TRITIUM WELL DEPTH AND TRITIUM WELL TIME

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ABSTRACT. Similarly to but quite different from the xenon poisoning effects resulting from fission-produced iodine during restart-up process of a fission reactor, we introduce a complete new concept of the tritium well depth and tritium well time in fusion energy research area. To show what the least required amount of tritium storage is used to start up a fusion reactor and how long a time the fusion reactor needs to be operated for achieving the tritium break-even during the initial start-up phase due to the finite tritium breeding time that is dependent on the tritium breeder, specific structure of breeding zone, layout of coolant flow pipes, tritium recovery scheme and extraction process, the tritium retention of reactor components, unrecoverable tritium fraction in breeder, leakage to the inertial gas container, and the natural decay etc, we describe this new phenomenon and answer this problem by setting up and by solving a set of equations, which express a dynamic subsystem model of the tritium inventory evolution in a fusion experimental breeder (FEB). Two different simulation models give almost the same results, It is found the tritium well depth is about 317-319g and tritium well time is approximately 240 full power days for reference case of the FEB designed detail configuration and it is also found that after one-year operation the tritium storage reaches 1.18kg that is more than the least required amount of tritium storage to start up three of FEB-like fusion reactors.

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1. INTRODUCTION

It is well known that a nuclear fission reactor occasionally falls into an iodine well as the operator tries to restart after it was shut down because of xenon-135 poisoning effect, which leads to much more neutron absorption by fission-produced nonfissionable xenon-135 resulting from iodine-135 via β-decay [1]. If the residual reactivity is not high enough at the shutdown moment, as a result, the reactor will have so called iodine well depth and iodine well time difficulty. If the initial tritium storage for fueling is not sufficient, then the fusion reactor will also fall into a tritium well and will have to be shutdown during the initial start-up phase. As a consequence, the careful tritium system design and the required least tritium storage for initiating a fusion reactor are the most important issues involving in fusion research circle. In illustration of this novel concept, i.e. tritium well depth and tritium well time (or TWD&TWT), we take the FEB design option [2] as an example. The FEB is an experimental breeder of 143MW fusion power, in which liquid lithium (LLi) is used as tritium breeder, which is designed for being periodically moved out from blanket to recover tritium every 10 days for outboard blanket and every 24h for inboard blanket. High-pressure helium is used as coolant. The beryllium grain particles are uniformly immerged in liquid lithium as the neutron multiplier. The plasma burn-up fraction β=2.08% and total tritium-breeding ratio $\Lambda = 1.10$ has been calculated. Based on the engineering outline design, the tritium cycle system is divided into ten dynamic subsystems to describe the tritium flow chart, which is shown in Fig.1. The more detailed physics bases and assumptions are given in our previous work (see Ref. 3), which are no longer mentioned farther more here for short. A set of governing equations describing the time evolution of tritium inventories in the ten subsystems for the FEB design reference case has been written as follows. The results obtained from two different simulation models, which are applied to describing the processes of tritium recovery from the FEB blanket, have only 0.7% difference.

2. SUBSYSTEMS AND GOVERNING EQUATIONS

For comparisons, two simulation models are developed in this article, one is the mean residence time (MRT) model [3-4], and another is IZPT model [5]. To describe the time evolutions of tritium inventory in the ten subsystems as shown in Fig.1, the governing equations for ten subsystems are created as follows:

Tritium storage and fuelling subsystem:

$$\mathrm{d}Y_0/\mathrm{d}t = \tau_6 Y_6 - N - \varepsilon_0 Y_0 - (\lambda+\varepsilon_0)TN,$$

$$Y_0(0.000) = 0.900 \qquad (1)$$

Tritium breeder LLi in outboard blanket:

$$\mathrm{d}Y_1/\mathrm{d}t = \beta N \Lambda_1(1-b-\gamma) - \lambda_1 Y_1 - \varepsilon_1 Y_1 - \lambda Y_1, \quad Y_1(0.000) = 0.000,\ t=0.000\text{-}9.999,$$

$Y_1(10.000)=f_T Y_1(9.999)$, $t=10.000$,
$Y_1(10.000)=f_T Y_1(9.999)$, $t=10.001\text{-}19.999$,
$Y_1(20.000)=f_T Y_1(19.999)$, $t=20.000$,
$Y_1(20.000)=f_T Y_1(19.999)$, $t=20.001\text{-}29.999$,
$Y_1(30.000)=\mathrm{f_T} Y_1(29.999)$, $t=30.000$, …in doing so up to $t=365.000$. (2)

Tritium breeder LLi in inboard blanket:

$$\mathrm{d}Y_2/\mathrm{d}t = \beta N \Lambda_2(1-b-\gamma) - \lambda_2 Y_2 - \varepsilon_2 Y_2 - \lambda Y_2, \quad Y_2(0.000) = 0.000,\ t=0.000\text{-}9.999,$$

$Y_2(1.000) = f_T Y_2(0.999)$, $t=1.000$,

$Y_2(1.000) = f_T Y_2(0.999)$, $t=1.001\text{-}1.999$,

$Y_2(2.000) = f_T Y_2(1.999)$, $t=2.000$,

$Y_2(2.000) = f_T Y_2(1.999)$, $t=2.001\text{-}2.999$,

$Y_2(3.000) = f_T Y_2(2.999)$, $t=3.000$, ……in doing so up to $t=365.000$. (3)

First wall, limiter and divertor (Plasma facing components, i.e. PFC):

$$\mathrm{d}Y_3/\mathrm{d}t = \sigma(1-\beta)N - \lambda_3 Y_3 - \varepsilon_3 Y_3 - \lambda Y_3,$$

$$Y_3\,(0.000) = 0.000. \qquad (4)$$

Plasma exhaust:

$$\mathrm{d}Y_4/\mathrm{d}t = (1-\beta)(1-\sigma)N - \lambda_4 Y_4 - \varepsilon_4 Y_4 - \lambda Y_4\,,$$

$$Y_4\,(0.000) = 0.000. \qquad (5)$$

FCU (Fuel cleanup unit, palladium membrane reactor, i.e. PMR):

$dY_5/dt = \tau_4 Y_4 - \lambda_5 Y_5 - \varepsilon_5 Y_5 - \lambda Y_5$,

$Y_5(0.000) = 0.000.$ (6)

ISS (Isotope separation system):

$dY_6/dt = \tau_5 Y_5 - \lambda_6 Y_6 + \tau_{10} Y_{10} + \tau_7 (1-g) Y_7 - \varepsilon_6 Y_6 - \lambda Y_6$,

$Y_6(0.000) = 0.000$ t=0.000-0.999

$Y_6(1.000) = (1-f_T) Y_2(0.999) + Y_6(0.999)$, t=1.000-1.999,

$Y_6(2.000) = (1-f_T) Y_2(1.999) + Y_6(1.999)$, t=2.000-2.999,…..in doing so,

$Y_6(10.000) = (1-f_T) Y_2(9.999) + (1-f_T) Y_1(9.999) + Y_6(9.999)$, t=10.000-10.999

$Y_6(11.000) = (1-f_T) Y_2(10.999) + Y_6(10.999)$, t=11.000-11.999,

$Y_6(12.000) = (1-f_T) Y_2(11.999) + Y_6(11.999)$, t=12.000-12.999,…in doing so

$Y_6(20.000) = (1-f_T) Y_2(19.999) + (1-f_T) Y_1(19.999) + Y_6(19.999)$,

t=20.000-20.999 …..Up to t=365.000. (7)

TWT (Tritium waste treatment):

$dY_7/dt = \sum_{i=4}^{6} \varepsilon_i Y_i - \lambda_7 Y_7 + \varepsilon_0 Y_0 + \varepsilon_0 TN - \lambda Y_7$,

$Y_7(0.000) = 0.000.$ (8)

Beryllium neutron multiplier:

$dY_9/dt = Nb\beta\Lambda + N\Lambda\beta\gamma - \lambda_9 Y_9$,

$Y_9(0.000) = 0.000.$ (9)

Helium coolant:

$dY_{10}/dt = \varepsilon_1 Y_1 + \varepsilon_2 Y_2 + \varepsilon_3 Y_3 + \varepsilon_9 Y_9 - \lambda_{10} Y_{10}$,

$Y_{10}(0.000) = 0.000$ (10)

Total inventory:

$dY_{11}/dt = N\Lambda\beta + (1-\beta)N - (\lambda + \varepsilon_0)TN - g\tau_7 Y_7 - N - \lambda(\sum_{i=1}^{7} Y_i + Y_9 + Y_{10})$,

$Y_{11}(0.000) = Y_0(0.000)$ (11)

The IZTP model might be more realistic, that means the time of removing liquid lithium out from blanket for tritium recovery is regarded to be negligible, i.e. the equations (2), (3) and (7) are always valid at any time unless at the specified time corresponding to the initial conditions as above in IZTP model. In the MRT model Eq. (1) should be replaced by (1)'

$$dY_0/dt = \tau_6 Y_6 - N - \varepsilon_0 Y_0 - (\lambda+\varepsilon_0)TN,$$

$$Y_0(0) = 0.5000 \qquad (1)'$$

and (2), (3), (7) will be replaced by (2)', (3)', (7)' respectively

$$dY_1/dt = \beta N \Lambda_1(1-b-\gamma) - \lambda_1 Y_1 - \varepsilon_1 Y_1 - \lambda Y_1,$$

$$Y_1(0) = 0.000 \qquad (2)'$$

$$dY_2/dt = \beta N \Lambda_2(1-b-\gamma) - \lambda_2 Y_2 - \varepsilon_2 Y_2 - \lambda Y_2,$$

$$Y_2(0) = 0.000 \qquad (3)'$$

$$dY_6/dt = \tau_1 Y_1 + \tau_2 Y_2 + \tau_3 Y_3 + \tau_5 Y_5 - \lambda_6 Y_6 + \tau_{10} Y_{10} + \tau_7(1-g)Y_7 - \varepsilon_6 Y_6 - \lambda Y_6,$$

$$Y_6(0) = 0.000 \qquad (7)'$$

In the preceding equations the following units are used: Y_i (i=0,1,2…11) is in kg; T and t are in days; τ_i, λ_i, ε_i, λ and ε_0 are per day; and N is in kg per day. The others, g, b, σ, β, Λ, γ, Λ_1, and Λ_2 are dimensionless. All of the parameters appearing in the Eqs.1 to Eqs.11 are derived from the physics bases, assumptions [3], and our previous experimental data [6]; and some parameters can also refer to the published materials of Tritium System Test Assembly (TSTA) [7] etc.... They are defined as the same as the definitions of nomenclature in Ref.3, except the tritium storage and fuelling subsystem has initial tritium storage Y_0 (0) =0.9kg, rather than 0.5kg.

3. REFERENCE CASE FOR SIMULATIONS

To our present knowledge, based on the assumptions of physics bases [3], our experimental data of hydrogen permeation in stainless steel [6], TSTA experimental results of hydrogen isotope separation [7], and the designed tritium recovery scheme [2], a group of relatively reasonable input parameters for simulation of the FEB reference case can be derived and given as follows

τ_1=0.100, τ_2=1.000, τ_3=0.010, τ_4=48.000, τ_5=24.000, τ_6=6.860, τ_7=

2.400, τ_{10} =0.010, β=0.0208, N=1.073, Λ_1=0.450, Λ_2=0.650, $\Lambda=\Lambda_1+\Lambda_2$=1.100, b=0.00949, γ=0.01157, σ=0.0001, $g=1\times10^{-7}$, λ=0.000154, λ_1=0.100, λ_2=1.000, λ_3=0.010, λ_4=48.000, λ_5=24.000, λ_6=6.860, λ_7=2.400, λ_9=0.000254, λ_{10}=0.010, T=0.0139, ε_1=0.0002, ε_2=0.0001, ε_3=0.0001, ε_4=0.0005, ε_5=0.0003, ε_6=0.002, ε_0=0.0001, ε_9 =0.000254, f_T=0.1.

In addition, an adjustable input parameter f_T is introduced to describe the fraction of unrecoverable tritium remaining in LLi, which depends on the existing technology development of tritium recovery from LLi [7]. In this computer simulation f_T=0.1 is specified for FEB reference case.

4. TRITIUM WELL DEPTH AND TRITIUM WELL TIME

As one of the most important results obtained by solving the Eqs.1 to Eqs.11, the tritium well can be shown in Fig.2 clearly, the tritium well depth (TWD) is about 317g occurred at the tenth day after start-up for IZPT model. It can be concluded that if the initial tritium storage for fueling is less than 317g, then the FEB will stay at the tritium well and has to be shut down, resulting in zero storage at the tenth day. In other words, if the initial tritium storage were not 0.9kg, but 317g, the reactor will not able to climb out the tritium well. The tritium well time (TWT) is approximately 240 full power days. At this time, the tritium inventory in the tritium storage subsystem reaches break even. It should be emphasized that the TWD and TWT are dependent on the designed details from reactor to reactor, such as burn-up fraction of plasma, the tritium breeder, coolant, specific structure and materials of breeding zone, layout of coolant flow pipes, tritium recovery scheme and extraction method, the tritium retention in reactor components, neutron multiplier, unrecoverable tritium fraction in breeder, leakage to the inertial gas container and natural decay etc. One more important thing should be reminded that according to our previous simulation results [3,5] ， which were focused on the tritium leakage analyses under normal operation and different accident circumstances, the tritium retentions in several subsystems, such as, plasma exhaust (Y_4), FCU-fuel cleanup unit, palladium membrane reactor, i.e. PMR(Y_5), ISS-isotope separation system(Y_6), tritium waste treatment (Y_7) etc. will be slowly approaching the saturations, implying that for the next restart-up, the TWD&TWT will be greatly improved and will be different from first initial start-up to the succeeded one. Even for the same reactor, the TWD&TWT are not the fixed constants and also will be mildly variable from time to time, that depend on the specific operation conditions of all subsystems.

For MRT model, the result is shown in Fig. 3. The TWD is about 319g which is occurred at the 30th day after start-up and only 0.7% difference exists between two models. The other data differences from comparing with IZPT model are resulted from the initial tritium storage 0.5kg rather than 0.9kg. The two different simulation models give quite consistent results.

It is also found that after one-year operation the tritium storage reaches 1.18kg that is more than the required tritium amount for starting up three of FEB-like fusion reactors.

5. DISCUSSION

A new phenomenon is described and illustrated with a specific instance in this work, which has not been explored openly in fusion energy research and development area. In addition, it is also one of the most of concern problems for the International Thermonuclear Experimental Reactor (ITER) project under designing. Suppose that all plasma steady state operation problems (such as steady-state current drive, a quiet plasma, EM issue and relevant material problems etc.) have been solved well, only the TWD and TWT are not solved well, the availability of the fusion power plant would not be high enough, therefore, the cost of electricity (COE) of fusion energy would not be so low to be comparable with the other energy sources. Therefore it is also a decisive problem on the way of fusion energy development.

However, considering that the plutonium-239 is also breaded through the reaction of uranium-238 with the fusion-produced neutron in the FEB blanket, we expect that the TWD & TWT would be greatly improved for a pure fusion reactor.

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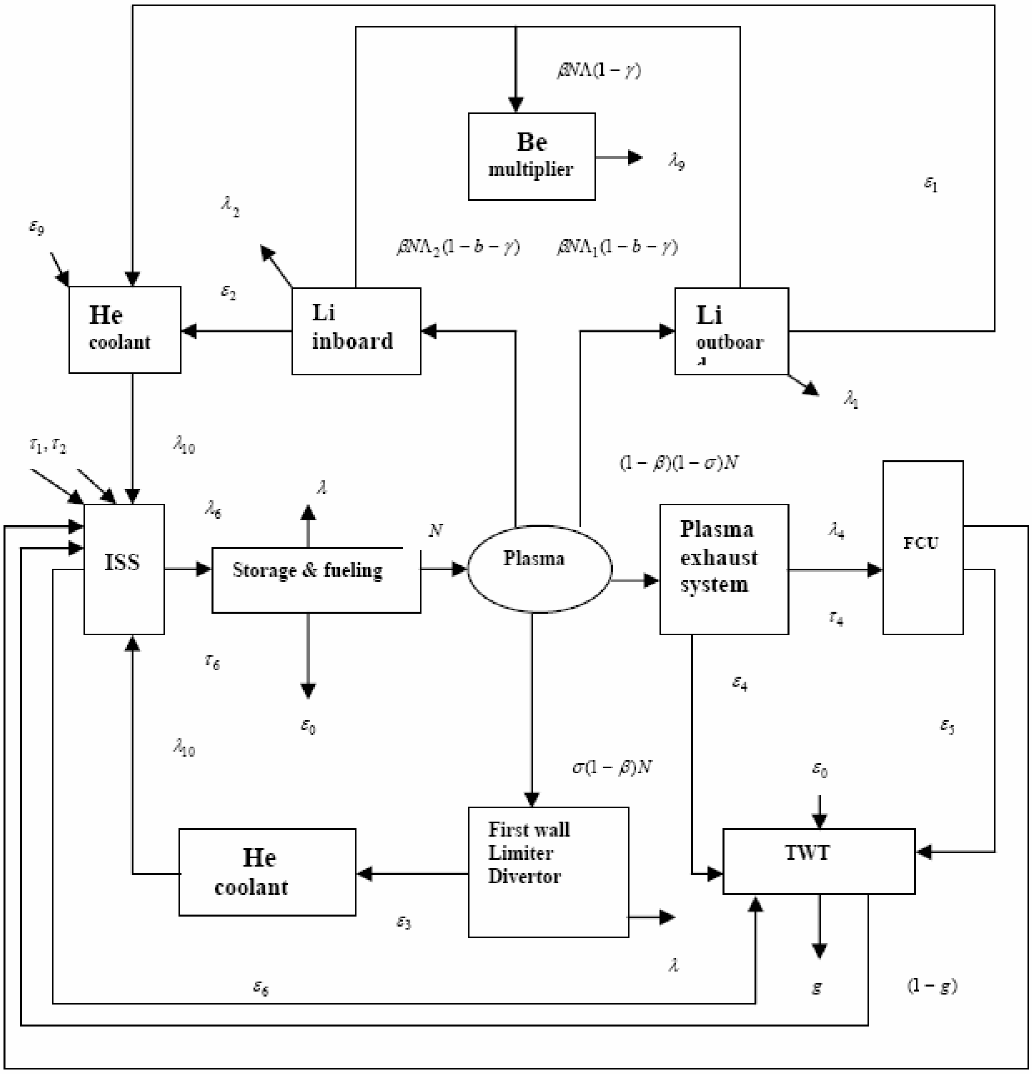

Fig. 1 Computer simulation model of FEB tritium cycle subsystems

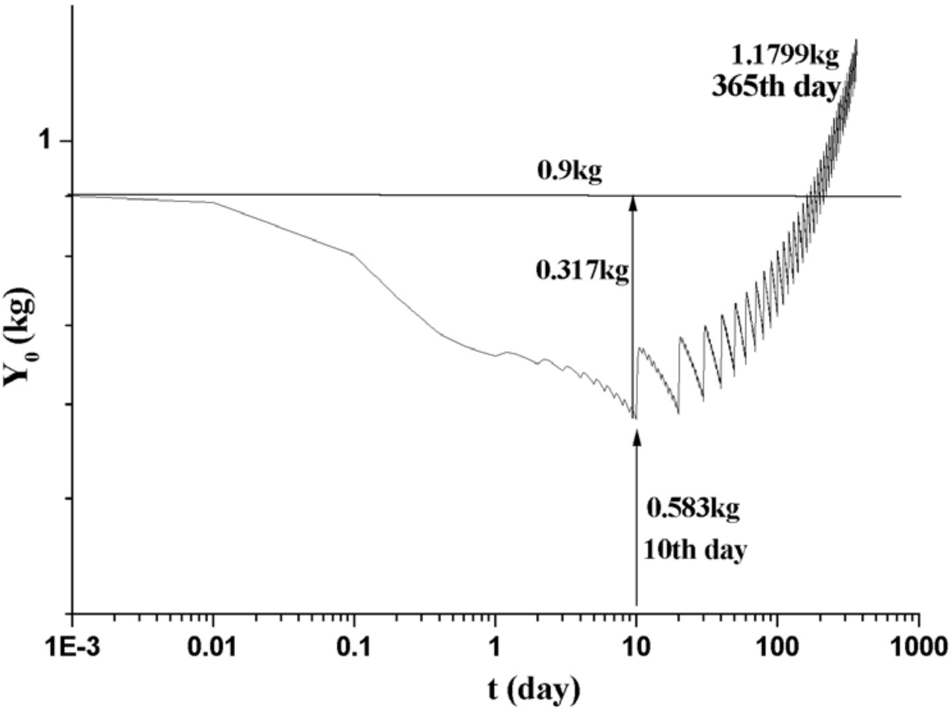

Fig.2 Tritium well depth and tritium well time of FEB

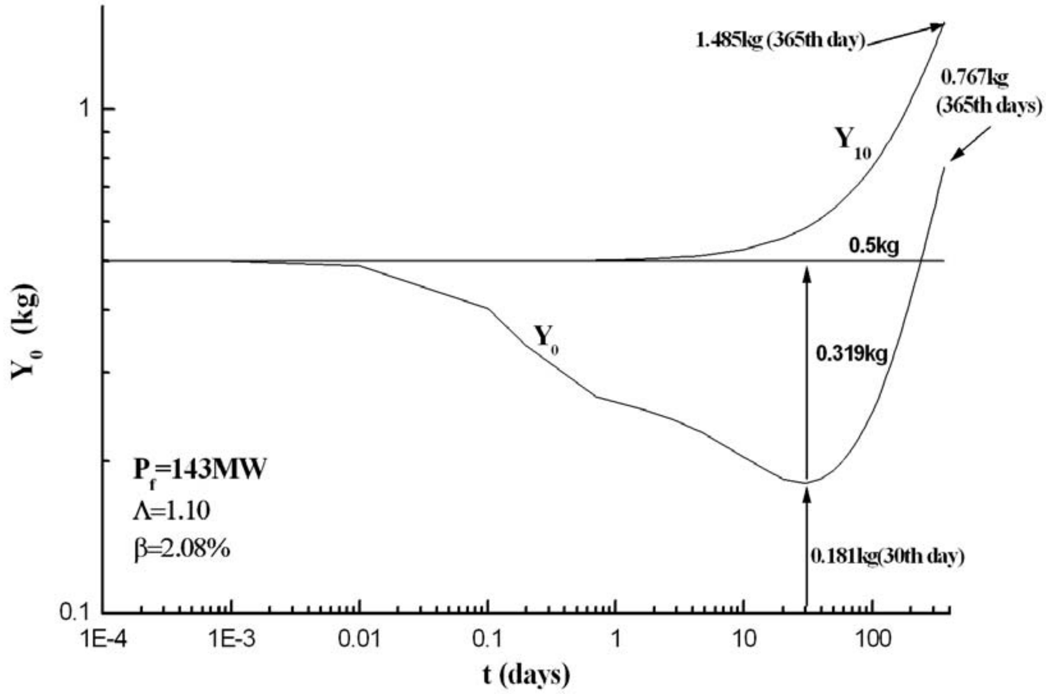

Fig. 3 The tritium well depth and tritium well time from MRT model