rate level is highest for the activated water at short cooling times due to the ^{16}N radionuclide emitting high energy gammas of 6.13 and 7.12 MeV. With the decay of ^{16}N, the contact gamma dose rate of the water coolant drops to a low level below the recycling limit of 10 mSv/h. At these cooling times, it is dominated by the activated corrosion products assumed to be present in the water (20 g ACP in 200 tons of water, see section 2.2). The gamma dose rate level of the radionuclide ^{17}N ($T_{1/2}$= 4.17 s), generated in the water via the reaction ^{17}O(n,p)^{17}N, is comparatively low (see Fig. 9b). The presence of ^{17}N in the water coolant is an issue of serious concern since it emits delayed neutrons (β^-n decay) which activate the coolant pipes outside the irradiation zone.

The dose rate level of the Pb-Li coolant, activated in the DCLL DEMO, is at a high level, although lower than the activated water at short times and during the plant operation. The dose rate is dominated at short cooling times (less than one month) by the Pb activation products and afterwards by radionuclides generated from the specified impurities, in particular ^{54}Mn. Contributions from ^{210}Po, generated through the reaction & decay sequence

$^{208}Pb(n,\gamma)^{209}Pb(\beta^-)^{209}Bi(n,\gamma)^{210}Bi)(\beta^-)^{210}Po$, to the contact gamma dose rate are not significant. The related (severe) radiation hazard arises from the release of gaseous Po and a potential inhalation of this strong a α-radiation emitter.

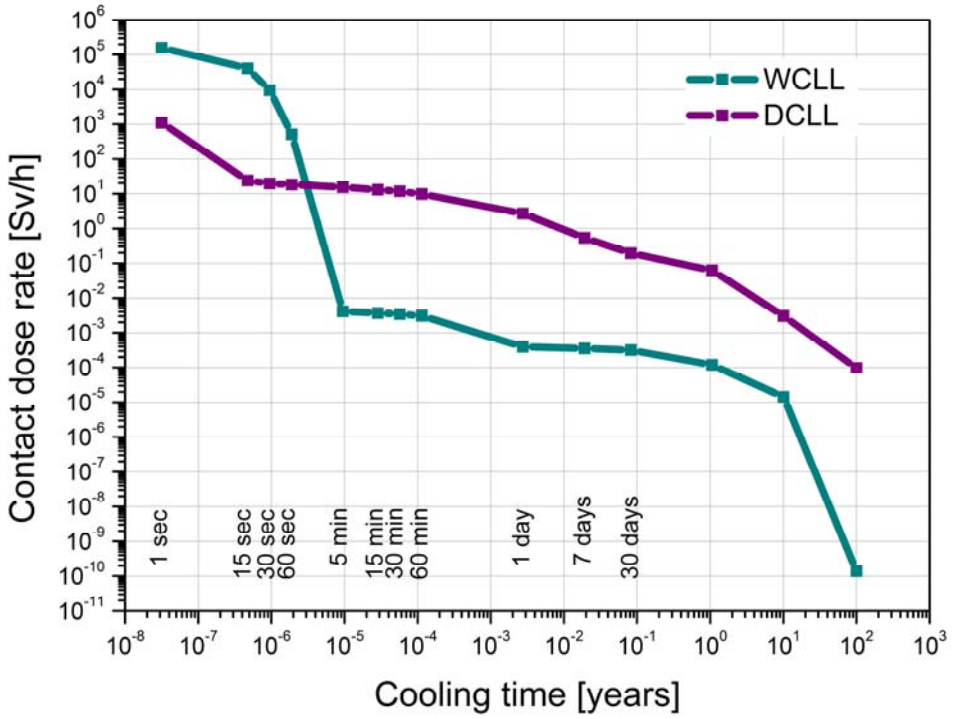
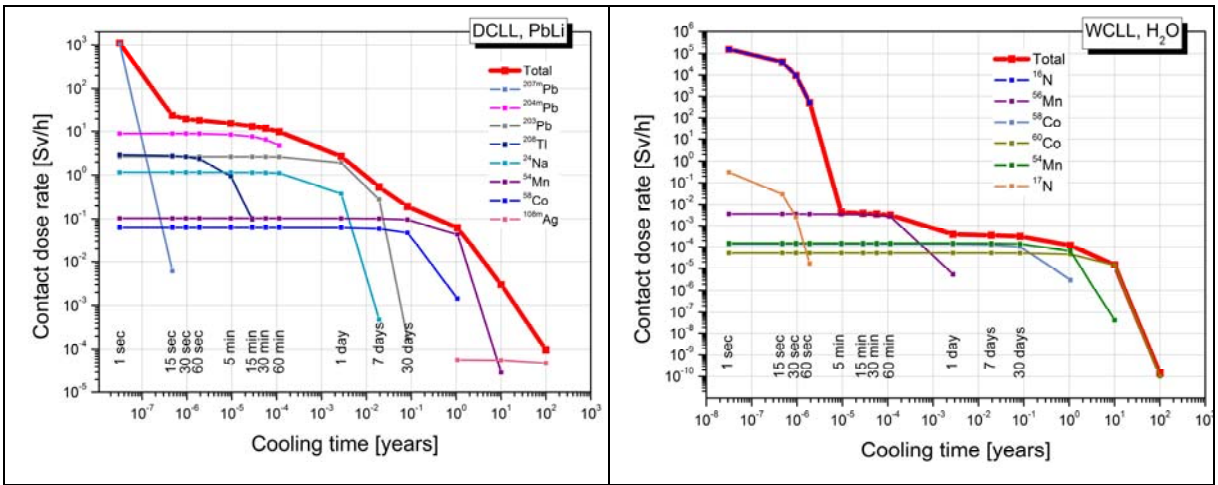


Fig. 9: Contact gamma dose rate for the water and the Pb-Li coolant activated in the WCLL and DCLL DEMO, respectively, as provided by FISPACT with the semi-infinite slab approximation.



a): Pb-Li activated in the DCLL DEMO | b) Water activated in the WCLL DEMO

Fig. 10: Contact gamma dose rates as function of cooling time as provided by FISPACT with the semi-infinite slab approximation.

2.3.5 Conclusion on activation characteristics

Activation characteristics of the coolants helium, water and Pb-Li were assessed as employed in the European designs for a water cooled lithium-lead (WCLL), a helium cooled pebble bed (HCPB) and dual coolant lithium-lead (DCLL) based DEMO fusion power plant. The results are summarized as follows:

- The **He coolant** shows a very low activity level which is only due to the tritium generated from the minor ^{3}He isotope (1.38 appm natural abundancy). There is no emission of gamma radiation from the activated He coolant.
- The **water coolant** shows a very high activity and gamma radiation level during plant operation and shortly (few minutes) after shut-down due to the radionuclide ^{16}N generated from ^{16}O. This results in a permanent γ-radiation source of the water circulating inside and outside the irradiation zone during the plant operation and requires the water pipes to be properly shielded in the entire water loop. At longer cooling times the activity and gamma dose rate levels are low due to the tritium generated in the water and the activated corrosion products (ACP) assumed in the water. Further consideration needs to be given to the tritium permeating into the water, the ACP, the radiolysis and the water chemistry affecting the activation behaviour of the water and the resulting radiation hazard.
- The **Pb-Li coolant** acts also as breeder material. The activity level is thus very high and dominated by the tritium generated in the ^{6}Li(n,α)t breeding reaction. The activity level of Pb-Li without considering tritium is significantly lower and is dominated by Pb activation products. The activity and dose rate levels during operation and at shut-down are though comparatively high. Further consideration needs to be given to ACPs, produced in the Pb-Li loop, for which no assessment is available so far. The generation (and potential release) of the strong α-radiation emitter ^{210}Po is another concern for Pb-Li requiring possibly the continuous extraction of the Bi produced from the irradiated Pb-Li.

3. Aspects of tritium extraction techniques for water, He and Pb-Li

The optimisation of the heat transfer at the level of the breeder blanket (BB) and the steam generator (SG) has as a consequence that large surface area with thin walls operated at high temperatures are required. Therefore, the tritium permeation from the BB to the steam generator is favourable and consequently a significant amount of tritium may be released into the environment.

The commonly accepted tritium losses originating from the BB shall be maintained below a target value of 0.6 g/y. As a reference it is considered that the reactor including the inner fuel cycle should maintain the total tritium losses below the 1 g/y limit. In various studies, a maximum tritium release from the blanket of 2 mg/d (about 20 Ci/d) has been considered. This reference is more than five orders of magnitude lower than the production rate of about 360 g/d.

In order to mitigate the amount of tritium release into the environment, two main strategies are under development that shall work in a balanced manner:

- the enhancement of the efficiency of the tritium extraction system (TES) at the level of breeder zone (BZ) and minimization at reasonable technical values of the tritium concentration in the coolants through the coolant purification system (CPS).

- the feasibility of implementing anti-permeation barriers at both BB and SG interfaces, made of ceramic coatings or “natural” oxide layers chemically controlled.

Significant developments have been achieved as far as tritium permeation modelling is concerned, covering the most relevant phenomena such as physical adsorption of molecules on high pressure side, dissociative absorption into metal (Sievert’s law), atomic diffusion by concentration gradient (Fick’s law), recombination at the low pressure side and the molecular desorption in the gas phase. The calculations have shown that the tritium inventories in the system loops reach the steady state in short time. For the case of the WCLL the steady state is reached in less than 10 hours as shown in Fig. 11 [8].

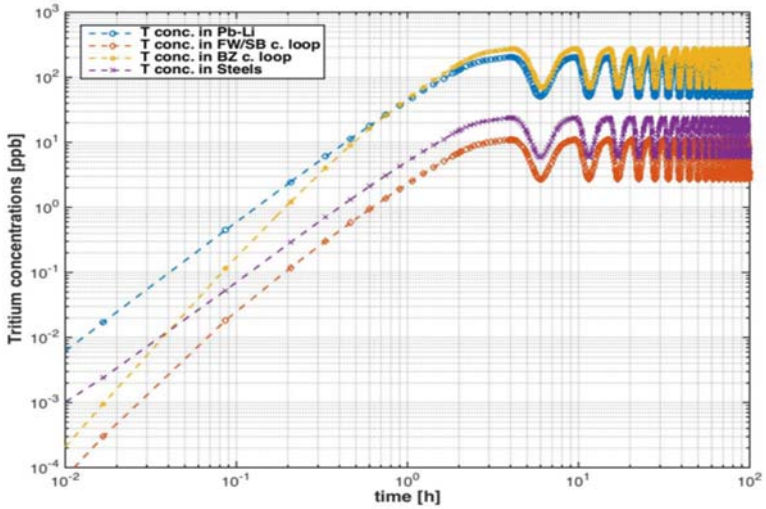


Fig. 11: Time evolution of tritium inventory in the WCLL systems

The reference data for the coolants flow-rates in the four blankets investigated for a DEMO reactor and the estimated tritium content in the coolants as a result of permeation from the breeding zone are summarized in the Table 3.

Table 3: The coolants flow-rates and estimated tritium content of the four reference BB

Operation parameters	HCLL	HCPB	WCLL	DCLL
Coolant flow rate (kg/s)	2,400	2,400	10,561	26,466
T pressure in the coolants [Pa]	20-30	1-10	50-80	0.001-003

Aiming to keep the tritium release below the 0.6 g/y mainly due to the tritium permeation the throughputs of the coolant purification systems have been calculated. Significant efforts are made in order to establish the allowable tritium concentration in the coolant loops that keeps the tritium permeation in the steam generation loop below the reasonable allowable tritium threshold.

3.1 Evaluation of the technologies for tritium removal from water used in the WCLL.

Technologies for tritium removal from tritiated water have been developed in the last decades, mainly focusing on tritium removal from the moderator of heavy water reactors. The technologies are based on a combination between the vapour phase catalytic exchange (VPCE), liquid phase catalytic exchange (LPCE), combined electrolysis catalytic exchange (CECE), direct electrolysis process followed by cryogenic distillation in order to enrich tritium up to 99%. The largest water detritiation facility with the throughput of 360 kg/h is still in operation at Darlington – Canada. The preliminary evaluation of the required flow-rate in the CPS of the WCLL gives a flow rate of 36,000 kg/h. For this very high throughput of a tritium removal facility, the only feasible technology can be water distillation under vacuum with heat pump as front end tritium enrichment. The tritium enriched water can be removed from the bottom of the water distillation column and further processed in a CECE system followed by full tritium recovery in the DEMO tritium plant. The block diagram of such configuration is shown in Fig. 12. In the case that the allowable tritium concentration in the cooling water will be in the ranges allowable for the operation of the CANDU reactors, the technology based on the CECE process followed by tritium recovery in the DEMO tritium plant offers the main benefits for implementation.

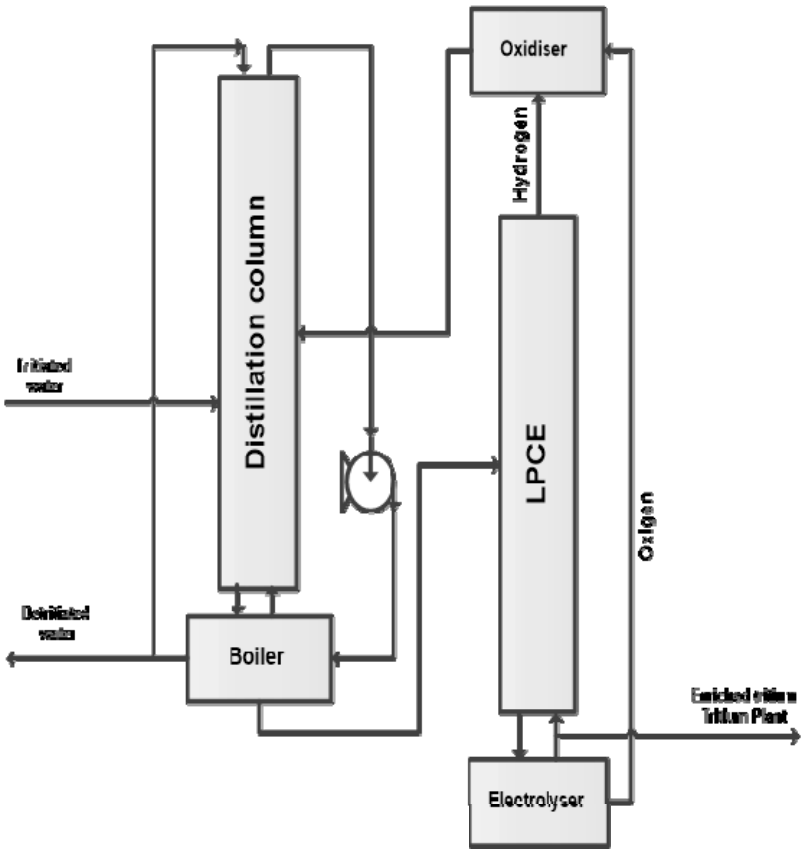


Fig. 12: Block diagram of the WDS for large throughput based on water distillation under vacuum and CECE process

The throughput of the water detritiation facility for the WCLL strongly depends by the allowable tritium concentration in the cooling loop and the experience from the operation of the CANDU reactors may be used for the definition of the allowable tritium concentration in the loop.

3.2 Evaluation of the technologies for tritium removal from helium used in the HCLL and HCPB.

In the evaluation of the possible technologies that have potential for industrialization in view of DEMO design and operation, the estimated throughput of the coolant purification system of 24 kg/s has been considered. Two technologies have been selected having in view the two possibilities of operation, continuous tritium extraction and batch mode tritium extraction. The following technologies have been investigated:

- oxidation, trapping of tritiated water on a reactive molecular sieve bed followed by tritium recovery by isotopic exchange with swamping deuterium;
- tritium recovery in permeation cascade.

Tritium recovery in a permeation cascade allows continuous tritium removal but the main drawback is that involves a significant amount of permeation stages, more than 20, with associated necessary components and hence is s very complex from the control system point of view. In addition, the complexity and the operation capacity of the components of such a system would require high energy consumption. Therefore, the tritium recovery based on tritium conversion to tritiated water is a preferable option. Such a system would require to be followed by isotopic exchange on reactive molecular sieve with deuterium and further processing in the DEMO Tritium Plant.

3.3 Evaluation of the technologies for tritium removal from LiPb used in the DCLL.

The selection of the tritium extraction technology for the DCLL is strongly dependent by the required throughput capacity of the facility. The selected technology shall allow operation at throughputs up to the entire flow rate of the cooling system that is approximately 26,500 kg/s. Therefore, several methods for tritium removal have been investigated and the most promising for the DEMO application are the followings:

- Gas Liquid Contactors (GLC),
- Permeation against vacuum (PAV),
- Regenerable getters,
- Droplets and Gas-liquid counter-current extraction tower or vacuum sieve tray (VST).

Significant efforts are ongoing related to the development of systems based on permeation against vacuum and vacuum sieve trays processes that have potential for application at DEMO requirements. These methods are preferable mainly due to the interface with the DEMO tritium plant where the tritium shall be recovered from the carrier gas, if any. In the case of the GLC, the tritium separation from the carrier gas requires a large separation system with significant impact on the energy consumption. The modelling of the tritium transport in the “vacuum chambers” of the VST and PAV and the definition of the requirements for the vacuum systems in view of qualification for tritium service are the main challenges of the two processes.

3.4 Conclusions on tritium extraction techniques

Significant efforts were made to enhance the tritium transport and permeation models aiming to accurate predict the tritium concentration and inventories in the coolants;

The experimental data base for tritium permeation to coolants in DEMO like operation conditions is very limited and the experimental procedures are not well harmonized;

The selection/development of the tritium removal technologies from coolants strongly depend on the allowable tritium concentration in the coolants that is the main issue from the licensing point of view. The lessons learned from the licensing and the operation of the CANDU reactors can be used as reference for defining allowable tritium concentration in the coolants;

Available detritiation technologies provide a good basis for the development of the tritium removal process from the coolants of WCLL, HCLL and HCPB blankets; as far as DCLL is concerned, the technologies are under development and the validation at relevant DEMO operation conditions shall be the priority for the upcoming years.

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