Breeding ratio, minimum startup inventory and doubling time in fusion power reactors

Alya A. Badawi
Nuclear Engineering Department, Alexandria University, Alexandria, Egypt

The tritium breeding ratio, the minimum startup inventory, and the doubling time are the leading parameters that determine the acceptance of any fusion reactor. These parameters are controlled by many factors such as the residence times, the nonradiative losses, and the plasma burnup. An analysis was carried out to investigate the effect of different reactor parameters on the minimum required startup inventory and the doubling time and to find out the value of the tritium breeding ratio that leads to reactor self-sufficiency. A reference case, corresponding to the predicted data of a 1 GW electric fusion power plant, was used as a base for calculations. The analysis showed that the minimum tritium-breeding ratio required attaining a self-sufficient reactor under the conditions of the reference case is 1.15. It also showed that the minimum startup inventory and the doubling time would be primarily affected with the tritium behavior inside the plasma exhaust-reprocessing unit and inside the blanket. It was found that the other parameters of the reactor components would not significantly affect the startup inventory and the doubling time in the range of values expected. The same holds for the plasma burnup.

تعتبر نسبة توليد التريتيوم، و الكمية الصغرى البادئة، و زمن التضاعف من أهم العوامل التي تحدد مدى صلاحية أي مفاعل اندماجي. هذه العوامل يمكن التحكم فيها عن طريق أزمنة التواجد و الفاقد غير المشع و معدل حرق البلازما. في هذا البحث تم عمل تحليل لبيان تأثير هذه العوامل على الحد الأدنى لكمية التريتيوم البادئة و زمن التضاعف. كما تم حساب قيمة أقل نسبة توليد للتريتيوم التي تكفي لتشغيل المفاعل ذاتيا. و في البحث تم اختيار حالة مقارنة فيها المفاعل ذات قدرة ١ جيجاوات كهربي. و قد أوضح التحليل أن مستوى التريتيوم اللازم لأن يكون المفاعل ذاتي التشغيل هي ١،١٥ و أن القيمة الدنيا للكمية البادئة لتشغيل المفاعل و زمن تضاعف كمية التريتيوم يكونون أشد تأثرا بالمعطيات الخاصة بمنطقة اعادة تصنيع عادم البلازما و بالغلاف. و قد تم التأكيد أيضا على أن العوامل الأخرى لمكونات المفاعل ليست ذات أهمية شديدة في الكمية البادئة و زمن التضاعف، و بالمثل لمعدلات حرق البلازما.

Keywords: Tritium fuel cycle, Breeding ratio, Startup inventory, Doubling time, Residence time, Nonradiative losses.

1. Introduction

In the design of fusion power reactors based on D-T fuel, consideration of the issues concerning tritium will be of prime importance. One of the most important issues is the tritium self-sufficiency. A self-sufficient reactor is a reactor that breeds tritium inside the blanket with sufficient amounts to: (1) sustain its normal operation, (2) compensate for the amounts lost by radioactive decay as well as other nonradiative losses, and, (3) produce enough tritium to startup another reactor [1]. Tritium breeding within the blanket does not ensure the continuous refueling of the reactor due to the tritium loss and the time scale associated with the tritium processing operations. Therefore, in order to successfully operate a fusion power reactor, the tritium breeding ratio (defined as the number of tritium atoms produced per atom consumed in the plasma [2]) will have a minimum value which the reactor has to achieve in order to be self-sufficient.

Successful operation of the reactor will also imply an initial tritium supply to start up the reactor [3] and sustain its operation until the tritium bred in the blanket reaches the plasma (i.e., until the reactor becomes self-sufficient). Due to the short supply of tritium and its very high price (~$30,000/g [4]), the startup requirements could have a

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considerable cost impact on the plant. For example, if the required initial inventory is 10 kg, the cost will be several tens of millions of dollars, which is in the range of other major plant components, such as the plasma confinement magnets [5]. Therefore, minimization of the startup inventory is often mentioned among the requirements that the fusion reactor must meet.

In order to achieve a satisfactory introduction pace of the fusion plants, the early fusion plants must be able to produce the initial inventories for the subsequent reactors in a reasonably short term [4]. If it takes a longer term, the pace of introduction becomes slower. Thus it is important to estimate this term, i.e., the tritium doubling time, defined as the time taken for the tritium in the storage to become twice the amount of the minimum startup inventory [1].

The above argument leads to the conclusion that the tritium breeding ratio, the doubling time, and the minimum startup inventory are three parameters that will considerably influence the design of any fusion reactor in order to prove its feasibility [6]. Therefore, careful evaluation of these parameters and investigation of their dependence on other parameters of the fuel cycle systems and of other plant components are necessary, since knowledge of the cause-effect relationship may then be used to identify the more critical design parameters and to define their domain of relevance.

The early models that considered the relation between breeding, inventory and doubling time ignored many of the reactor parameters, such as the transient times inside various reactor components [7]. A model has been developed by the author in order to investigate the tritium inventory in different components of the fusion reactor [8]. In this paper, the calculation results of the model are used to study the effect of different reactor parameters on the minimum required startup inventory and the doubling time and to investigate the value of the tritium-breeding ratio that leads to reactor self-sufficiency.

2. Model description

A model has been developed for estimating the time dependent tritium inventory inside different reactor component [8]. Details of the model are found in Ref [8]. The model divides the reactor into 12 subsystems, as shown in Fig. 1:

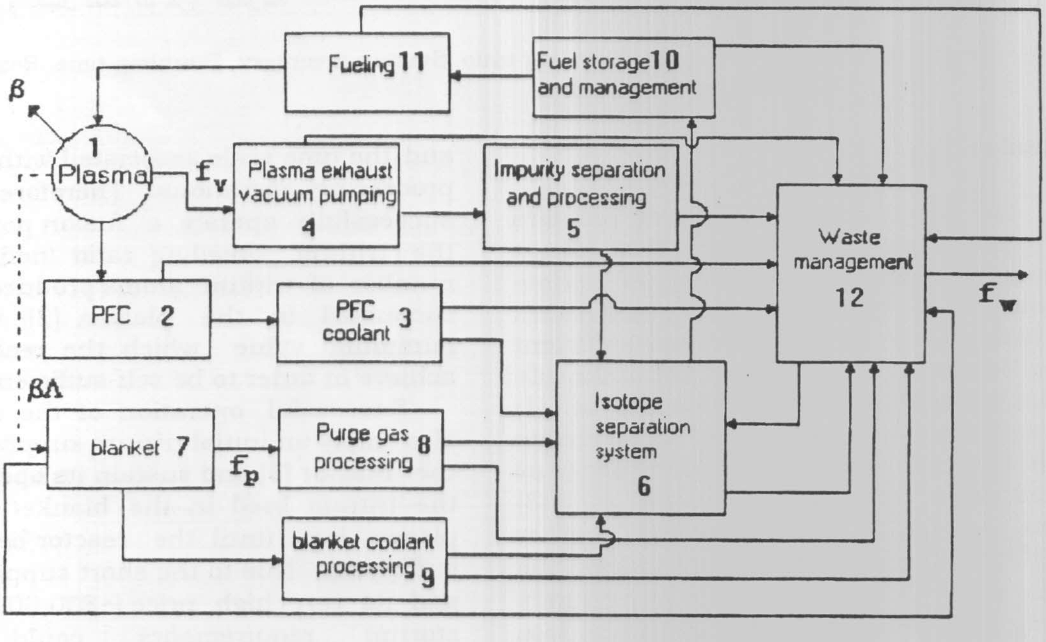

Fig. 1. Schematic diagram showing the different components of a fusion reactor [8].

1. Plasma.
2. Plasma facing components (PFC).
3. PFC coolant.
4. Plasma exhaust reprocessing system.
5. Impurity separation and processing.
6. Isotope separation system (ISS).
7. Breeding blanket.
8. Purge gas processing.
9. Blanket coolant processing.
10. Fuel storage and management.
11. Fueling system.
12. Tritium waste treatment.

Each unit is characterized by a tritium mean residence time, τ, and a tritium loss term accounting for the complexity of the recovery operations. For each subsystem, the following equation is applied [4]:

$$\frac{dI_i}{dt} = \sum_{j \to i} \left(\frac{I_j}{\tau_j} \right) - \frac{I_i}{\tau_i} - (a_i + \lambda) I_i \qquad i = 1, \ldots, 12; i \neq 7. \qquad (1)$$

Where I is the tritium inventory (kg), a is the fraction of tritium lost per day to the body of the reactor, to the atmosphere, or by leakage/permeation to the liquids present in the reactor (such as water, oils, etc.), and λ is the tritium decay constant (day^{-1}). The subscripts i and j denote the subsystem of interest and the other subsystems, respectively. For the breeding blanket, the equation becomes [8]:

$$\frac{dI_i}{dt} = \beta \Lambda \frac{I_1}{\tau_1} - \frac{I_7}{\tau_7} - (\lambda + a_7) I_7 \qquad i = 7. \qquad (2)$$

Where β is the plasma burn up (defined as the fraction of tritium atoms fusing inside the plasma) and Λ is the tritium breeding ratio (TBR).

Applying Eq. (1) to each reactor component and Eq. (2) to the blanket, the time-dependent tritium inventory in each component of the fusion system can be determined in terms of component parameters such as mean residence times, tritium loss rates, fuel fractional burnup, and tritium breeding ratio.

Initially, all tritium inventories in the reactor are equal to zero, with the exception of the fuel inventory in the storage [8], i.e.,

$$I_i(t=0) = 0 \quad i = 1,\ 2,\ 12, \quad i \neq 10\ , \qquad (3)$$

$$I_{10}(t=0) = I_{st}. \qquad (4)$$

Note that the minimum value of I_{st} that can be used to keep the reactor operating is the minimum required startup inventory. The doubling time, t_d, is equal to the time at which $I_{10} = 2\, I_{st}$.

3. Results and discussion

3.1. Calculation procedure

The model was used to perform an analysis of the tritium fuel cycle inside a fusion power reactor in order to investigate the influence of different parameters on the minimum required startup inventory and the doubling time. Eqs. (1) and (2) show that the plasma burnup, the tritium breeding ratio, the residence times, and nonradiative losses are the parameters that affect I_{st} and t_d. Therefore the calculations were made in order to assess how these parameters can influence the startup inventory and doubling time, and to find out the range of acceptable parameters that can achieve reactor self-sufficiency. Table 1 shows the numerical data used as a reference case in the calculations, which correspond to the predicted values in a 1 GW electric power reactor [6,9,10]. This data was used as input in the computer code developed from the model. Each time the code was run using the reference data with the exception of one value that was changed to see its effect on I_{st} and t_d. The residence times were changed between 0.001 - 500 days. The nonradiative losses were changed between 0 - 5%. The plasma burnup was changed between 1 - 100% and the tritium breeding ratio was changed between 0.8 -1.7.

Table 1. Performance parameters used in the calculation model for the reference case [6, 9, 10].

Parameter	Value
Tritium burnup in plasma (kg/day)	0.5
Tritium fractional burnup in plasma, β (%)	5
Nonradioactive losses (%)	
Plasma	1×10^{-10}
Plasma facing components (PFC)	0.1
PFC coolant	0.1
Plasma exhaust	0
Impurity separation and processing	0
Isotope separation system	0.1
Breeder blanket	0.1
Purge gas	0.1
Blanket coolant	0.1
Fueling system	0.1*
Fuel storage	0.1*
Waste management	0.1*
Tritium mean residence times (day)	
Plasma	1.5
Plasma facing components (PFC)	100
PFC coolant	100
Plasma exhaust	1
Impurity separation and processing	0.1
Isotope separation system	0.1
Breeder blanket	10
Purge gas	1
Blanket coolant	100
Fuel system	0.014
Fuel storage	--
Waste management	100*
Tritium fractional leakage from	
Blanket to blanket coolant (%)	1
Plasma to plasma exhaust processing (%)	99.99
Waste management to isotope separation system (%)	10*
Fraction of tritium processed in the waste management unit (%)	10

* Estimated values.

3.2. *Evaluation of the tritium-breeding ratio required for attaining reactor self-sufficiency*

Figure 2 shows the effect of the tritium breeding ratio on the minimum startup inventory. When TBR values less than 1.15 are used the reactor is not self-sufficient. An external amount of tritium is required throughout the reactor lifetime to compensate for different losses in the reactor. At values ≥ 1.15 the reactor becomes self-sufficient and only an initial amount will be required. Increasing the tritium breeding ratio above 1.15 does not change the required I_{st}. This can be explained as follow: in conventional fusion reactors, most of the tritium will flow through the plasma fueling/exhaust line because the tritium fractional burnup in the plasma is relatively small, for example, in the order of a few percent [4].

Because of this burnup inefficiency, most of the tritium fuel does not participate in fusion reaction burn but is exhausted through the diverter/limiter and onto the plasma exhaust reprocessing components. The tritium in the fuel storage subsystem will feed this loop during the start of operation when the tritium produced in the breeder has yet to flow through this loop [4]. Therefore the amount of tritium needed during the start will not depend on how much tritium is being bred in the breeder blanket (represented in the TBR) but on how fast it can reach the plasma (represented in the residence times) [11].

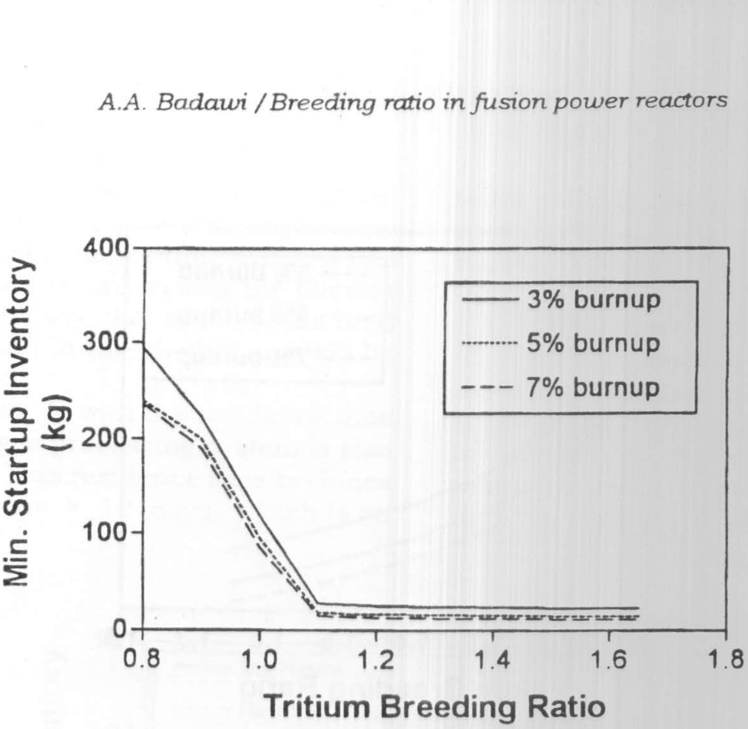

Fig. 2. Effect of the tritium breeding ratio on the minimum required startup inventory for different plasma burnup.

At low TBR values, the increase in I_{st} does not correspond to an increase in the amount of tritium required to startup the reactor, but rather on the presence of an external amount required throughout the life of the reactor, since the amount of tritium bred in the blanket is not sufficient to sustain reactor operation.

The effect of the plasma burnup on the required tritium-breeding ratio is also shown in the figure. At 3% burnup, self-sufficiency is reached at TBR ≥ 1.2. At 7% burnup, the minimum TBR is 1.1. However, changing the plasma burnup between 3-7% does not produce a significant change in the value of I_{st} (see Fig. 2). Values of β higher than 7% are not shown in the figure because increasing β more than 7% is not practical or feasible at this stage [4]. However, if the burnup increases to 10% the required startup inventory decreases by ~ 40%. For 100% burnup, which corresponds to the case when all the tritium reaching the plasma will be consumed in fusion, the required startup inventory will be less than one third the amount required at 5% burnup. This is because an increase in the fractional burnup means a decrease in the time the tritium atoms spend going through the fuel cycle. This in turn means a decrease in the radioactive and nonradiative losses. This decreases the part of I_{st} that is required to compensate for these losses. On the other hand, decreasing the burnup to 1% leads to a significant increase in the required external source of tritium (about one order of magnitude higher than the reference case). The reactor in this case is not self-sufficient due to the large losses in different components.

Figure 3 shows the effect of the tritium breeding ratio on the doubling time. Again, for values of the tritium breeding ratio < 1.15, the reactor is not self-sufficient, and therefore there is no doubling time. For values more than 1.15, the doubling time decreases with increasing the TBR. Increasing the TBR to 1.2 decreases the doubling time by ~40%. For the same TBR, increasing the plasma burnup decreases the doubling time. This is done via minimizing the amount of tritium taken from the storage to compensate for the losses throughout the fuel cycle.

The tritium breeding ratio has an effect on the doubling time at all values. This is to be expected because as the TBR increases, the number of tritium atoms produced increases, which means that the amount of tritium in the storage increases faster than the cases with low TBR.

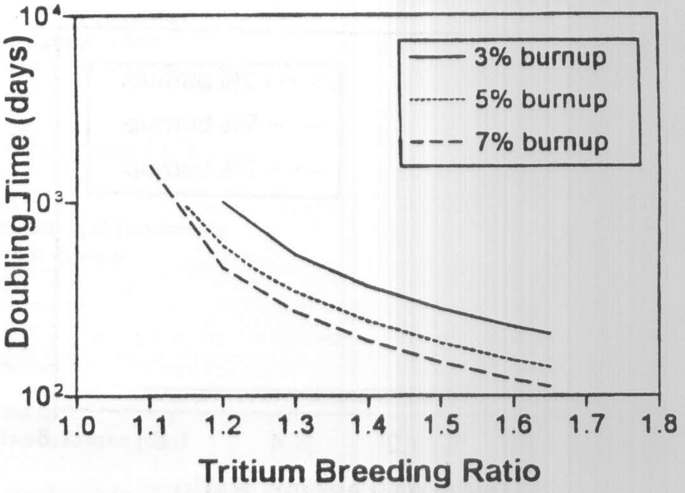

Fig. 3. Effect of the tritium breeding ratio on the doubling time for different plasma burnup.

3.3. The minimum required startup inventory

In addition to the effect of the TBR and the plasma burnup on the minimum required startup inventory, the effect of different residence times was investigated. A TBR of 1.15 was used in all the calculations. This value represents the minimum tritium breeding ratio required to attain self-sufficiency for a reactor operating with the reference data. The results are shown in Figures 4 and 5. The residence times of the components that are not shown in the figures have no influence on I_{st}. It can be seen from Fig. 4 that the tritium residence time inside the plasma does not have a significant effect on I_{st} except at values > 10 day, which is an order of magnitude higher than the reference case (1.5 day). When the TBR is increased to 1.2 the minimum value which produces an effect on I_{st} increases to 30 day (not shown). Therefore, it is safe to conclude that the plasma residence time will not be of prime concern in designing the reactor.

The plasma exhaust processing residence time starts affecting the startup inventory at values as low as 0.1 day (see Fig. 4). Increasing τ from 0.1 to 1 day doubles I_{st}. Above this value I_{st} increases proportionally to τ. When τ is $\geq$ 2 days, the reactor is not self-sufficient. Increasing the tritium breeding ratio has an insignificant effect on this relation (not shown in the figure). Increasing the burnup decreases I_{st}. However, it does not diminish the effect of τ. This is explained by noting that β is usually $\lesssim$ 10%, which means that about 90% of the tritium entering the plasma leaves without fusing and flows into the plasma exhaust system. Thus it is very important for this tritium to leave this subsystem and be recycled back into the plasma as soon as possible.

From Fig. 4 it can be seen that the effects of the residence times inside the impurity separation and processing unit and the isotope separation system are identical. Note that both units are connected in series. Therefore, the unit with the higher residence time will be the one affecting the cycle. The figure shows that the change in I_{st} with values of $\tau > 1$ day is approximately linear. However, since the reference values of both units are 0.1 days, these residence times will not be of strong influence.

The change in the minimum startup inventory with the tritium residence time in the blanket is shown in Figure 5. The reference value used is $\tau = 10$ day. Below this value the change in I_{st} is not big. However increasing τ to 50 day doubles the value of I_{st} and requires maintaining an external tritium source during reactor operation. Noting that the blanket is the only source of tritium (beside the external source), the importance of decreasing the residence time inside it can be understood, since increasing the blanket residence time means that much of the bred tritium will remain in the blanket and will be of little use as fuel.

The change in I_{st} with the residence time inside the purge gas processing system is also shown in Fig. 5. This residence time becomes important at values > 10 days, which is an order of magnitude higher than the reference case (1 day).

Figure 5 shows the effect of the residence time in the fueling system on I_{st}. At values of $\tau \leq 1$ day, there was no change in I_{st}. Values of $\tau > 1$ day prevents the reactor from tritium input to the plasma. A large reaching self-sufficiency. Note that the fueling system has to provide a constant residence time will require a large tritium inventory inside the unit in order to provide the same input.

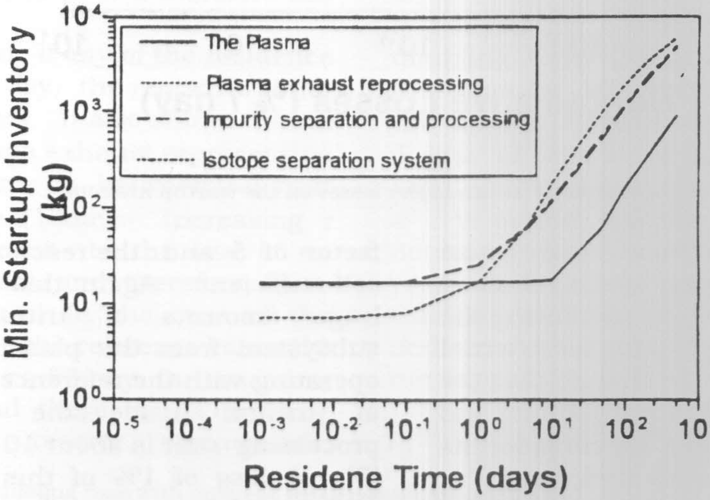

Fig. 4. Effect of the residence time on the required min tritium inventory.

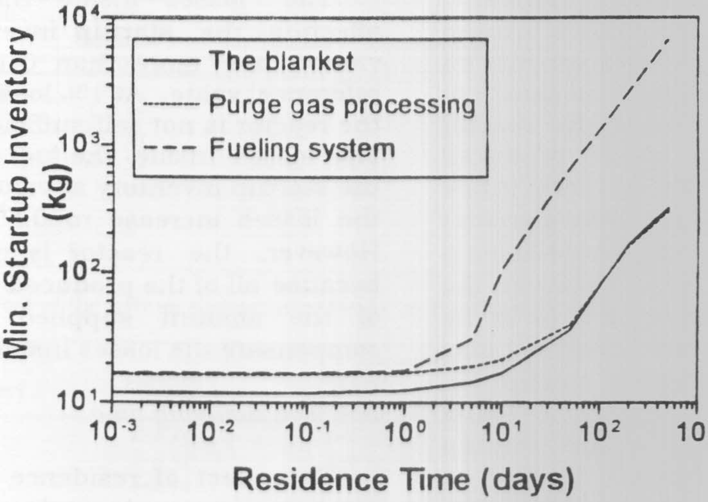

Fig. 5. Effect of the residence time on the required min tritium inventory.

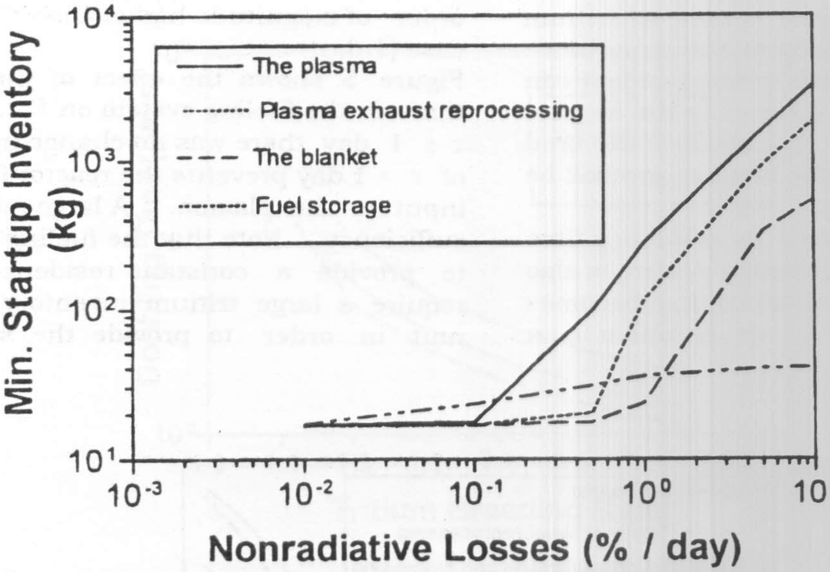

Fig. 6. Effect of the nonradiative losses on the startup inventory.

However, a large inventory will cause significant losses in tritium, which will need to be compensated either by increasing the tritium breeding ratio or by using an external source. It should be noted though that the reference case is τ = 0.014 day (20min) and therefore there is no need to consider its effect on the minimum startup inventory.

From Figs. 4 and 5 and the above discussion, it can be concluded that I_{st} will be mainly affected by the residence times inside the plasma exhaust unit and inside the blanket.

The effect of the nonradiative tritium losses inside different reactor components on the minimum startup inventory is shown in Fig. 6. Only the losses inside the reactor components shown in the figure produced significant changes in I_{st}. The loss term in the plasma starts affecting I_{st} for values greater than 0.1%. After this I_{st} increases linearly with increasing the loss term. However, the losses in the plasma are expected to be in the order of 10^{-10}%, and, therefore, it will not play an important role in designing the reactor.

The loss term in the plasma exhaust processing unit also affects the startup inventory. Values lower than 0.1% had no effect on I_{st}. Increasing the losses to 1% increased the required inventory by about a factor of 5 and the reactor does not become self-sufficient. Again this is because of the huge amounts of tritium entering this subsystem from the plasma. For a reactor operating with the reference data, the amount of tritium inside the plasma exhaust processing unit is about 10 kg at steady state [8]. A loss of 1% of this amount per day corresponds to more than 100kg during a reactor operation of 5 years. This is a very large amount to be compensated.

The losses inside the blanket starts affecting the startup inventory when their values are more than 0.1%, which is the reference value. At 1% loss I_{st} is doubled and the reactor is not self-sufficient.

The losses inside the fuel storage unit affect the startup inventory at values = 0.1%. When the losses increase to 0.5%, I_{st} is doubled. However, the reactor is not self-sufficient, because all of the produced tritium plus some of the amount supplied externally go to compensate the losses inside the storage.

3.4. The doubling time

The effect of residence times in different reactor components on the doubling time was investigated.The results are shown in Table 2.

There are seven components whose residence times influence t_d. Those are: the plasma, the plasma exhaust reprocessing system, the impurity separation and processing unit, the isotope separation system, the blanket, the purge gas reprocessing unit, and the fueling system. Only ranges of data and not exact values are shown, since the requirement in a fusion reactor is a short doubling time, usually defined as less than 5 years. This is opposed to the minimum startup inventory, which has to be precisely specified, since a 1kg increase will cost ~ $\$ 30 \times 10^6$ [4]. The missing data in Table 2 correspond to cases that are not self-sufficient and therefore has no doubling time.

The table shows that if any of the residence times become = 50 day, the reactor will not achieve self-sufficiency. It also shows that in the case of the plasma exhaust reprocessing unit the doubling time is between 2-3 yr at the reference value (1 day). Increasing τ above this value leads to the use of an external tritium source, and, therefore, there is no doubling time. In the case of the blanket, for τ equal to the reference value (10 day), t_d = 2-3 yr. For $\tau > 50$ day, the reactor is not self-sufficient and there is no doubling time. For other reactor components, increasing τ by a factor of 10 will not cause a problem. Thus, the blanket and the plasma exhaust reprocessing unit will be the two components significantly affecting t_d.

The effect of the nonradiative losses on the doubling time is shown in Table 3. As expected, the reactor subsystems that have a high inventory will affect the doubling time. These subsystems are: the plasma (~15 kg), the plasma exhaust reprocessing system (~ 10 kg), the blanket (~6 kg), and the fuel storage (~ 92 kg at the end of a 5-yr operation period) [8]. From Table 3 it can be seen that increasing the losses more than 0.5% in any subsystem prevents the reactor from being self-sufficient. The loss term that affects the doubling time the most is the loss inside the fuel storage, which is logic since it contains the largest amount of tritium in the reactor. A loss of 0.05% of the tritium inventory per day corresponds to the loss of a 40 kg during a 5 yr-period. This causes an increase in the doubling time to about 1920 days. Above this value the reactor is not self-sufficient. Note that the reference value is 0% (no losses) and, therefore, a 0.05% is a high value that is not expected.

Table 2. Change of the doubling time with different residence times.

Residence Time (day)	Doubling time						
	Plasma	Plasma exhaust unit	Impurity separation	Isotope separation system	Blanket	Purge gas	Fueling System
0.001	2-3 yr	1 yr	2-3 yr	2-3 yr	1-2 yr	2-3 yr	2-3 yr
0.01	2-3 yr	1-2 yr	2-3 yr	2-3 yr	1-2 yr	2-3 yr	2-3 yr
0.1	2-3 yr	1-2 yr	2-3 yr	2-3 yr	1-2 yr	2-3 yr	2-3 yr
1	2-3 yr	2-3 yr	3-4 yr	3-4 yr	1-2 yr	2-3 yr	3-4 yr
5	2-3 yr	-----	> 5 yr	> 5 yr	2-3 yr	3-4 yr	-----
10	3-4 yr	-----	> 5 yr	> 5 yr	2-3 yr	3-4 yr	-----
50	-----	-----	-----	-----	> 5 yr	> 5 yr	-----
100	-----	-----	-----	-----	-----	-----	-----

Table 3. Effect of the tritium nonradiative losses on the doubling time.

	Doubling time			
Loss (%/day)	Plasma	Plasma exhaust unit	Blanket	Storage
0	2-3 yr	2-3 yr	2-3 yr	2-3 yr
.01	2-3 yr	2-3 yr	2-3 yr	2-3 yr
.1	4-5 yr	2-3 yr	2-3 yr	> 5 yr
.5	-----	> 5 yr	4-5 yr	-----
1	-----	-----	-----	-----

4. Conclusions

The minimum required tritium breeding ratio and startup inventory, and the doubling time have been investigated for a fusion power reactor, using a developed calculation model that simulated the tritium fuel cycle. The effect of changing various reactor parameters, such as the residence times in different reactor components, the nonradiative losses, and the plasma burnup, have been determined using reference data that corresponds to the predicted values of a 1 GW electric fusion reactor. The following conclusions were made:

1. The minimum tritium breeding ratio required to attain a self-sufficient reactor under the conditions of the reference case is 1.15. This is considered to be a feasible breeding ratio that can be reached without difficulty.
2. The dominant parameters are those of the plasma exhaust reprocessing unit and the blanket. It is expected that their residence times will be extremely critical in determining the minimum startup inventory and the doubling time. It was also noted that increasing the value of the residence times of either unit above the reference value would lead to a reactor that requires an external tritium source, which is not practical. The nonradiative losses should be kept lower than 0.1% per day in both units.
3. Although the parameters of the fuel storage system did not influence the minimum startup inventory much, it had a huge impact on the doubling time. Increasing the amount of losses in the unit increased the doubling time dramatically. It can also prevent the reactor from being self-sufficient. The nonradiative losses inside the fuel storage should be kept lower than 0.01%.
4. The parameters of the plasma can play a significant role in determining the startup inventory and the doubling time. However, in the range of values expected, it will not be important. The same is true for the impurity separation and reprocessing and the isotope separation system.
5. Although the plasma fractional burnup can have a huge impact on the required tritium breeding ratio, the minimum startup inventory and the doubling time, restricting its value between 3-7%, which is the feasible values at present [4,6], limits its impact on the parameters of concern.

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