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Tritium Plant Technology Development for a DEMO Power Plant

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Tritium Plant Technology Development for a European DEMO Power Plant

Abstract

Any future European DEMO reactor which is based upon the D-T fusion reaction will require a tritium plant to reprocess gases such that they can be effectively resupplied to the tokamak fuelling systems, and to protect the environment and personnel from tritium releases. The plant must also be designed to allow replacement of burnt fuel with tritium and deuterium. This document outlines the preliminary stages of the design of the European DEMO tritium plant, from initial interface and requirements determination, through to identification of required subsystems and proposal of a new tritium plant architecture. It then goes on to cover the review, assessment and selection of potential technologies for each tritium plant subsystem.
Where possible, a proposed technology is put forward. Elsewhere the required further research is identified.[1]

Key words:

Tritium plant, DEMO, fusion, fuel cycle

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Introduction

The European DEMO will be a pulsed tokamak demonstration fusion power plant. It will aim to demonstrate and integrate all the required technologies for a working fusion power plant. This will include, but is not limited to, tritium breeding and processing, utilisation of advanced fusion ready materials, and the ability to produce electricity and connect to the grid. The EU is currently working on a pre-conceptual design for DEMO. The work contained in this document was carried out as part of the pre-conceptual design under the EUROfusion Tritium Fuelling and Vacuum project. Only work undertaken in the Tritium sub-project will be discussed.

The successful development of a DEMO power plant requires that the entire fuel cycle is identified in detail and developed such that the reactor performance can be optimised, whilst meeting overall cost, risk and safety constraints. It is therefore necessary to understand how the fuel cycle interacts with the tritium plant, the tokamak, fuelling processes, pumping systems, the supply sources of tritium and deuterium, as well as the environment.

In order to begin development of the EU DEMO tritium plant, a thorough analysis of requirements and available technologies has been undertaken. A brief overview of this work is presented here.

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Progress to date

External interfaces

The first step in the development of a DEMO tritium plant design is identification of the external system interfaces [1]. These interfaces have been identified as the following:

1. Reactor matter injection – this interface covers all forms of matter injection into the torus including tritium and deuterium fuelling together with any Plasma Enhancement Gases (PEGs) introduced.

2. Reactor pumping – this interface leads to the specification of the vacuum conditions that must be delivered to the reactor, as well as gas quantities based on fuel burn-up and reactor fuelling efficiencies.

3. Breeder plant – this comprises the transfer of tritium to replace that burnt in the fusion reaction.

4. Coolant – this interface exists as a result of the need to recover tritium from coolants used to transfer heat from the reactor core and breeder assemblies to the power generation plant.

5. Safety and Environment – this interface specifies the safety, environmental and tritium inventory conditions applicable to the inner tritium plant.

Each of the identified interfaces will be designed under separate EUROfusion PPPT projects, but coordination and communication of requirements between these projects is essential. Prior to beginning the design of the tritium plant, the requirements presented by each of these interfaces was pinpointed as clearly as possible. This was a difficult task due to the immaturity of the DEMO project, and exact requirements are liable to change as the design progresses. In some cases it has been extremely difficult to identify specific requirements, in these cases efforts have been made to design to a requirements window. This should mean that solutions reached by other groups are capable of operating within a set range of requirements, whilst allowing design of the tritium plant to proceed. This approach dictates that clear and regular communication between projects remains essential.

A number of the identified requirements will present significant design challenges. For instance:

- Approximately 313g of tritium a day will need to be produced by the breeder blankets and processed (0.4g a day will be produced at ITER). This number is calculated directly from the burn-up required to produce 2GW, and does not account for any tritium losses in the system. [1]
- Helium flow rates in the breeding zone may be up to 10,000 m^3h^{-1}, this will contain ~1ppm of tritium to be removed
- Helium flow rates required in the coolant purification system will be 50,000 m^3h^{-1} (75 m^3h^{-1} at ITER), this will contain ~10 ppb of tritium which will need to be removed
- The use of Plasma Enhancement Gases (PEGs) presents a particular challenge since species and quantities are currently still unknown. Activation of PEGs will occur and must be taken into consideration when designing plants systems

Tritium plant architecture design

Following the determination of the key interface requirements, the development of the tritium plant architecture was initiated. Some assumptions have been made about the operation of DEMO in order to undertake this work [2] [3]:

- DEMO will operate in a pulsed mode; estimates suggest that it will be on for 2 hours with a dwell time not currently defined (but older scenarios suggest approximately 40 minutes.)
- Fuel injection is able to take a mixed deuterium-tritium input rather than separate isotopic feeds, negating the need for isotope separation in the innermost tritium plant loop, with the possible exception of isotope rebalancing. This represents a significant departure from previous fusion tritium plants.
- The tritium plant will consist of as few systems as possible – to reduce cost and complexity and ensure reliability.
- Minimisation of tritium inventory is a prime requirement.
- The culmination of all inefficiencies, from fuelling through to burn-up in the plasma itself, means that the fusion process remains highly inefficient, only ~1% of the DT mixture injected into the tokamak will be consumed in the fusion reaction, the remaining gas will need to be pumped out of the tokamak and reprocessed.

- Consequently the innermost tritium plant loop will be dimensioned to process this large volume of recirculating gas; however most of the plant outside of the innermost tritium plant loop should not have to process the same volume of tritium.
- It is cost effective and environmentally preferable for plasma enhancement gases to be reused rather than be exhausted to atmosphere, so minimising the load on the exhaust detritiation facility
- The amount of tritium present in the coolant loops is low; however the volumes of material to be processed may be comparatively large. Batch mode processing of this area may be possible.

However the above may be found to be incorrect as requirements gathering progresses, requiring rework of the system architecture.

Figure 1 demonstrates the current proposed tritium plant architecture based upon current requirements.

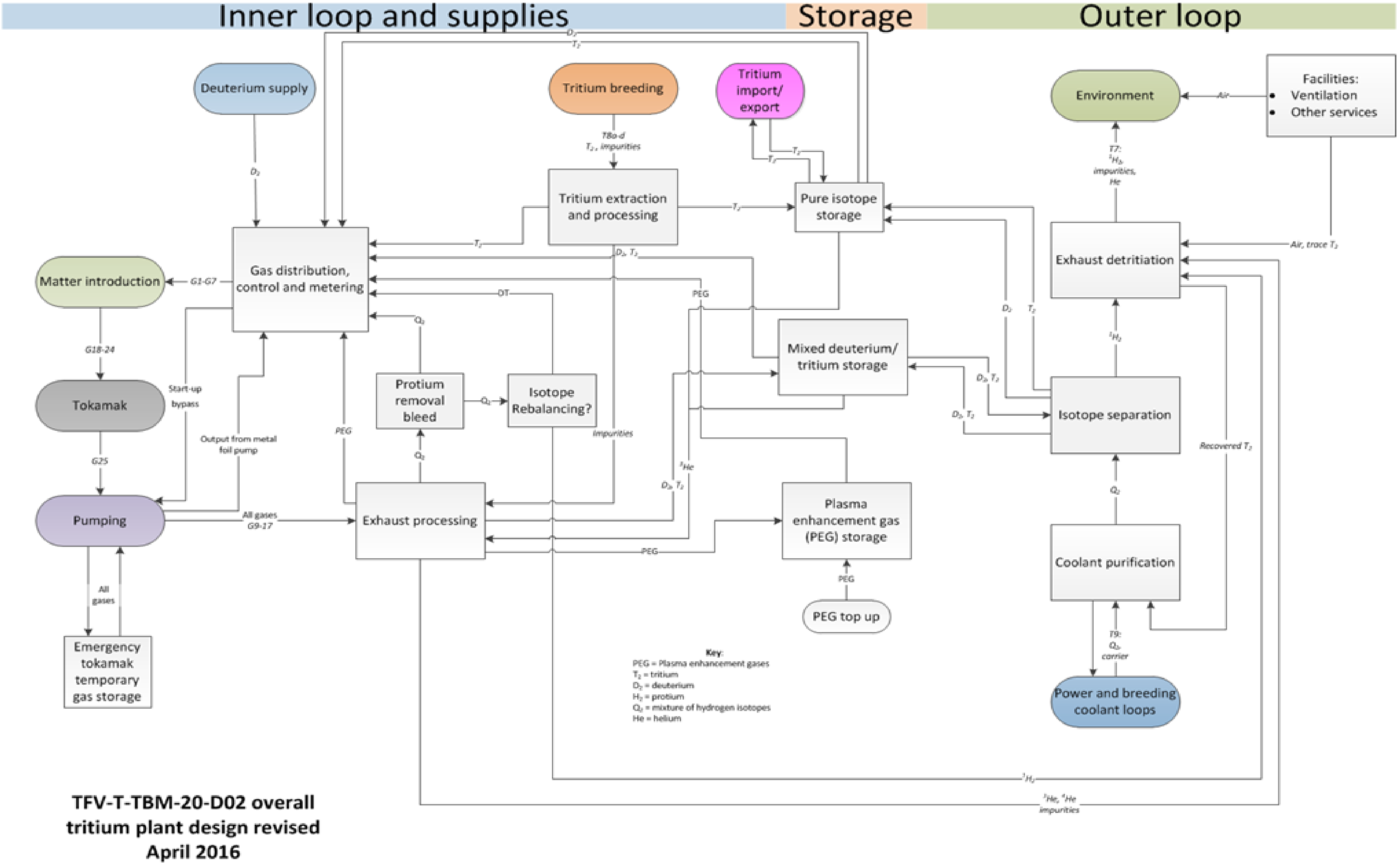

Figure 1: Tritium plant architecture

Table 1 details the required system blocks, along with their required properties and functions.

Functional system block	**Function**	**When required**	**Input species**	**Indicative flow rates (mol.s-1)**	**Output species**	**Purity requirements**
Exhaust Processing	Removal of impurities that must not be re-injected into the tokamak	Pulse ON and pulse OFF	D_2, T_2, Ne, Ar, Kr, Xe, He, N_2, NH_3, H_2, air, H_2O	2 (based on 1% burn up efficiency)	D_2, T_2, Ne, Ar, Kr, Xe	He < 1%
Primary loop protium removal	Removal of protium from the primary tritium loop	Pulse ON and pulse OFF	D_2, T_2	Trace	D_2, T_2	TBA
Isotope rebalancing	Tuning of the D:T ratio prior to fuelling the tokamak	Pulse ON and pulse OFF	D_2, T_2, H_2	2.10^{-2}	D_2, T_2	Tuning D:T ratio by +/- 10% (TBC)
Gas distribution control and metering	Switching, metering and accounting for gases passed to the tokamak, tokamak bypass	Pulse ON and pulse OFF	D_2, T_2, Ne, Ar, Kr, Xe, N_2	2	D_2, T_2, Ne, Ar, Kr, Xe	Homogenous gas streams – i.e. new D & T must mix with reprocessed D-T
Mixed hydrogen isotope storage	Storage of mixed hydrogen isotopes	Always	D_2, T_2	TBA	D_2, T_2	Acceptable isotopic effects

Functional system block	Function	When required	Input species	Indicative flow rates (mol.s-1)	Output species	Purity requirements
Pure hydrogen isotope storage	Segregated storage of tritium and deuterium	Always	D_2, T_2	TBA	D_2, T_2	n/a
Purification of tritium supply from breeder systems	Extraction of tritium from breeder stream	Possible batch process	T_2, He, H_2O	6.10^{-1}	T_2	TBA
Plasma enhancement gas supply and storage	Supply of PEGs	Always	Ne, Ar, Kr, Xe, N_2	2.10^{-3} (very rough estimate)	Ne, Ar, Kr, Xe, N_2	Aim for basic industrial standard gas purities
Deuterium supplies	Supply of deuterium	Always	D_2	6.10^{-1}	D_2	Aim for basic industrial standard gas purities
Coolant loop tritium extraction	Extraction of tritium from the coolant loop	Always	T_2, He, H_2O	TBA	T_2	High separation factor
Isotope separation within the tritium recovery system	Separation of tritium and possibly deuterium from coolant and exhaust streams	Possible batch process	D_2, T_2, H_2	TBA	D_2, T_2, H_2	
Exhaust detritiation and tritium recovery	Extraction of residual tritium from exhaust streams. Captured tritium returned to tritium storage facility for reuse	Always	D_2, T_2, Ne, Ar, Kr, Xe, He, N_2, NH_3, H_2, Air, H_2O	TBA	T_2	Release limits TBA.
The overall facility	Containment & defence in depth	Always	T_2, air	Trace	Air	Maintains <<1DAC; tba

Table 1: Tritium plant functional system blocks

The principle features of the proposed architecture (Figure 1) comprise:

- Application of the Direct Internal Recycling concept such that D-T fuel is not unnecessarily separated into constituent isotopes whilst circulating in the primary tritium plant loop from tokamak exhaust to matter introduction [4]
- Tritium inventory minimisation, requiring
    - The continual recirculation of gases without storage
    - Tritium plant designed to minimise the hold-up of tritium in each process stage
    - Immediate use of tritium released from tritium breeder blankets
- Steady state loading of the tritium plant systems during pulsed reactor operation by diversion of gases during the dwell phase of pulses
- A gas distribution and control system that fully provides the separated gas volume and composition requirements of the matter introduction system
- A tritium extraction and processing capability that resides within the tritium plant and which fully processes the gaseous output from the breeder blankets
- Residual tritium recovery exhausted from all plant systems and coolant systems
- Environmental protection, and dose minimisation under normal operating and accident conditions
- Accurate tritium accountancy throughout the fuel cycle

Technology selection

Following on from the identification of the required system blocks, it was necessary to consider technologies that might be capable of meeting the requirements of each block.

Optioneering exercises were undertaken to identify the best technology candidates for each functional system block within the tritium plant given the current status of the DEMO project. The process comprised of:

1. Identifying generic selection criteria, for instance safety and environment concerns, capital and operational costs, and fitness for purpose
2. Making these criteria relevant to system blocks on an individual basis, i.e. the development of specific selection criteria for each system block
3. Determining the relevance of the selection criteria for each system block using the Pairs analysis method and weighting the criteria accordingly
4. Scoring each technology candidate for a system block against each selection criteria
5. Applying the weighting factors determined from the Pairs analysis method for the selection criteria to develop a ranked set of technology candidates for each functional system block

Not all of the functional system blocks required a formal ranking process. In some cases, decisions on technology solutions for the system blocks are either straightforward, or not enough is known about requirements at this stage of development. In all other cases candidate technologies have been determined.

Of the above functional system blocks which fall within the remit of the tritium plant element of the TFV project, the areas of gas distribution control, exhaust processing (excluding PEG separation), exhaust detritiation with tritium recovery, and plasma enhancement gas supply and storage may most likely be delivered using conventional available technologies.

An example of the optioneering process is included below [5]; Table 2 was used to determine important factors for an isotope separation system employed for primary loop protium removal, and Table 3 shows the scores allocated to each technology for the various criteria. From this analysis we are able to obtain a ranked list of technologies, as shown in Table 4.

Criteria	Capital Expenditure	Operational Expenditure	Safety and Environment	Continuous Processing Possible	Easily Modify Purity	Throughput	Technology Readiness	High Purity	Low Tritium Inventory	Separation Factor of a Single Step
Capital Expenditure		2	2	1	0	2	0	2	2	2
Operational Expenditure	0		2	1	0	1	0	2	2	2
Safety and Environment	0	0		0	0	0	0	0	1	0
Continuous Processing Possible	1	1	2		0	2	0	2	2	2
Easily Modify Purity	2	2	2	2		2	1	2	2	2
Throughput	0	1	2	0	0		0	1	2	1
Technology Readiness	2	2	2	0	0	2		2	2	2
High Purity	0	0	2	2	1	2	2		1	0
Low Tritium Inventory	0	0	2	0	0	1	0	2		0
Separation Factor of a Single Step	0	0	1	0	0	0	0	1	2	
Rank weighting	**5**	**8**	**17**	**6**	**1**	**12**	**3**	**14**	**16**	**11**

Table 2: Pairs analysis for primary loop protium removal

Selection Criteria	CD	GC	TCAP	LIS	MLIS	PSP	Gaseous Diffusion	EMIS	Centrifuge	Quantum sieving	Kinetic isotope effects	Pressure swing adsorption
Capital Expenditure	4	5	3	1	2	2	2	2	1	2	2	2
Operational Expenditure	2	3	4	3	3	5	2	1	1	3	3	3
Safety and Environment	2	4	5	4	2	5	4	4	2	3	2	3
Continuous Processing Possible	5	1	4	3	3	3	2	2	3	3	3	3
Easily Modify Purity	4	3	4	3	3	4	2	3	3	2	3	3
Throughput	5	3	3	3	2	4	4	2	2	3	3	3
Technology Readiness	5	5	4	1	2	1	2	4	2	2	1	2
High Purities achievable	5	4	4	3	3	2	3	5	3	5	3	4
Low Tritium Inventory	2	3	4	3	2	5	3	3	2	4	3	3
Separation Factor of a Single Step	2	2	2	5	5	5	2	4	1	4	4	4
Accuracy	4	3	5	4	4	3	2	4	3	4	4	4

Table 3: Ranking against selected criteria

Rank	Technology
1st	Thermal cycling absorption process
2nd	Plasma Separation Process
3rd	Cryo-distillation
4th	Gas chromatography
5th	Electromagnetic isotope separation
6th	Quantum Sieving
7th	Pressure Swing Adsorption
8th	Laser Isotope Separation
9th	Gaseous Diffusion
10th	Molecular Laser Isotope Separation
11th	Kinetic Isotope Effects
12th	Centrifugation

Table 4: Primary loop protium removal technologies ranked in order of preference

Using the methodology described above, the following technologies have been identified as suitable candidates for future research and development for the following functional systems [5]:

1. Isotope rebalancing:
    a. Plasma separation processes
    b. TCAP
    c. Cryo-distillation
    d. Quantum sieving
    e. Laser isotope separation

2. Primary loop protium removal:
    a. TCAP
    b. Plasma separation processes
    c. Cryo-distillation
    d. Gas chromatography
    e. Electromagnetic isotope separation

3. Tritium storage technologies – alternative materials to using depleted uranium:
    a. Magnesium catalysed ball milled
    b. Zirconium cobalt
    c. Super diamond nanotube
    d. Ammonia borane SBA 15

4. Coolant loop tritium extraction – the proposed technologies are already known even if they are not currently used for the coolant loop tritium extraction:
    a. Getter
    b. Molecular Sieve Bed
    c. Cryo-molecular sieve bed
    d. Pd/Ag diffuser

5. Plasma Enhancement Gas Separation Techniques – some suitable technologies able to separate such gases are listed below; however their feasibility has to be verified:
    a. Cryogenic distillation
    b. Solid adsorption on activated charcoal and zeolites
    c. Zeolite membranes for noble gas separation

Further work is currently being undertaken to develop technologies in the area of tritium detection, monitoring, flow control and accountancy.

The impact of ITER

Directly scaling up tritium technologies to be used at ITER is not possible for DEMO for a number of reasons, the most important being that the inventory would be far too large [5]. It is however, still important to take into account lessons to be learned from ITER. The technologies currently planned for use at ITER have been evaluated for suitability for use in a DEMO tritium plant, allowing both alignment of research and development effort, and allowing DEMO related work to be focussed on the technologies most in need of effort. In assessing technologies to be used at ITER for their relevance to DEMO, the following criteria were used:

1. Function – does the system perform the necessary processes applicable to a DEMO reactor?
2. Proven technology – if an ITER technology is not mature then it has no advantage over that which might arise from DEMO R&D
3. Scale – could the system process the required gas flow rates?
4. Inventory minimisation
5. Continuous operation

Depending on the final ITER timeline, and the data collected at the tritium plant, technologies to be trialled at ITER may not require further testing to verify their suitability for implementation at DEMO. However, some systems will still require further R&D in order to identify a suitable technology candidate.

This project has been able to identify appropriate technologies for a number of the DEMO subsystems. A selection of these is outlined below [6].

- Exhaust processing will make use of Pd-Ag permeators, catalytic reactors, and molecular sieve beds. However, new techniques will be required for the separation of plasma enhancement gases
- Gas Distribution, Control and Metering will utilize conventional gas handling components
- Hydrogen Isotope Storage, depleted uranium is the current baseline, however work is ongoing to investigate the social acceptance of the use of uranium in a fusion facility, as well as investigating any potential issues around decommissioning etc. Other candidate materials are also being explored.
- Plasma Enhancement Gases will be injected via conventional gas handling components, but will need new techniques to facilitate separation
- Exhaust detritiation is likely to utilize a combination of room and high temperature oxidizers, wet scrubber columns and molecular sieves
- Deuterium supplies can be handled in conventional tanks.

Conclusions and Future work

The preliminary stages of the design of a tritium plant for the European DEMO have been initiated. This has involved pinpointing interface requirements where possible, and in other cases estimating likely requirements, to be updated once more information becomes available. In depth literature surveys have been conducted in order to establish and compare the most promising candidate technologies. Areas requiring further research have been identified, taking into account experience to be gained at ITER.

The following key technologies have been selected for further examination and experimental development [6]:

- Isotope rebalancing: plasma separation processes, TCAP, cryo-distillation, quantum sieving, laser isotope separation
- Primary loop protium removal: TCAP, plasma separation processes, cryo-distillation, gas chromatography, electromagnetic isotope separation
- Tritium storage technologies – alternatives to using depleted uranium: magnesium catalysed ball milled, zirconium cobalt, super diamond nanotube, ammonia borane SBA 15

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