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CONCEPTUAL DESIGN AND OPTIMISATION FOR JET WATER DETRITIATION SYSTEM CRYO-DISTILLATION FACILITY

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The aim of the Exhaust Detritiation System (EDS) of the JET Active Gas Handling System (AGHS) is to convert all Q-based species (Q_2, Q-hydrocarbons) into Q_2O (Q being indifferently H, D or T) which is then trapped on molecular sieve beds (MSB). Regenerating the saturated MSBs leads to the production of tritiated water which is stored in Briggs drums. An alternative disposal solution to offsite shipping, is to process the tritiated water onsite via the implementation of a Water Detritiation System (WDS) based, in part, on the combination of an electrolyser and a cryodistillation (CD) facility. The CD system will separate a Q_2 mixture into a detritiated hydrogen stream for safe release and a tritiated stream for further processing on existing AGHS subsystems. A sensitivity study of the Souers' model using the simulation program ProSimPlus (edited by ProSim S.A.) has then been undertaken in order to perform an optimised dimensioning of the cryodistillation system in terms of available cooling technologies, cost of investment, cost of operations, process performance and safety.

I. INTRODUCTION

The primary role of the Active Gas Handling System (AGHS) aims to provide the deuterium and the tritium for the fusion reaction for the Joint European Torus (JET) at the Culham Centre for Fusion Energy. Moreover, the AGHS has been designed to pump down the torus and the Neutral Injection Beam (NIB) crowns, to process and to analyse the exhaust gasses using several subsystems[1], and to store the reprocessed molecular deuterium (D_2) and tritium (T_2). Prior to the final release to the stack, the gas stream is sent to the Exhaust Detritiation System which converts any remaining tritiated gas QT (Q = H, D or T) and tritiated hydrocarbons into tritiated water which is trapped on molecular sieve beds (MSB). Each MSB regeneration produces approximately 40 L of tritiated water which are stored in Briggs drums which were, until recently, processed offsite.

An alternative solution is to process the tritiated water onsite via the implementation of a Water Detritiation System (WDS)[2,3]. This will be based, in part, on the combination of an electrolyser and a cryodistillation (CD) facility. The CD system will separate a Q_2 mixture into a detritiated hydrogen stream for safe release and a tritiated stream for further processing using existing AGHS separation subsystems.

As cooling is a large part of the WDS capital and running costs, the CD system must be designed to minimize these costs whilst still meeting the processing specifications. A sensitivity study of the Souers' model[4] has then been undertaken in order to perform an optimized dimensioning of the cryodistillation system in terms of available cooling technologies, cost of investment, cost of operations, process performance and safety. The simulation program ProSimPlus (edited by ProSim S.A.) has been chosen to carry out this study, similar to that used in previous works[5]. The parameters of interest of this work are the reflux ratio, the number of theoretical plates and the amount of tritium. The CD system layout (1 or 2 columns) is also discussed.

II. SOUERS' MODEL SENSITIVITY STUDY

II.A. CD column initial design.

TABLE I: First dimensioning of the CD column.

Plates number	200
Feed position (plate 1 at top)	150
Reflux ratio	3.3
Condenser power (plate 1)	282 W
Intermediate reboiler power (position)	200 W (@ plate 150)
Reboiler power (Plate 200)	80 W

Initial dimensioning of this CD column has been made assuming the 500 W condenser already used for the existing CD column is reused[6], leading to the preliminary dimensioning detailed in TABLE I.
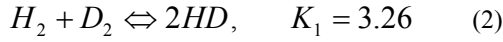
The reference water for this study possesses an activity of ~2 GBq/L and contains ~400 ppm of atomic deuterium. After the reduction of Q_2O by the electrolyser, this initial activity corresponds to 32 ppb of atomic tritium (using equation 1).

$$Parts = \frac{A}{\alpha \times M(T) \times \frac{1000}{M(H_2O)}} \qquad (1)$$

Where
- A is the activity of the initial water (GBq.L^{-1}).
- α is the specific activity of tritium (359000 GBq.g^{-1}).
- $M(i)$ is the molar mass of i-species (g.mol^{-1}).

Using the equilibrium constants at 300 K (see equations 2 to 4), one then obtains the relative mole fractions of the Q_2 species detailed in the first column of TABLE II:

$$H_2 + D_2 \Leftrightarrow 2HD, \qquad K_1 = 3.26 \qquad (2)$$
$$H_2 + T_2 \Leftrightarrow 2HT, \qquad K_2 = 2.58 \qquad (3)$$
$$D_2 + T_2 \Leftrightarrow 2DT, \qquad K_3 = 3.82 \qquad (4)$$

Finally, the numerical calculation using the column properties listed in TABLE I assuming a feed flow of 300 mol.h^{-1} and a bottom flow of 5.10^{-4} mol.h^{-1} gives the respective proportions of the bottom and distillate streams.

TABLE II: Q_2 speciation of the reduced reference water in the feed, distillate and bottom product of a CD column as defined in TABLE I.

Species	Relative proportions		
	Feed	Distillate	Product
H_2	~1	~1	4.70E-11
HD	4.00E-04	3.98E-04	~1
HT	3.20E-08	2.06E-23	1.92E-02
D_2	4.91E-08	6.62E-30	2.93E-02
DT	8.63E-12	0.00E+00	4.91E-06
T_2	3.97E-16	1.03E-29	2.15E-10
Flow (mol.h^{-1})	300.0005	300	0.0005

TABLE II sums up the results of the simulation of the performance of a column designed using TABLE I. It is visible that the distillate is highly tritium depleted, by around 15 orders of magnitude (equation 5).

$$DF = \frac{F \times \left(\sum y^f (QT) \right)}{D \times \left(\sum y^d (QT) \right)} \qquad (5)$$

Where
- DF is the Detritiation Factor.
- F is the feed molar flow (mol.h^{-1}).
- D is the distillate molar flow (mol.h^{-1}).
- QT stands for HT, DT and T_2 species.
- $y^f(i)$ and $y^d(i)$ are the mole fractions of i-species in the feed and the distillate, respectively (-).

Moreover, it becomes possible to calculate the tritium discharge per time unit:

$$\text{Rel}(T) = Av \times M(T) \times D \times \alpha \times \sum y^d (QT) \qquad (6)$$

Where
- $\text{Rel}(T)$ is the tritium release (Bq/time unit)
- Av is the system availability (as a function of the desired time unit, $Av = 1$, 24, and 4800 for hour, day and year, respectively, assuming 200 available days per year).

TABLE III gathers simulations carried out using different tritium amounts. It then becomes possible to assess the potential tritium release of a Cryo-Distillation system designed as in TABLE I.

TABLE III: Detritiation factor and annual release of a CD system as defined in TABLE I vs. [T], [D] = 400ppm. (ProSim)

Original activity of water (GBq.L^{-1})	^{3}H fraction (ppb)	DF (-)	Rel(T) (Bq.y^{-1})
1.92	32	1.79E15	0.028
6.01	100	1.73E15	0.090
24.05	400	1.44E15	0.434
60.13	1000	7.91E14	1.970
96.21	1600	2.74E13	91.04
120.26	2000	5.23E00	5.96E14

It is shown in TABLE III that the very large detritiation factors lead to very low tritium discharges up to 1600 ppb of atomic tritium. From 2000 ppb, for this bottom flow ($5x10^{-4}$ mol.h^{-1}), the column becomes saturated (~100% of HT in the product), which explains the drop of DF and consequently the exponential increase of the tritium release.

The feed position from the bottom of the column is not discussed in this study, as the simulations reveal a tritium concentration in the product high enough (~1-2%) to allow its reprocessing by existing AGHS subsystems.

Reuse of the existing AGHS 500W Cryogenic Refrigeration System (CRS) is impractical due to the need to fulfil AGHS tritium reprocessing and water detritiation functions simultaneously. It has thus been decided to manufacture a stand-alone system, CRS included. Therefore, the condenser power needs to be optimised in

order to obtain the best compromise between investment costs, running cost and separation efficiency.

II.B. Optimisation of the CD column.

II.B.1. Influence of the reflux ratio

The reflux ratio is a key parameter for a distillation process. It represents the ratio of the amount of vapour which has been liquified by the condenser over the distillate flow. This value is directly proportional to the condenser power duty and the enthalpy of vaporisation of the liquefied species, H_2 in our case (equation 7):

$$P = \Delta H_v\left(H_2\right) \times R \times \frac{D}{3600} \qquad (7)$$

Where:
- P: condenser power duty (W)
- ΔH_v (H_2): Enthalpy of vaporization of H_2 (= 906 J.mol^{-1})
- R: Reflux ratio (-)
- D: Distillate flow (mol.h^{-1})

Fig.1 shows the behaviour of the detritiation factor and the condenser power duty as a function of the reflux ratio. As expected from eq (7), a linear behaviour of the required condenser power is observed. However, the behaviour of the DF clearly reveals two distinct regimes. Between reflux ratio values of 1 and 2, the reflux ratio has a very high influence on the DF where the detritiation factor varies from 4.52 to ~10^{14} (a simulation with a reflux ratio of 1.5 gives a DF of ~10^9). Above R=2, the DF reaches a "plateau" (note that the left y-axis is plotted in logarithmic scale).
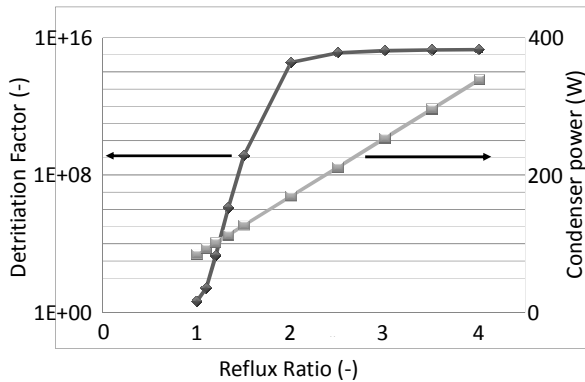

Fig. 1. DF (dark) and condenser power (bright) as a function of the reflux ratio. [T]=32ppb, [D]=400ppm. (ProSim)

It should be noted that a reflux ratio of 3.3, as initially planned, would have requested a condenser power of 282W whereas only 170W are needed for a reflux value of 2. A good compromise between power duty (P=127W) and a sensible tritium release is obtained using a reflux ratio of 1.5 (10MBq/year for a tritium amount of 1600ppb, which corresponds to an initial activity of water of ~ 100GBq.L^{-1}).

II.B.2. Influence of the number of plates

The number of plates is also an important parameter for the CD column design. Indeed, the number of plates defines the number of liquid/vapour equilibriums taking place in the column as well as the height of the column.
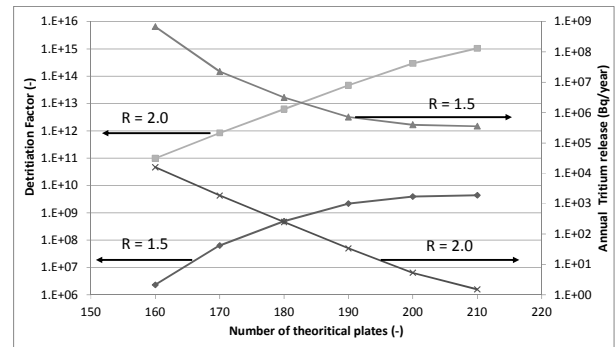

Fig. 2. DF and tritium release vs. of the plates number for R = 1.5 and 2.0. [T]=1000 ppb, [D]= 400 ppm (ProSim)

Fig. 2 shows the influence of the number of plates on the DF and the tritium release for reflux ratios of 1.5 and 2.0 (both y-axis in logarithmic scale). The influence of the number of plates is much more pronounced in the lowest range of the chart. An increase of 10 plates between 160 and 170 leads to a 30 times annual tritium release drop (from 6.78 x 10^8 to 6.37x10^7 Bq/year for R = 1.5) and this factor is only 1.12 (so +12%) between 200 and 210 plates. Moreover, this effect is much more visible for lower reflux ratio. As a comparison, for a reflux ratio of 2, the calculated tritium release is only 8.5 times higher for 160 plates (1.58 x 10^4 Bq/year) than for 170 plates (1.86 x 10^3 Bq/year).

Consequently, increasing the number of plates beyond that initially foreseen would not be very useful in terms of gain of performance, whereas a decrease of the number of plates might lead to a significant loss of performance. Therefore, 200 plates have been selected.

II.C. Influence of the system layout

It has been shown in the previous section that it was possible to optimise the power duty of the condenser by lowering the power required from 280 to 120 W, which represents a saving of ~60%. Nevertheless, for fixed experimental conditions (constant feed flow: 300 mol.h^{-1}, product flow: 0.5mmol.h^{-1}), the column becomes saturated above a tritium concentration of 2000 ppb

(120GBq.L^{-1} of initial water activity, see TABLE III) regardless of the reflux ratio. This phenomenon is due to the total tritium flow in the feed exceeds the total product flow. The remaining tritium migrates to the distillate, leading to a massive increase of tritium released and a collapse of the DF between 1600 and 2000 ppb. A solution would be to increase the product flow. In order to design the system to be as stable as possible, it is preferential to design the system to comprise of two columns instead of one (still fed at 50 plates from the bottom), as shown schematically in fig. 3.
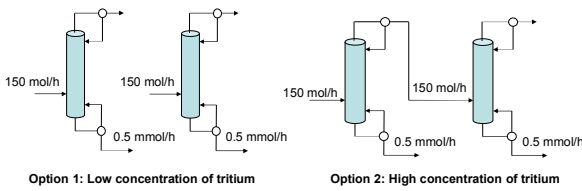

Fig. 3. Schematic representation of the 2 columns layout.

Two independent systems would be able to work in parallel for low concentrations of tritium (see option 1 in fig. 3), and in series when the activity exceeds a given value, lowering temporarily the productivity by half in case of very high activity (see option 2). The latter option would also increase the availability of the system if the maintenance of the columns is undertaken at different times.
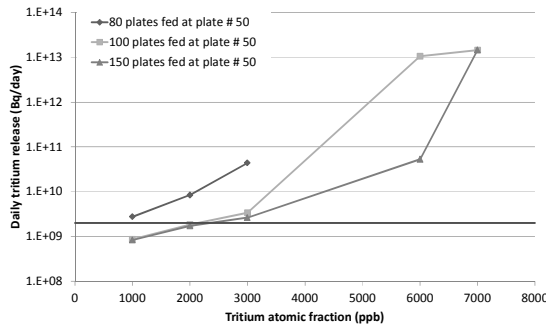

Fig. 4. Daily tritium discharge vs. [T] after column #1. F = 150 mol.h^{-1} (ProSim)

In order to design a twinned column system, it is necessary to estimate a sensible threshold tritium release value beyond which it is necessary to work in series. It has been decided to fix this value at 10% of the maximal authorised AGHS limit of discharge (40 GBq.day^{-1}, see ref 6), that is 2GBq.day^{-1}.column^{-1}. It should be noted this threshold is subject to change, and has been chosen for illustrative purposes.

Fig. 4 illustrates the influence of the tritium amount on the daily discharge from column # 1 for a reflux ratio of 1.5 (P = 64 W for F = 150 mol.h^{-1}) for different numbers of plates. The black straight line on fig. 4

represents the "switching threshold" set at 2GBq.day^{-1}.column^{-1}. It is visible that for 80 plates, it is necessary to work in series even below 1000 ppb of tritium; so in this case, there is no benefit in adopting the twinned column layout. Conversely, simulations using 100 and 150 plates reveal that it is possible to work in parallel up to 2000 ppb and to work in series beyond this amount.

TABLE IV: Detritiation factor and annual release of the 2nd CD column vs. [T] ([D] = 400ppm). R = 1.5. (ProSim)

Plates.column^{-1}	[T] (ppb)	DF (-)	Rel (Bq.day^{-1})
100	6000	8.70E03	2.69E09
	7000	1.83E01	1.49E12
150	6000	9.86E03	2.37E09
	7000	1.83E01	1.49E12

TABLE IV gathers the results of the simulations for high tritium amounts at the outlet of CD column number 2. It is visible that a 100-150 plates twinned system is able to cope with 6000 ppb of tritium when the work in undertaken in series.

100 plates per column is then the optimised value for each column, which is not surprising, 200 plates being the optimised value for a one column layout.

III. CONCLUSIONS

Twinned 100 plate CD columns have been designed in order to process the tritiated water produced by the AGHS EDS. The optimisation of the system has led to a reduction of ~60% of the condenser power (2x64W instead of 285W), and a tritium treatment capacity of 6000 ppb, three times higher than the original design. Studies for the physical sizing (choice of packing, internal diameter, calculation of HETP) are currently underway.

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