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ANALYSIS OF THE TRITIUM REQUIREMENTS FOR A POWER REACTOR

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ABSTRACT

The tritium cycle of a fusion reactor is hereafter investigated by a synthetic model of the tritium circulation between the blanket, the tritium recovery units from the breeder, the coolant, the plasma exhaust and the storage unit. Analytical expressions of the minimum required breeding capability and of the initial tritium supply are derived to analyse the sensitivity of these crucial parameters to the fractional burn up, to the tritium losses (radioactive and others) and to the processing time associated with the various units. As confirmed by the parametric study of a few typical situations, the necessary breeding capability and the initial tritium supply are essentially functions of the total equilibrium inventory. In addition, the distribution of this total inventory among the various units and the possible disproportion of the time scales required by different recovery processes, strongly influence the initial tritium requirement and the doubling time associated with given breeding performances.

I. INTRODUCTION

Effective tritium regeneration and minimization of the blanket inventory are often mentioned among the requirements, that the fusion reactor blanker studies must meet. However, the effective regeneration within the blanket, is not a strong enough requirement to ensure the continuous refueling of the reactor since the tritium loss and the time scale associated with the tritium processing operations may imply a minimum breeding capability and an initial tritium supply to start up the reactor, that may be out of reach. Likewise, the minimization of the tritium inventory within the blanket is not an objective in itself since it makes the recovery at a lower concentration more difficult and consequently leads to an increased inventory in the processing unit. An estimation of the minimum tritium requirements and of the necessary trade-offs between the inventories of the different units must be derived from the total fuel cycle optimization. The purpose of the present work is to identify the leading parameters and to derive some guidelines for such an optimization, from the synthetic analysis of the tritium cycle.

II. SYNTHETIC MODEL OF TRITIUM CIRCULATION

As shown on figure 1, the here adopted representation of the tritium cycle, consists of 6 units: the blanket, the plasma chamber and the storage unit are coupled together with 3 tritium processing units, respectively devoted to the recovery from the breeder, from the coolant and from the plasma exhaust. Each unit is characterized by a tritium mean residence time (T) and eventually by a tritium loss (ε) accounting for the complexity of the recovery operations and for the radioactive decay (λ). In addition, the fusion reactor is assumed to operate with a daily tritium consumption (αP) and a fractional burn up β. Typical values for a 1200 Mwe fusion reactor (3000 Mwth fusion power) could be αP=450 g/d and β= 5%. A fraction f of the bred tritium is assumed to permeate through the cooling tubes and to be recovered from the coolant ; the remaining (1-f) fraction is then recovered from the breeder.

Using the notation Λ for the blanket global breeding ratio, and those of figure 1 for the various other parameters, yields the following set of equations to describe the evolution of the tritium inventory in each peculiar unit :

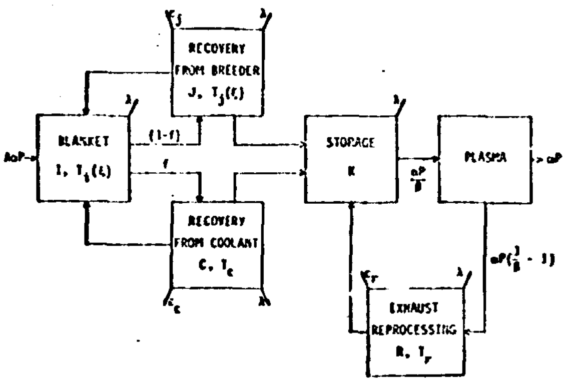
Blanket $$\frac{dI}{dt}=\Lambda\alpha P-\frac{I}{T_i}-\lambda I \quad (1)$$

Blanket processing unit $$\frac{dJ}{dt}=\frac{(1-f)I}{T_i}-(1+\varepsilon_j)\frac{J}{T_j}-\lambda J \quad (2)$$

Coolant processing unit $$\frac{dC}{dt}=\frac{fI}{T_i}-(1+\varepsilon_c)\frac{C}{T_c}-\lambda C \quad (3)$$

Plasma exhaust processing unit $$\frac{dR}{dt}=\alpha P(1/\beta-1)-(1+\varepsilon_r)\frac{R}{T_r}-\lambda R \quad (4)$$

Tritium storage unit $$\frac{dK}{dt}=\frac{J}{T_j}+\frac{C}{T_c}-\frac{\alpha P}{\beta}+\frac{R}{T_r}-\lambda K \quad (5)$$



Notations :

(I,J,K,C,R) : Inventories of the various considered units
T_U : Tritium mean residence time in unit U
ε_U : Non radioactive tritium loss in unit U
λ : Tritium decay constant
ξ : Recovered proportion of the tritium stream fed into the breeder reprocessing unit
f : Fraction of the bred tritium recovered from the coolant
αP : Daily burnt tritium mass
β : Fractional burn up
Λ : Effective tritium breeding ratio

Fig. 1. Synthetic model for the fusion reactor fuel cycle analysis

The proposed model assumes a steady inventory in the plasma chamber and in the coolant ; this corresponds to equilibrium inventories obtained in very short times. This assumption is obvious for the plasma chamber. It is also obvious for the coolant, once the permeation flux has gone through the cooling structure, since the total inventory does not exceed 80g with a 500 m^3 primary coolant circuit and a tolerable concentration of 1.5 Ci/l. However, the time for the permeation flux to reach the coolant may require days or months depending on wall thickness and temperature if trapping in irradiation defects[1] are assumed.

The tritium mean residence time T_i within the liquid blankets can be controlled over the blanket life time by an appropriate regulation of the breeder circulation. For the ceramic blanket however, T_i depends on the nature and texture of the breeder, on the temperature and on the size of the elementary grain ; it is fixed once only and cannot be adjusted over the life time.

The complete analytical expressions for the various inventories are indicated below :

Blanket :

$$I(t)=I_\infty\left[1-\exp\left(-\left(\frac{1}{T_i}+\lambda\right)t\right)\right] \text{ with } I_\infty=\frac{\Lambda\alpha P\, T_i}{(1+\lambda T_i)} \qquad (6)$$

Blanket and coolant processing units :

$$J(t)=J_\infty\left[1-\exp\left(-\left(\frac{1+\varepsilon_j}{T_j}+\lambda\right)t\right) - \left(\frac{1+\varepsilon_j+\lambda\, T_j}{1+\varepsilon_j-T_j/T_i}\right)\exp(-\lambda t)\left(\exp\left(\frac{-t}{T_i}\right)-\exp\left(-\left(\frac{1+\varepsilon_j}{T_j}\right)t\right)\right)\right] \qquad (7)$$

$$C(t)=C_\infty\left[1-\exp\left(-\left(\frac{1+\varepsilon_c}{T_c}+\lambda\right)t\right) - \left(\frac{1+\varepsilon_c+\lambda\, T_c}{1+\varepsilon_c-T_c/T_i}\right)\exp(-\lambda t)\left(\exp\left(\frac{-t}{T_i}\right)-\exp\left(-\left(\frac{1+\varepsilon_c}{T_c}\right)t\right)\right)\right] \qquad (8)$$

with

$$J_\infty=\frac{\Lambda\, \alpha P(1-f)\, T_j}{(1+\lambda\, T_i)(1+\varepsilon_j+\lambda\, T_j)} \text{ and } C_\infty=\frac{\Lambda\, \alpha P\, f\, T_c}{(1+\lambda\, T_i)(1+\varepsilon_c+\lambda\, T_c)}$$

Plasma exhaust processing unit :

$$R(t)=R_\infty\left[1-\exp\left(-\left(\frac{1+\varepsilon_r}{T_r}+\lambda\right)t\right)\right] \text{ with } R_\infty=\frac{P(1/\beta-1)T_r}{(1+\varepsilon_r+\lambda\, T_r)} \qquad (9)$$

Tritium storage unit :

$$K(t)=K_0\exp(-\lambda t)+\left(\frac{J_\infty}{T_j}+\frac{C_\infty}{T_c}+\frac{R_\infty}{T_R}-\frac{\alpha P}{\beta}\right)\left(\frac{1-\exp(-\lambda t)}{\lambda}\right)$$
$$-\frac{J_\infty\exp(-\lambda t)}{(1+\varepsilon_j-T_j/T_i)}\left[(1+\varepsilon_j+\lambda\, T_j)\frac{T_i}{T_j}\left(1-\exp\left(\frac{-t}{T_i}\right)\right) - \left(\frac{T_j/T_i+\lambda\, T_j}{(1+\varepsilon_j)}\right)\left(1-\exp\left(-\left(\frac{1+\varepsilon_j}{T_j}\right)t\right)\right)\right]$$
$$-\frac{C_\infty\exp(-\lambda t)}{(1+\varepsilon_c-T_c/T_i)}\left[(1+\varepsilon_c+\lambda\, T_c)\frac{T_i}{T_c}\left(1-\exp\left(\frac{-t}{T_i}\right)\right) - \left(\frac{T_c/T_i+\lambda\, T_c}{1+\varepsilon_c}\right)\left(1-\exp\left(-\left(\frac{1+\varepsilon_c}{T_c}\right)t\right)\right)\right]$$
$$-\frac{R_\infty\exp(-\lambda t)}{(1+\varepsilon_r)}\left(1-\exp\left(-\left(\frac{1+\varepsilon_r}{T_r}\right)t\right)\right) \qquad (10)$$

where K_0 is the initial tritium supply.

The blanket and the plasma exhaust processing units undergo a progressive saturation to the equilibrium level ; their derivative at t=0 take the respective values of $\Lambda\alpha P$ and $\alpha P(1/\beta-1)$ according to equations (1) and (4). The blanket and coolant processing units also converge to their equilibrium inventory ; however, their derivatives vanish at $t=0$, since no tritium has been bred so far in the blanket. The storage unit first undergoes a steep decrease, corresponding to a consumption rate of $\frac{\alpha P}{\beta}$ to feed the plasma chamber without any compensation from the recovery units. For sufficient values of Λ, the tritium provision takes a minimum value at a time t_0 and then builds up progressively, while the recovery units are becoming saturated. The initial tritium supply K_0 takes the minimum value when $K(t_0)$ vanishes.

The doubling time t_D is the time by which, the start up provision K_0 is built up in the storage unit. Simple first order expressions will be derived for these parameters, in order to facilitate the identification of the leading terms and the sensitivity analysis.

III. FIRST ORDER EXPRESSIONS OF THE MINIMUM BREEDING REQUIREMENTS

The equilibrium level of the storage inventory is easily derived from (5)

$$K_\infty = \frac{1}{\lambda}\left[\frac{J_\infty}{T_j} + \frac{C_\infty}{T_c} - \frac{\alpha P}{\beta}\right] \qquad (11)$$

The minimum requirement on Λ is given by $K_\infty \geq 0$. It expresses the minimum condition to keep the plant running : Λ must at least compensate for the radioactive decay of the total equilibrium inventory. A first order expression for Λ min is the following

$$\Lambda \text{ min} \;\#\; 1 + \varepsilon + \lambda T \qquad (12)$$

with $\varepsilon = (1-f)\,\varepsilon_j + f\,\varepsilon_c + (1/\beta-1)\,\varepsilon_r$

and $T = T_i + (1-f)\,T_j + f\,T_c + (1/\beta-1)\,T_r$

ε and T respectively express the global tritium loss and residence time integrated over the total fuel cycle.

The minimum requirement on Λ, for a single reactor to be able to regenerate its initial tritium provision is given by $K_\infty \geq K_0$ about equal to the total equilibrium inventory ($\alpha P.T$) for such low breeding performances.

$$\Lambda_\infty \;\#\; 1 + \varepsilon + \lambda T + \lambda\frac{K_0}{\alpha P} \;\#\; 1 + \varepsilon + 2\,\lambda T \qquad (13)$$

Λ_∞ compensates for the radioactive decay of twice the total equilibrium inventory ; this corresponds to an infinite doubling time t_D.

The first order expression of Λ to achieve a doubling time t_D is the following :

$$\Lambda(t_D) \;\#\; 1 + \varepsilon + T\left(\frac{1}{t_D} + \frac{\lambda}{2}\right) + \frac{\lambda K_0}{\alpha P} \qquad (14)$$

This equation obviously expresses the necessity to compensate for the tritium loss, for the accumulation over the t_D period of the equilibrium inventory plus the associated radioactive decay and for the decay of the initial provision. Expression (14) is derived for small values of λt_D (<1) and cannot be extrapolated to infinite t_D ; a $\frac{\lambda T}{2}$ discrepancy is indeed observed with the exact expression of Λ_∞ given by (13).

IV. TYPICAL ORDERS OF MAGNITUDE FOR THE INPUT PARAMETERS

The study of the INTOR (Li_2SiO_3 blanket) tritium system[2] gave a recent estimation of the various inventories associated with consumption and regeneration rates of 77 g/d and 50 g/d and with a fractional burn-up of 5%.

Tab. 1.	Inventory (g)	Mean residence time (d)
Plasma exhaust and neutral injectors	370	T_r=0.25
Blanket	500-1000	T_i=10-20
Recovery from the blanket	737	T_j=14.7
Recovery from the coolant with a 0.1 g/d permeation	65	T_c=650

The main conclusions from the above table are :

*that $T_r \ll T_i \;\#\; T_j \ll T_c$

*that the T_i value of 10 days for a solid blanket can probably be decreased to the level of about 1 day by adjusting the circulation rate of a liquid blanket

*that the very large value of T_c is mainly due to the (H_2+T_2) cryogenic distillation step, devoted to the 50% enrichment in tritium of the stream to be fed into the plasma exhaust reprocessing system

*that the disproportion between the times required for the various recovery processes will make the tritium requirements very sensitive to the fraction f of the tritium recovered from the coolant.

It is interesting to note, that the about equal distribtuion of the tritium inventory over both units of the blanket processing line ($T_i \# T_j$) also approximately corresponds to the minimum of ($I_\infty + J_\infty$). In the case of a liquid blanket T_i

and T_j may be expressed as functions of the extracted fraction ξ of the tritium stream from the breeder :

$$T_i = \tau(\frac{1}{\xi} - \frac{1}{2}) \text{ and } T_j = \tau_p \text{ Log } (\frac{1}{1-\xi})$$

with τ and τ_p respectively equal to the time for a complete blanket circulation and to the characteristic time for the exchange-like recovery process.

It is indeed remarkable, that whatever input values are assumed for τ and τ_p the ξ_{min} value that minimizes (T_i+T_j) yields about equal importance for both terms.

Tab. 2.

τ_p (d)	1			7		
τ (d)	1/2	1	2	1/2	1	2
ξ_{min}	0.50	0.62	0.73	0.23	0.31	0.41
T_i	0.75	1.12	1.73	1.89	2.68	3.86
T_j	0.69	0.96	1.32	1.87	2.64	3.71

V. PARAMETRIC STUDY OF A FEW TYPICAL SITUATIONS

The following table illustrates the sensitivity of the tritium requirements (Λ_{min}, Λ_∞, K_0) and of the variations of the tritium provision ($K(t)$, t_0, t_D) in a few typical situations with no other tritium loss than radioactive (ε=0).

T_r=0.25 d T_c=650 d ε=0 $0.\leq f \leq 0.1$ and

T_i=T_j=1 or 14 d.

Tab. 3.

		Λ=1.01		Λ=1.03		Λ=1.05		Λ=1.10		
f=0.	f=0.1	f=0.	f=0.1	f=0.	f=0.1	f=0.	f=0.1	f=0.	f=0.1	
T_i=T_j=1 d		6.752		6.619	33.393	6.556	19.523	6.433	7.117	$K_0/\alpha P$
T=6.75 d	T=71.65 d	6.8		5.4	920	4.8	520	4	70	t_0
Λ_{min}=1.00104	1.01105									
Λ_∞=1.00203	1.02210	207.6		239.4	3513	141.3	1532	70.1	410	t_D
T_i=T_j=14 d		32.374		31.165	62.567	30.247	47.060	28.480	33.2[illegible]	$K_0/\alpha P$
T=32.75 d	T=96.35 d	10[illegible].1		78.5	1070	67	600	57	110	t_0
Λ_{min}=1.00506	1.01487									
Λ_∞=1.01012	1.02974	~ ∞		1489.5	7283	799.3	2650	287.2	920	t_D

The following conclusions may be derived from the above studied examples :

V.A. <u>No tritium permeation to the coolant (f=0.)</u>

K_0 is about equal to the total equilibrium inventory (equal to T, when expressed in days of production αP) and very little sensitive to Λ. This corresponds to a rapid obtention of the time t_0 by which K(t) is minimum and to the impossibility to recover enough tritium from the blanket to compensate for the decrease of the provision to feed the reactor by then.

The time t_0 is given in first approximation by

$$\left(1 + \frac{t_o}{T_i}\right) \exp\left(\frac{-t_o}{T_i}\right) = \left(1 - \frac{\Lambda_{min}}{\Lambda}\right) \qquad (15)$$

This shows obviously that t_0 is proportional to T_i=T_j and weakly dependent on Λ only.

Indeed, the explored situation correspond to t_0 values of about $5T_i$ when Λ ranges from Λ_{min} to 1.10.

The first order expression of K_0 as a function of t_0 is given by

$$K_0 = I_\infty + R_\infty + J_\infty \left[1 - \left(1 - \frac{\Lambda_{min}}{\Lambda}\right) \frac{t_o}{T_i}\right] \qquad (16)$$

It expresses the fact that K_0 is about equal to the total inventory (equal to T, when expressed in days of production), minus the bred tritium in excess of Λ_{min}, by the time t_0 ; this potential reduction of K_0 is proportional to J_∞=I_∞ and does not exceed 40% J_∞ for $\Lambda \leq 1.1$.

Expression (14) with $K_0 \# T.\ \alpha P$ yields correct estimations of the doubling time as a function of T and Λ :

$$\frac{1}{t_D} \# \frac{(\Lambda - \Lambda_{min})}{T} - \frac{\lambda}{2} \qquad (17)$$

V.B. <u>Significant tritium leak towards the coolant (f=0.1)</u>

The precedent situation is strongly affected by the delayed recovery of a significant proportion of the bred tritium and by the consequent increase of the total equilibrium inventory T by 65 days of production ; the direct consequence is a strengthening of the required theshold for Λ.

As the coolant processing unit becomes very slowly saturated compared to the other units, and as the equilibrium inventory C_∞ is more than 60% of the total inventory in the above examples, the time t_0, when K(t) undergoes a minimum, is significantly increased compared with the f=0. situation. As a consequence K_0 becomes very sensitive to Λ and the appreciable amount of tritium recovered from the breeder by t_0 represents a substantial saving on the initial supply. The incentive for high breeding performances is obvious, while considering, that K_0 can be reduced to a small fraction of the equilibrium inventory : 10% to 35% with Λ=1.10 depending on T_i=1 or 14 days. It is worth to notice, that, in the extreme situation with T_i=1 day, the doubling time t_D is so short (410 d) that the equilibrium inventory is not yet obtained in the coolant processing unit.

First order approximations for t_0 and $K_0(\Lambda)$ may be derived :

$$t_0 \# T_i + T_c \operatorname{Log}\left(\frac{f}{1-\frac{\Lambda_{min}}{\Lambda}}\right) - \lambda\, T_c\, ((1-f)\, T_c + fT_i) \qquad (18)$$

$$K_0(\Lambda) \# I_\infty + R_\infty + J_\infty \left[1 - \left(1-\frac{\Lambda_{min}}{\Lambda}\right)\frac{t_0}{T_j}\right] + C_\infty\left[\left(1+\frac{T_i}{T_c}\right)\left(1-\exp\left(-\frac{t_0}{T_c}\right)\right) - \left(1-\frac{\Lambda_{min}}{\Lambda}\right)\frac{t_0}{T_c}\right] \qquad (19)$$

Equation (18) expresses a quasi proportionality of t_0 to T_c and its dependence on the leading parameters f and Λ. Equation (19) indicates the potential savings on K_0 associated with high breeding performances ; the great sensitivity to Λ is explained by the amplication of the t_0 dependence on Λ by the factor T_c in equation (18) rather than by T_i in equation (15). The maximum saving on K_0 is the equilibrium inventory of the coolant processing unit ; in return, values of Λ about Λ_{min} require to provide the total equilibrium inventory to start up the reactor.

A satisfactory approximation of t_D is given by

$$\frac{1}{t_D} \# \frac{(\Lambda-\Lambda_{min}) - \lambda K_0(\Lambda)/_{\alpha P}}{T} + \frac{\lambda}{2} \qquad \text{with} \qquad (20)$$

$$T = \left[T_i + (1-f)T_j + f\ T_c\left(1-\exp\left(-\frac{t_D}{T_c}\right)\right) + \left(1/\beta-1\right)T_r\right]$$

and $K_0(\Lambda)$ expressed by (19).

The modified expression of the global residence time T accounts for the possibility of having the coolant processing unit not fully saturated at t_D.

V.C. Non radioactive tritium loss

Above examples assume only radioactive tritium loss (ε-0.). Accounting for other loss (trapping, leak) in the above considerations is immediate, while integrating the ε term in the Λ_{min} expression (12). The amplification factor $(1/\beta-1)$ (equal to 19 for β=5%) makes ε_r the leading term. If all processing losses are about equal, the 10% margin corresponding to a Λ value of 1.10 would require these non radioactive losses not to exceed 5‰. More realistic considerations about the tolerable contribution of ε to Λ_{min} would require to reduce ε_r to about 1‰. Figure 2 indicates the requirement on $(\Lambda-\varepsilon_r/\beta)$ as a function of the total residence time T to achieve a given doubling time t_D ; the possibility of obtaining a total inventory T with different contributions of the various units (variable values of f in the 0, 10% range) corresponds to an about 1% dispersion on the required values of Λ.

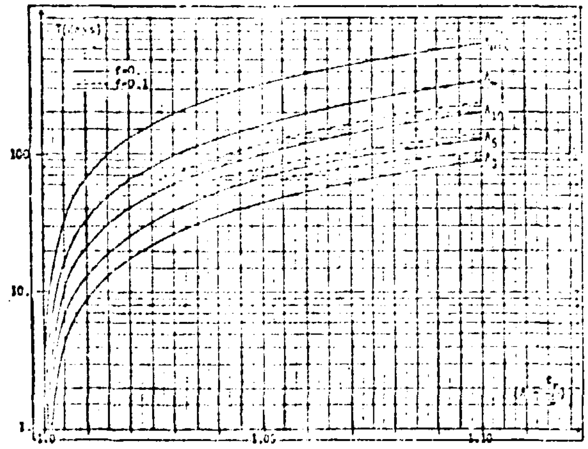


Fig. 2. Breeding requirements $(\Lambda-\frac{\varepsilon_r}{\beta})$ for t_D=3, 5, 10, ∞ years versus total residence time T

VI. CONCLUSION

The global tritium residence time and tritium loss associated with all the reprocessing operations are the leading parameters of the breeding and initial supply requirements. However, those requirements also depend on the distribution of the total inventory among the various units and on the possible disproportion of the time scales required by different recovery processes. As an example, the table 4 indicates these requirements for a fusion reactor characterized by the presently anticipated operating conditions for INTOR (Table 1), with 0 and 10% of the tritium permeating to the coolant.

For a β value as low as 5%, each increase by 1‰ of the non radioactive tritium loss ε_R implies an increase by 2% of the required breeding performances.

Tab. 4.		t_D (years)	∞	10	5	3
f	T (days)	$\Lambda_{min} - \frac{\epsilon_r}{\beta}$	$\Lambda_{\infty} - \frac{\epsilon_r}{\beta}$	$\Lambda_{10} - \frac{\epsilon_r}{\beta}$	$\Lambda_5 - \frac{\epsilon_r}{\beta}$	$\Lambda_3 - \frac{\epsilon_r}{\beta}$
0.	32.75	1.005	1.010	1.015	1.025	1.035
$K_o/\alpha P$ (days)		32.8	32.4	32.1	31.5	30.9
0.1	96.75	1.015	1.030	1.040	1.065	1.090
$K_o/\alpha P$ (days)		96.8	62.6	54.8	43.0	36.0

Even if achieving effective breeding performances significantly in excess of one still remains questionable, the requirements of table 4 derived with rather pessimistic assumptions do not seem absolutely out of reach if the envisaged recovery processes can restrict the non radioactive loss to about 1‰. However, the deleterious effects of a delayed recovery of an appreciable fraction of the bred tritium appears to be a serious concern and the optimization of the tritium cycle clearly requires the minimization of the total plant inventory. This is the main incentive to investigate either reduced inventory coolant processing units or efficient permeation barriers ; the selection of the best option may arise from the comparison of the equilibrium inventory of the plant to process the permeation flux, with the increased trapped inventory associated with the permeation barrier.

As a conclusion, the proposed model of tritium circulation is a first approach to evaluate and to compare the capacity of any blanket solution to effectively sustain the fuel cycle of a fusion reactor. Combining the blanket performances with realistic input parameters to characterize the tritium processing units, also permits a preliminary optimization of the total plant inventory by adjusting the leading parameters emphasized by the analytical expressions and thus providing some guidelines for the necessary trade-offs among the various tritium processing units.

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