Computer simulation of the fusion fuel cycle

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Accurately estimating the tritium inventory in the fusion power plant is necessary to determine the self-sufficiency and safety of the fusion reactor. A tritium fuel cycle model was developed to calculate the time-dependent tritium inventory in different reactor components. The model was applied to a case of a 1GW electric fusion power plant, and the tritium inventories were calculated at 100%, 50% and 25% reactor availabilities. The results showed that the total tritium inventory in the reactor after 300 days would be less than 100kg, with more than half of it in the fuel storage, where it can be easily retrieved. The results also showed that even if the reactor availability drops to 25% during operation, it would still be tritium self-sufficient.

من الضروري حساب كمية التريتيوم الموجودة في محطة القوى الاندماجية, و ذلك من أجل معرفة مدى اكتفاء المحطة ذاتيا و مدى أمان المفاعل الاندماجي. تم تطوير نموذج لحساب كميات التريتيوم في مختلف أجزاء المفاعل و حساب تغيرها مع الزمن. و قد طبق النموذج على محطة قوى اندماجية تنتج طاقة ١ جيجاوات. و تم حساب كميات التريتيوم في حالات تشغيل المفاعل بقدرة ١٠٠%, ٥٠%, و ٢٥%.أظهرت النتائج أن كمية التريتيوم الكلية ستكون أقل من ١٠٠كيلوجرام بعد ٣٠٠ يوم, مع وجود أكثرمن نصف هذه الكمية في مخزن الوقود, حيث يمكن أزالتها من المفاعل بسهولة. كما أظهرت النتائج أنه في حالة نقص قدرة تشغيل المفاعل من ١٠٠% الى ٢٥%, فان المفاعل سوف يظل مكتفي ذاتيا.

Keywords: fuel cycle, Fusion, Tritium inventory, Availability, Residence time.

1. Introduction

Deployment of controlled thermonuclear fusion reactor power plants utilizing deuterium and tritium fuels will require large amounts of deuterium and tritium [1]. Deuterium exists in nature; but tritium does not exist and decays with a half-life of 12.3 year. The most economic way to provide tritium is to breed it in fusion reactors [2]. Therefore, one of the major requirements of a fusion reactor would be its ability to produce sufficient amounts of tritium [3]. Safety requirements would be focused on the reduction of the tritium inventories inside different reactor components in order to minimize the radiological hazards [4]. Therefore, it is important to be able to estimate the amount of tritium in each component.

There is an initiative to develop a model for the tritium fuel cycle that can be used to calculate the steady state and transient inventories inside the different components of the reactor. This model will provide a tool for proper specification of system design requirements for a safe and feasible fusion reactor.

Modeling studies have been conducted for tritium fuel cycle simulation in DT fusion power reactors. However, these models are either used only for steady state calculations, such as CHEMCAD [5] and TETRA [6], or are too complex, such as DIFFUSE [7], FLOSHEET [8] and TRUFFLES [9]. Simpler transient models, such as KATRIM [10] and the model by Asaoka et al. [11] do not include all the tritium containing components.

This paper describes a model developed for the simulation of the fuel cycle inside a fusion reactor. A code, based on the model, is used to carry out a study of the behavior of the tritium inventory inside each reactor component with time as well as investigate the effect of the availability on the those inventories.

2. Fuel cycle modeling

In a fusion reactor, the major steps needed to handle tritium are combined in the "tritium fuel cycle." Several processing stations, or key subsystems can be identified within that cycle. Thus, it is possible to simulate the cycle using compartment models, with each compartment representing a processing station [10, 12].

A model has been developed for calculating the tritium inventory in each tritium processing subsystem in a fusion reactor. The model divides the tritium fuel cycle into a number of compartments, each representing a major subsystem in the reactor. The major subsystems that can be represented as independent blocks are [12-14]:

1. Plasma: Part of the tritium will burn inside the plasma. The rest will pass through the plasma exhaust vacuum pumping system in order to be separated from the plasma ash and impurities.
2. Plasma facing components (PFC): A small fraction of the tritium in the plasma will go to the first wall and other plasma facing components. However, this fraction is greatly increased in the case of plasma disruption.
3. PFC coolant: The tritium reaching the plasma facing components is carried out via the coolant to the isotope separation system.
4. Plasma exhaust vacuum pumping: The tritium in the plasma is extracted by the limiter or diverter to the plasma exhaust vacuums pumping. This is done mainly to remove the alpha particles resulting from the fusion reaction and the impurities that are found in the plasma as a result of first wall sputtering.
5. Impurity separation and processing: In this process the alpha particles and other impurities are removed from the tritium and deuterium extracted from the plasma.
6. Isotope separation system (ISS): The tritium is separated from the deuterium in order to be reused as plasma fuel.
7. Breeding blanket: The tritium is produced inside the blanket via Li(n,α) reactions.
8. Purge gas processing: The purge gas carries the tritium from the blanket to the isotope separation system.
9. Blanket coolant processing: Some of the tritium inside the blanket permeates through the coolant channels to the blanket coolant.
10. Fuel storage and management: After extracting the tritium in the ISS, it goes to the storage where it is kept for use either as plasma fuel or as use in other fusion reactors.
11. Fueling system: Where the tritium is prepared for injection into the plasma.
12. Tritium waste treatment: Some of the tritium that was lost from different reactor components can be retrieved and sent to the waste treatment. The tritium is separated from the impurities in this unit.

Fig. 1 shows the connection between the different subsystems. The dotted line between the plasma and the blanket denotes that neutrons, and not tritium, flow between the two subsystems. These neutrons produce tritium in the blanket through n(Li, T)α reactions [2].

For each subsystem, the tritium inventory (I) is related to the other subsystems through the following ordinary differential equation [12]:

$$\frac{dI_i}{dt} = \sum_{j \to i} \left(\frac{I_j}{\tau_j} \right) - \frac{I_i}{\tau_i} - (a_i + \lambda) I_i \tag{1}$$

Where τ is the residence time inside the component (days), 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.

Applying eq. (1) to each part of the cycle represented in fig. 1 leads to:

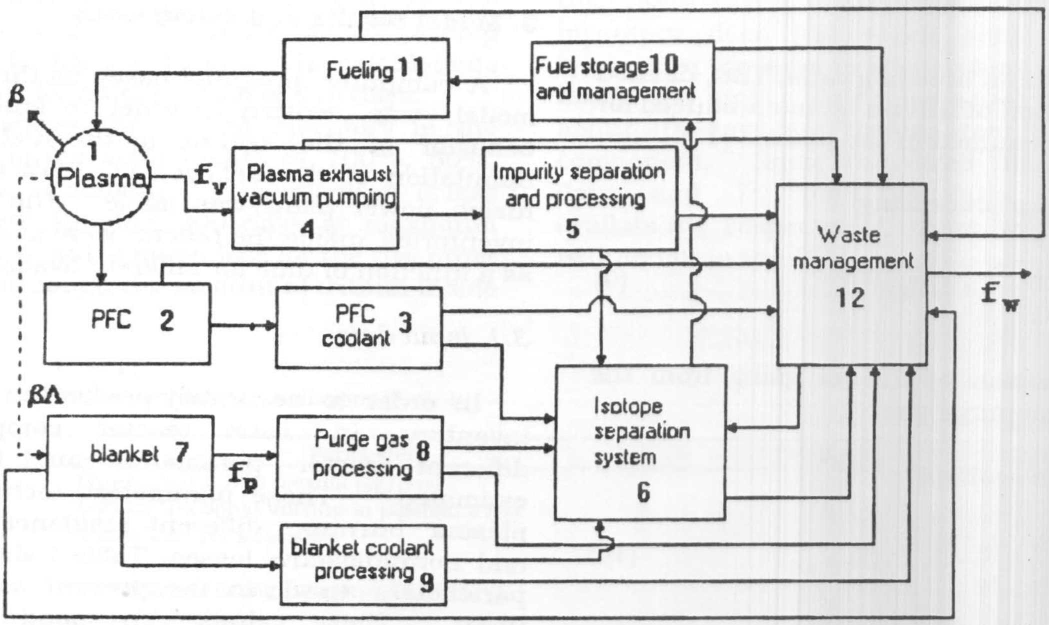

Fig. 1. Schematic of the fuel cycle model.

i = 1 (Plasma)

$$\frac{dI_1}{dt} = \frac{I_{11}}{\tau_{11}} - \frac{I_1}{\tau_1} - (\lambda + a_1)I_1, \tag{2}$$

i = 2 (PFC),

$$\frac{dI_2}{dt} = (1 - f_v)(1-\beta)\frac{I_1}{\tau_1} - \frac{I_2}{\tau_2} - (\lambda + a_2)I_2. \tag{3}$$

Where β is the plasma burn up (defined as the fraction of tritium atoms fusing inside the plasma), f_v is the fraction of tritium atoms going to the plasma vacuum pumping systems. The term (1- β) represents the fraction of tritium flowing out of the plasma and (1-f_v)(1- β) represents the fraction of tritium going from the plasma to the plasma facing components.

i = 3 (PFC coolant)

$$\frac{dI_3}{dt} = \frac{I_2}{\tau_2} - \frac{I_3}{\tau_3} - (\lambda + a_3)I_3, \tag{4}$$

i = 4 (Plasma exhaust)

$$\frac{dI_4}{dt} = f_v(1-\beta)\frac{I_1}{\tau_1} - \frac{I_4}{\tau_4} - (\lambda + a_4)I_4, \tag{5}$$

i = 5 (Impurity separation and processing)

$$\frac{dI_5}{dt} = \frac{I_4}{\tau_4} - \frac{I_5}{\tau_5} - (\lambda + a_5)I_5, \tag{6}$$

i = 6 (Isotope separation system)

$$\frac{dI_6}{dt} = \frac{I_5}{\tau_5} + \frac{I_3}{\tau_3} + \frac{I_8}{\tau_8} + \frac{I_9}{\tau_9} + (1-f_w)\frac{I_{12}}{\tau_{12}} - \frac{I_6}{\tau_6} - (\lambda + a_6)I_6. \tag{7}$$

f_w is the fraction of tritium atoms going from the waste processing to the ISS.

i = 7 (Breeder blanket)

$$\frac{dI_7}{dt} = \beta\Lambda\frac{I_1}{\tau_1} - \frac{I_7}{\tau_7} - (\lambda + a_7)I_7. \tag{8}$$

$$\frac{dI_7}{dt} = \beta\Lambda\frac{I_1}{\tau_1} - \frac{I_7}{\tau_7} - (\lambda + a_7)I_7. \quad (8)$$

Λ is the tritium breeding ratio, TBR, defined as the fraction of tritium atoms produced for each atom consumed in the plasma [13].

i = 8 (Purge gas processing)

$$\frac{dI_8}{dt} = f_p\frac{I_7}{\tau_7} - \frac{I_8}{\tau_8} - (\lambda + a_8)I_8 . \quad (9)$$

f_p is the fraction of tritium going from the blanket to the purge gas.

i = 9 (Blanket coolant)

$$\frac{dI_9}{dt} = (1 - f_p)\frac{I_7}{\tau_7} - \frac{I_9}{\tau_9} - (\lambda + a_9)I_9, \quad (10)$$

i = 10 (Fuel storage)

$$\frac{dI_{10}}{dt} = \frac{I_6}{\tau_6} - \frac{I_{10}}{\tau_{10}} - (\lambda + a_{10})I_{10} \quad (11)$$

i = 11 (Fueling system)

$$\frac{dI_{11}}{dt} = \frac{I_{10}}{\tau_{10}} - \frac{I_{11}}{\tau_{11}} - (\lambda + a_{11})I_{11}, \quad (12)$$

i = 12 (Waste treatment)

$$\frac{dI_{12}}{dt} = \sum_{i=2}^{11} f_i a_i I_i - \frac{I_{12}}{\tau_{12}} - \lambda I_{12}, \quad (13)$$

f_i is the fraction of tritium waste from component (i) that reaches the waste processing system.

Initially, all the fuel cycle systems contain no tritium inventory, except the tritium storage, which contains an initial inventory that will enable the startup of the reactor as well as sustain its operation in the beginning. Therefore:

$$I_i(0) = 0 \qquad i = 1, 2, ..., 12, \quad i \neq 10 \quad (14)$$

$$I_{10}(0) = I_{in} \quad (15)$$

3. Model results and discussions

A computer program, based on the above model, was written in order to study the behavior of the tritium in the fuel cycle. Simulation of the fuel cycle of a 1GW electric fusion power plant was made. The tritium inventories inside the reactor were calculated as a function of time for different availability.

3.1. Input data

In order to accurately predict the tritium inventory in each reactor component, different reactor parameters must first be estimated. These parameters include the plasma burnup, different residence times, and nonradioactive losses. Table 1 shows the parameters used in the present model as input. These values correspond to the predicted values in a 1 GW electric power reactor [4, 10, 11].

The tritium inventory in the plasma is kept constant in the cases with 100% availability. At 50% availability the tritium inventory in the plasma is constant for 25 days burn time and equals zero for 25 days dwell time [12]. At 25% availability, the dwell time is increased to 75 days. Assumption of missing data is based on consideration of other reactor subsystems.

The tritium breeding ratio used is 1.3. This value exceeds unity by a margin to cover losses and radioactive decay, to supply inventory for startup of other fusion reactors, and to provide some reserves for periods of scheduled maintenance or failures of the fuel processing subsystem [3]. Note that a realistic value of the TBR is ≤ 1.5 [13].

3.2. The tritium inventories and the availability

The tritium inventories in the different reactor components were calculated as a function of time for 100%, 50%, and 25% availability. The 100% availability case corresponds to a reactor operating at steady state with no interruption. The other two cases correspond to cases with pulsed operation. The tritium inventory in the plasma was set equal to constant for the cases of 100% availability or as a step function for the other cases. The calculations were made for a time period of 300 days.

Fig. 2 shows the tritium inventory in the plasma facing components at 100%, 50%, and 25% availability. The inventory is less than 0.08 kg after 300 days at maximum availability and is much less for the two other cases. Although the amount of tritium inside the PFC decreases during the dwell times for the cases with 50% and 25% availability, the inventory does not reach zero. This is because of the large residence time (100 days) inside the unit. This means that it will take about 100 days for a tritium atom to leave the component. Since the dwell times are 25 days and 75 days for 50% and 25% availability, respectively, there will be some tritium left in the PFC.

Table 1
Values used in the calculations [5, 9, 10]

Parameter	Value
Tritium burnup in plasma (kg/day)	0.5
Tritium fractional burnup in plasma, β (%)	5
Nonradioactive losses (%)	
Plasma	1 x 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.

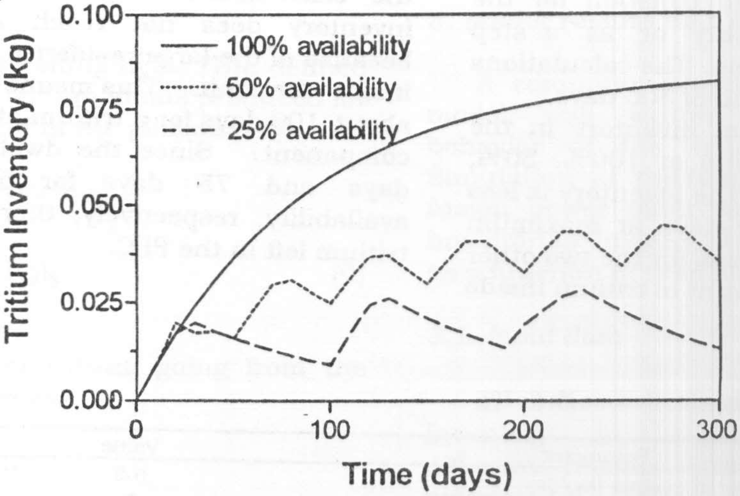

Fig. 2. Variation of tritium inventory in the PFC with time for 100%, 50% and 25% availability.

Fig. 3 shows the tritium inventory inside the plasma facing components coolant at 100%, 50%, and 25% availability. In this case the tritium inventory is seen to increase even during the dwell time. This can be explained by referring to eq. (4). The positive term (I_2/τ_2) represents the tritium gain via flowing into the component from the PFC, while the other terms are negative and represent the tritium loss via flowing out of the component, leakage and radioactive decay. The gain term is proportional to I_2, the tritium inventory in the PFC. I_2 is always > 0. Therefore, there is always tritium flowing into this system. This term evens out with the loss terms during the dwell times, with a net result of either slightly increasing inventory (in the case of 50% availability) or a constant inventory (in the case of 25% availability).

The change of tritium inventory in the plasma exhaust vacuum pumping with time is shown in fig. 4. At 100% availability, the tritium inventory reaches steady state after less than 10 days. At 50% availability, the tritium inventory fluctuates between a maximum of 10 kg during the burn time and 3 x 10^{-6} during the dwell time. Note that the tritium flowing into the system comes from the plasma, and is therefore zero during the dwell time. At 25% availability, the tritium inventory decreases to zero during the dwell time. This is because of the small residence time in the plasma exhaust pumping system (1 day), compared to the large dwell time (75 days).

The tritium inventory inside the impurity separation and processing system exhibited the same behavior as the plasma exhaust vacuum pumping system, and, therefore will not be shown. This inventory, however, changed between a maximum of 1 kg at 100% availability and during the burn times and a minimum of 3 x 10^{-7} during the dwell time at 50% availability and zero during the dwell time at 25% availability.

Fig. 5 shows the change in the tritium inventory in the isotope separation system (ISS) with time for different availability. At 100% availability, the inventory reaches steady state of 1 kg in less than 50 days. At 50% availability, the inventory changes between a maximum of 1 kg and a minimum of 7 x 10^{-3} kg at the dwell time. At 25% availability, the minimum inventory was 8.5 x 10^{-4} kg at the dwell time. It does not decrease to zero because there is still tritium flowing into the component during the dwell time from the PFC coolant, the blanket, the purge gas processing, and the waste treatment units.

The variation of tritium inventory in the breeder blanket with time for 100%, 50%, and 25% availability is shown in fig. 6. At 100% availability, the tritium inventory reaches steady state of about 6.5 kg after 70 days. At 50% availability, the tritium inventory changes between 5.6 kg during the burn time and 0.5 kg during the dwell time. At 25% availability, the inventory decreases to a minimum of 6 x 10^{-3} kg during the dwell time. Again the inventory does not reach zero because of the relatively large residence time (10 days).

The tritium inventory inside the purge gas processing system changed in the same manner as the blanket and will not be shown. The inventory in this case, however, was an order of magnitude lower than that in the blanket.

Fig. 7 shows the change of the tritium inventory in the blanket coolant with time for different availability. In this case the tritium inventory did not reach steady state at 100% availability due to the large residence time (100 days). Which is also the reason why the inventory does not decrease to zero during the dwell times. The tritium inventory in the waste treatment system exhibited the same behavior as the blanket coolant although it was an order of magnitude lower (not shown).

Fig. 8 shows the change of tritium inventory inside the fuel storage system. The initial inventory was 40 kg. At 100% availability, the tritium inventory decreases to a minimum of about 24.5 kg at 25 days, and then starts increasing. Therefore the startup inventory required under the conditions used is equal to 15.5 kg. I_{10} increases after this and is 51 kg at the end of the 300 days. At 50% availability, I_{10} changes in pulses corresponding to the pulses inside the plasma. During the burn time, the inventory decreases because of the tritium that is being supplied to the plasma. During the dwell time the inventory increases because of the tritium flowing in from the ISS.

Due to the importance of calculating the tritium inventory in the storage, another case was examined in order to investigate whether decreasing the availability during the reactor operation will require an external supply of tritium. The tritium inventory in the fuel storage system, I_{10}, was calculated during a period of 1100 days (~3 years, the normal reactor operation time). The availability was set equal to 100% for 550 days and 25% during the last 550 days. The results are shown in fig 9. I_{10} decreases to minimum then increases linearly with time during the 100% availability period. When the availability decreases to 25%, I_{10} starts fluctuating. It can be seen that the maxima and minima of the pulses increase slightly with time (less than 5% increase in each pulse). Note that even though the inventory decreases during the burn times, the amount of tritium is more than enough to sustain the reactor operation. Therefore, the reactor is self-sufficient.

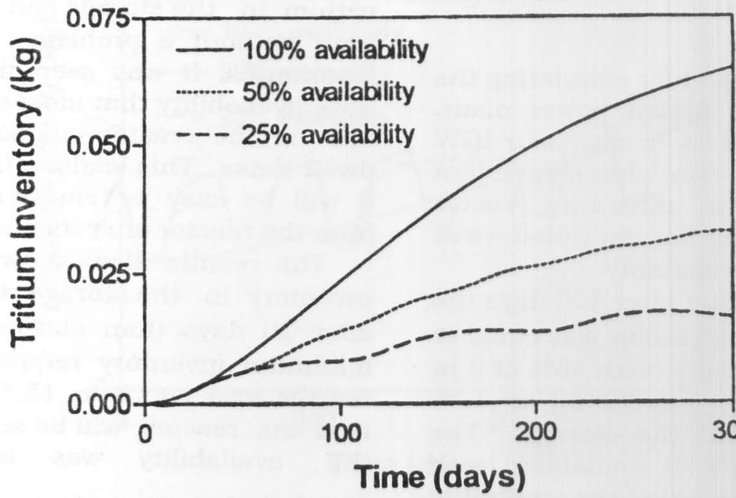

Fig. 3. Variation of tritium inventory in the PFC coolant with time for 100%, 50% and 25% availability.

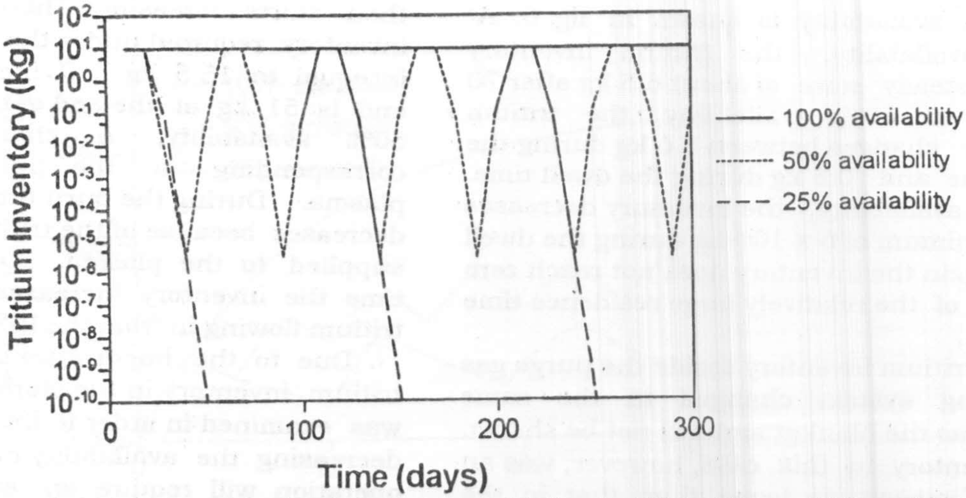

Fig. 4. Variation of tritium inventory in the plasma exhaust with time for 100%, 50%, and 25% availability.

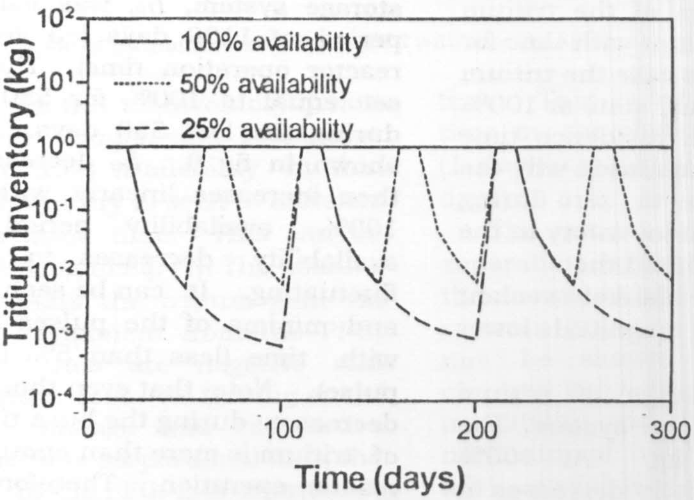

Fig. 5. Variation of tritium inventory in the ISS with time for 100%, 50%, and 25% availability.

4. Conclusions

A model was developed for simulating the tritium fuel cycle in a fusion power plant. The model was applied to a case of a 1GW electric power plant. The time-dependent tritium inventories in different reactor components were calculated for 300 days at 100%, 50%, and 25% availability.

The results showed that after 300 days the total inventory inside the reactor was equal to 92 kg at 100% availability, with 55% of it in the fuel storage. It was 72 kg at 50% availability, with 75% in the storage. The inventory was 47 kg at 25% availability, with 99% in the storage. Note that the amount of tritium in the storage can be removed at any time without a problem. As for the other inventories, it was seen from the case with 25% availability that most of the tritium came out of the reactor components during the dwell times. This leads to the conclusion that it will be easy to remove most of the tritium from the reactor after its end-of-life.

The results also showed that the tritium inventory in the storage reached a minimum after 20 days than started increasing. The minimum inventory required to start up the reactor was equal to 15.5 kg. It was found that the reactor will be self-sufficient even if the availability was less than 100%.

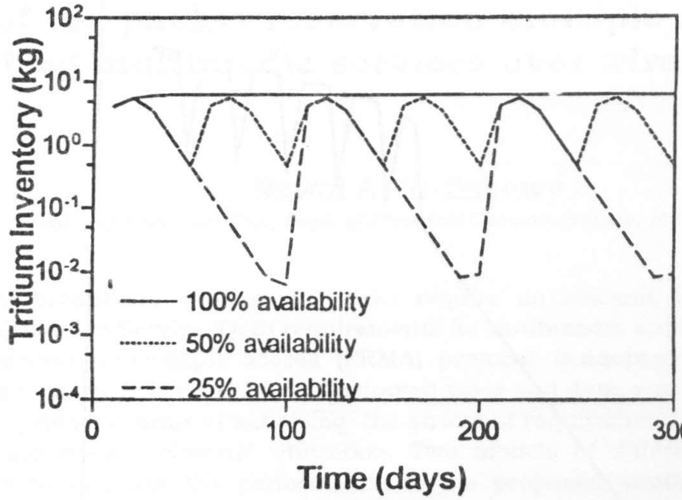

Fig. 6. Variation of tritium inventory in the blanket with time for 100%, 50%, and 25% availability.

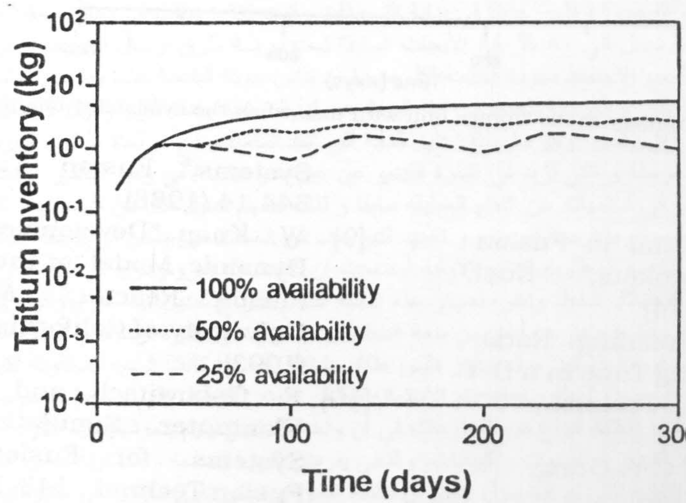

Fig. 7. Variation of tritium inventory in the blanket coolant with time for 100%, 50%, and 25% availability.

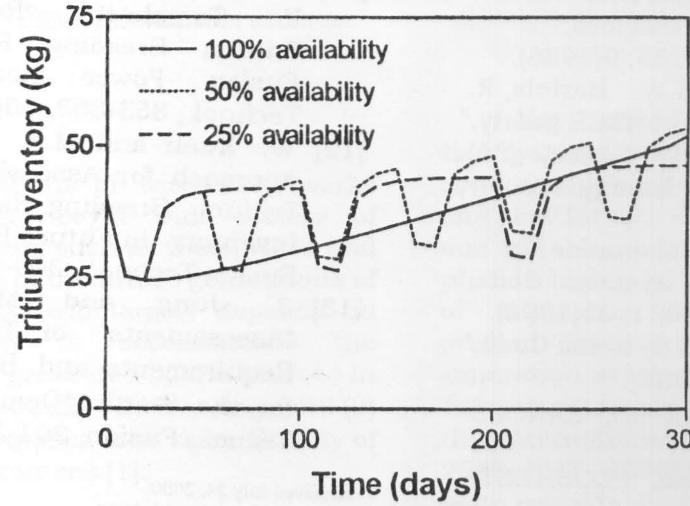

Fig. 8. Variation of tritium inventory in the fuel storage system with time for 100%, 50%, and 25% availability.

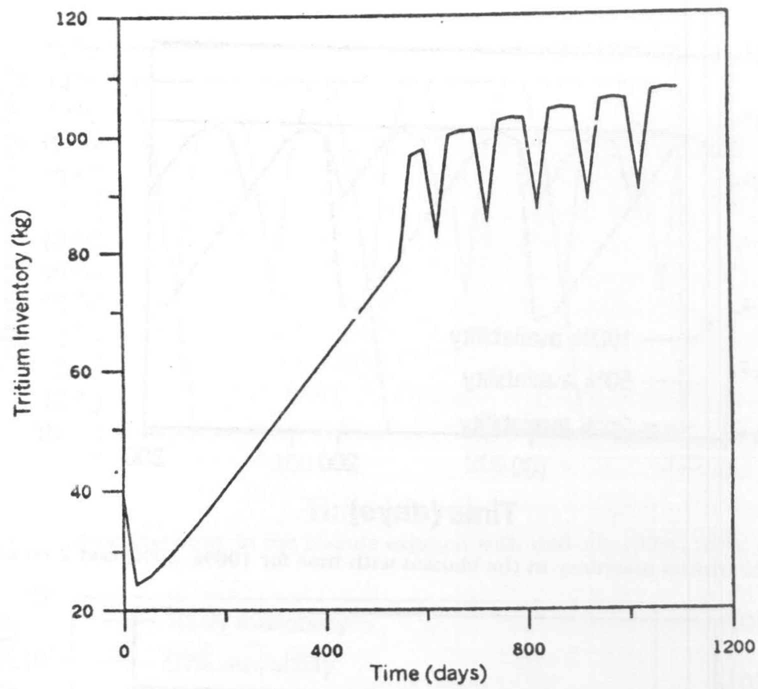

Fig. 9. Variation of the tritium inventory in the storage unit with time when the availability changes from 100% to 25%.

References

[1] R.H. Hickman, "Tritium in Fusion Power Reactor Blankets," Nucl. Technol., 39-49, 21(1974).

[2] W.F. Vogelsang, "Breeding Ratio, Inventory and Doubling Time in a D-T Fusion Reactor," Nucl. Technol., 470-474, 15(1972).

[3] M.A. Abdou, E.L. Vold, C.Y. Gung, M.Z. Youssef, and K. Shin, "Deuterium-Tritium Fuel Self-Sufficiency in Fusion Reactors," Fusion Technol., 250-285, 9(1986).

[4] J. Raeder, S. Piet, H.W. Bartels, R. Bunde and S. Brereton, "ITER Safety," ITER Documentation Series, (36), International Atomic Energy Agency, Vienna, (1991).

[5] S.J. Brereton, "Development of a Fusion Fuel Cycle Systems Code," Fusion Technol., 926-931, 21(1992).

[6] R.L. Reid, "ETR/ITER Systems Code," ORNL/FEDC-87/7 (1988).

[7] M.I. Bakes, "DIFFUSE 83," SAND83-8231 (1983).

[8] A. Busigin and S. Sood, "FLOSHEET – A Computer Program for Simulating Hydrogen Isotope Separation Systems," Fusion Technology, 529-544,14 (1988).

[9] W. Kuan, "Development of a Modular Dynamic Model for the Fuel Cycle in a Fusion Reactor," Master's Thesis, University of California at Los Angeles, (1993).

[10] E. Gabowitsch and G. Spannagel, "Computer Simulation of Tritium Systems for Fusion Technology," Fusion Technol., 143-148, 16(1989).

[11] Y. Asaoka, K. Okano, T. Yoshida, and K. Tomabechi, "Requirements of Tritium Breeding Ratio for Early Fusion Power Reactors," Fusion Technol., 853-863, 30(1996).

[12] W. Kuan and M.A. Abdou, "A New Approach for Assessing the Required Tritium Breeding Ratio and Startup Inventory in Future Fusion Reactors," Fusion Technol., 309-353, 35(1999).

[13] J. Jung and M. A. Abdou, "Assessments of Tritium Breeding Requirements and Breeding Potential for the Starfire/Demo Design," Nucl. Tecnol./Fusion, 361-366, 4(1983).

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