

TRITIUM ANALYSIS FOR THE US-ITER SOLID BREEDER BLANKET

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ABSTRACT

This paper presents an analysis of the tritium release and inventory in the US-ITER solid breeder blanket, based on the MISTRAL code. Since the effect of LiOT formation and precipitation at low temperature can be quite important in Li_2O , the selected solid breeder for the blanket, these processes have to be accounted for in the calculations. A simple way of estimating the LiOT precipitation as a function of temperature and moisture partial pressure was added to MISTRAL by including the calculations of T_2O , H_2O and HTO concentrations in the pore, in addition to T_2 , H_2 and HT. The analysis was carried out for both steady state and transient cases. The transient cases are based on the given burn and dwell times during the Physics and Technology Phases and the corresponding temperature profile and tritium generation history in the solid breeder region. For the steady state case, a tradeoff analysis is done for the helium purge flow rate, based on an acceptable tritium inventory which imposes a lower limit on the purge flow rate and an acceptable purge pressure drop which imposes a higher limit on the purge flow rate.

MODEL DESCRIPTION

The tritium release and inventory in the US-ITER solid breeder blanket shown in Figure 1 [1] is analyzed, based on the MISTRAL code [2]. This code includes the effects of the following transport processes:

1. diffusion of atomic tritium within the grain to the grain boundary;
2. diffusion of tritium along the grain boundary paths between adjacent grains to the solid/gas interface;
3. dissociative adsorption of gas species present in the pore onto the surface, "adsorption" of atomic tritium from the solid, surface recombination reactions and associative desorption of tritium-bearing species to the pore;
4. diffusion of tritium-bearing species through the network of interconnected pores to the purge carrier.

In the original model, the assumed species in the pore were H_2 , T_2 and HT. However, because of concern about LiOT precipitation in Li_2O being substantial at low temperature and high moisture partial pressure, the code was modified to include H_2O , T_2O and HTO also in the pore. Consideration of the six reduced and oxidized species of hydrogen/tritium, in addition to oxygen, would require solving seven atom conservation and chemical equilibrium equations at each pore location and at each time step in order to obtain the corresponding concentrations of each of the seven species. This would be quite a complicated procedure which, added to the relatively complex modeling already existing in MISTRAL, would result in longer computing time and lengthy calibration runs. For the purpose of obtaining an initial estimate of the effect of LiOT precipitation on the ITER blanket transient tritium release, three simplifying assumptions were made for the species calculations:

1. all oxygen atoms present in the interconnected porosity system are combined with hydrogenic species (protium or tritium) so that no O_2 is present;
2. for the net desorption of every two tritium atoms to the pore, an oxygen atom is assumed to desorb also; and
3. at any given pore location the ratio of hydrogen to tritium atoms in oxidized form is assumed to be equal to the ratio of the total number of hydrogen to tritium atoms, i.e.

$$\frac{N_{\text{HTO}} + 2N_{\text{H}_2\text{O}}}{N_{\text{HTO}} + 2N_{\text{T}_2\text{O}}} = \frac{N_{\text{H}}}{N_{\text{T}}} \quad (1)$$

where N is the atom concentration of the species at the given pore location and the subscript refers to the atomic species.

These assumptions greatly simplify the calculations of the species concentration, which was carried out as follows: conservation of hydrogen atoms result in the following expression following the first assumption

$$N_{\text{HTO}} + N_{\text{T}_2\text{O}} + N_{\text{H}_2\text{O}} = N_{\text{O}} \quad (2)$$

and N_{O} is the total atom concentration of oxygen atoms obtained at each time step as the sum of N_{O} at the previous time steps and of the net desorption of oxygen at the new time step based on the second assumption. From the chemical equilibrium equations, the following expression is obtained, assuming for simplicity that equilibrium is achieved at each time step:

$$\frac{[N_{\text{HTO}}]^2}{[N_{\text{T}_2\text{O}}][N_{\text{H}_2\text{O}}]} = K_{(o)} \quad (3)$$

where $K_{(o)}$ is the chemical equilibrium constant for the oxidized species, which is a function of temperature, and is estimated from the expression of Billone [3] based on experimental data from the literature (for $T = 100 - 500^\circ\text{C}$):

$$K_{(o)} = \frac{0.575 + 4.15 \times 10^{-3} (T - 273)}{0.163 + 1.00 \times 10^{-3} (T - 273)} \quad (4)$$

From eqs. (1) to (3) the concentrations of HTO, H_2O and T_2O can be calculated at each pore location at each time step. The concentrations of H_2 , T_2 and HT are then calculated in the same way as previously calculated in MISTRAL, from the following equations:

$$N_{\text{HT}} + 2N_{\text{H}_2} = N_{\text{T}} - N_{\text{HTO}} - 2N_{\text{T}_2\text{O}} \quad (5)$$

$$N_{\text{HT}} + 2N_{\text{T}_2} = N_{\text{H}} - N_{\text{HTO}} - 2N_{\text{H}_2\text{O}} \quad (6)$$

$$\frac{[N_{\text{HT}}]^2}{N_{\text{T}_2} N_{\text{H}_2}} = K_{(t)} \quad (7)$$

where $K_{(r)}$ is the chemical equilibrium constant for the reduced species. Again for simplicity, chemical equilibrium is assumed to be fast and to occur at each time step. $K_{(r)}$ was estimated from tabulated values for different temperatures given in Ref. [4]. Once the species concentrations are estimated at each time step and pore location, the LiOT calculations proceed.

Since there is no present model to describe the LiOT precipitation, a simplified model was added to MISTRAL. As a first order approximation no differentiation is made between supersaturation and precipitation, and the term precipitation from now on is used in a larger sense effectively meaning that the tritium in the bulk is frozen due to either supersaturation or precipitation. At each time step and each pore location it is assumed that if the total moisture pressure corresponding to the sum of the partial pressures of H_2O , T_2O and HTO is higher than the critical moisture pressure, all the tritium in the bulk surrounding the given pore location is frozen. Otherwise, no precipitation is assumed to occur and the code proceeds with the normal solution to the tritium release equations [2]. Thus the time constants for precipitation to occur and for LiOT to decompose are assumed to be very small so that both these processes occur within the computational time increment.

The critical moisture pressure, P_m^c , above which LiOT precipitation is assumed to occur, is calculated from the following equation for the given local pore temperature, T_c , based on Ref. [3]:

$$P_m^c = \begin{cases} (3.469 \times 10^{11} \text{ Pa}) \exp(-1.552 \times 10^4/T_c) & \text{for } T_c \leq 744 \text{ K} \\ (1.89 \times 10^8 \text{ Pa}) \exp(-1.010 \times 10^4/T_c) & \text{for } T_c > 744 \text{ K} \end{cases} \quad (8)$$

CASES STUDIED

A detailed calculation was carried out for the solid breeder outboard region 1 of the blanket, which is closer to the first wall (see Fig. 1), for both transient and steady state conditions. Only one case for the solid breeder outboard region 2 was considered to verify any unexpected discrepancies, but the tritium release behavior exhibited the same characteristics as that of region 1. The main parameters used in the calculations are shown in Table 1.

Each transient case was considered twice: once using a pore diffusion coefficient equal to the reference value ($f_{dp}=1$), and once using a coefficient equal to one tenth of its value ($f_{dp}=0.1$). This was done to ascertain the sensitivity of the tritium behavior to pore diffusion which could be significantly lower than expected because of the particular breeder microstructure and the possible effect of multi-size pores on the diffusion process [2].

The effect of the presence of tritium in the purge was also considered. For both the Physics and Technology Phases, the effective tritium partial pressure (calculated

assuming all tritium were in T_2 form) was varied from 0-100 Pa and the tritium inventories, corresponding to each pressure at steady state, were calculated for each case. Then the total tritium inventory was plotted versus the tritium pressure in the purge, which is inversely proportional to the purge flow rate. For the transient calculations, only two limiting cases of zero tritium concentration (which would occur at the entrance to the solid breeder region) and of tritium concentration corresponding to the steady state level (which is more representative at the conditions at the purge exit) were analyzed in each case.

Table 1

Main Parameters Used for Tritium Calculations for the Li_2O Solid Breeder for Outboard Region 1 of US Solid Blanket Design for ITER

Mass (kg)	6005
Volume (m^3)	3.94
Thickness (mm)	8
T Generation Rate (atoms/s m^3):	
Physics Phase	2.31×10^{19}
Technology Phase	2.01×10^{19}
Total Porosity (%)	20
Open porosity (%)	18
Average Grain Size (μm)	10
BET Surface Area (m^2/kg)	50
Li_2O Theoretical Density (kg/m^3)	1905
Grain Diffusion Coefficient:	
Pre-exponential (m^2/s)	6.81×10^{-7}
Activation Energy (kJ/mol)	84.8
Desorption Activation Energy (kJ/mol)	122
Hydrogen Concentration in Purge	0.2%
Pore Diffusion Coefficients for Tritium and Hydrogen (m^2/s):	
Reduced form: see Ref. [2]	
Oxidized form: $(3.56 \times 10^{-5}/P)T^{2.334}$	
(where P is in Pa)	

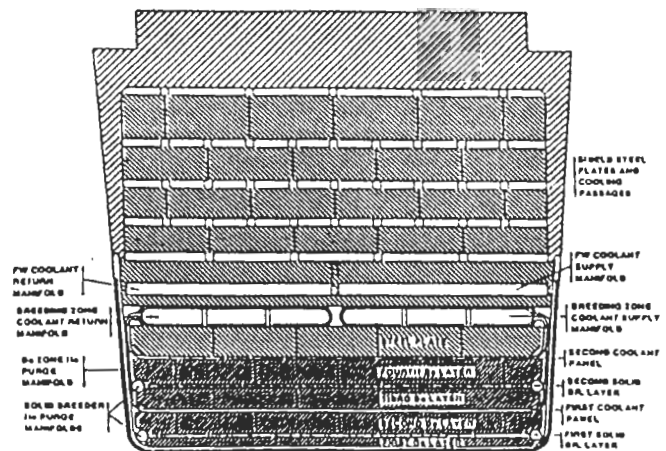


Fig. 1 Outboard Midplane Cross Section of the side Module for the US Solid Breeder Blanket for ITER

The transient calculations were limited to 7 hours for the Technology Phase and 2 hours for the Physics Phase. For each phase, the time chosen was enough to reach a quasi-steady-state condition.

ANALYSIS AND RESULTS

Since both Physics and Technology Phases showed a similar tritium behavior, the Technology Phase cases will be discussed in more details.

1. TRANSIENT CASES

The tritium generation rate and maximum temperature profile histories obtained from Ref. [1] for the cycles of operation during the Technology Phase are shown in Figures 2 and 3. The histories of the maximum and minimum temperatures across the solid breeder are used as input in the code and the spatial temperature distribution at each time step is estimated from them, based on a parabolic profile.

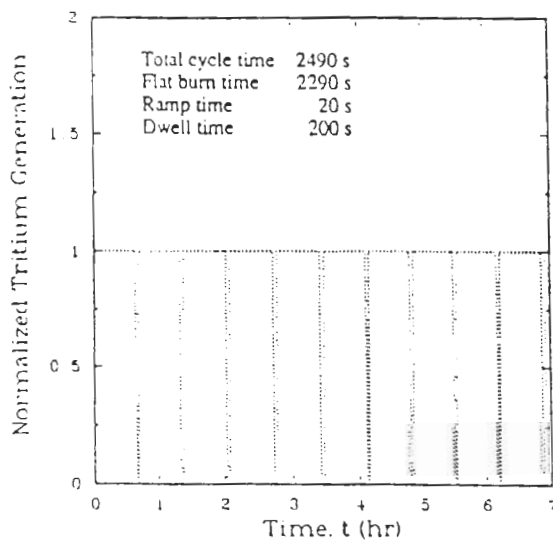


Fig. 2 Normalized Tritium Generation History During Technology Phase

The tritium release results for an effective tritium partial pressure of 20 Pa in the purge are shown in Figure 4 for a pore diffusion coefficient equal to the reference value. The tritium release exhibits a characteristic initial peak at the start of the burn time due to the combined effects of the generation rate starting and temperature rising. This is followed by a return to a normalized release of 1 during the rest of the burn time. The release then falls to zero during the dwell time. The tritium release profile reaches a quasi-steady-state within a couple of cycles. The same case was also run for a pore diffusion coefficient equal to one tenth of its initial value ($f_{dp}=0.1$). The tritium exhibits the same behavior for the case of $f_{dp}=0.1$ as for $f_{dp}=1$, except for a slight reduction in the tritium release peak due to the relatively longer time the tritium spends in the pore. However, since the tritium inventory in the pore is small in both cases, the effect of pore diffusion coefficients of these magnitudes on the overall tritium behavior is not significant.

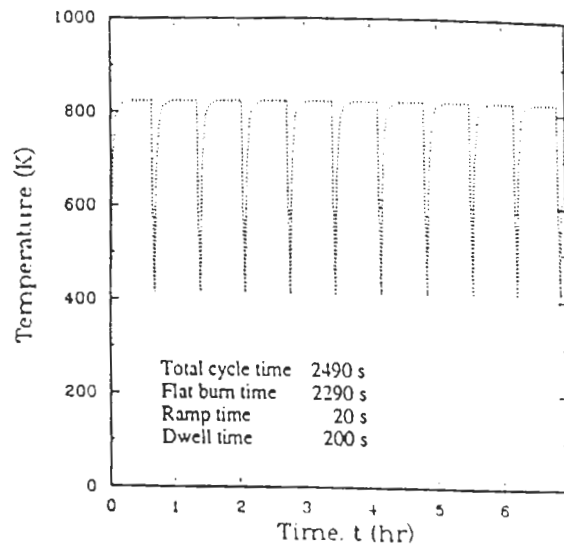


Fig. 3 Maximum Li_2O Temperature History for the Outboard Li_2O Region 1 for Technology Phase

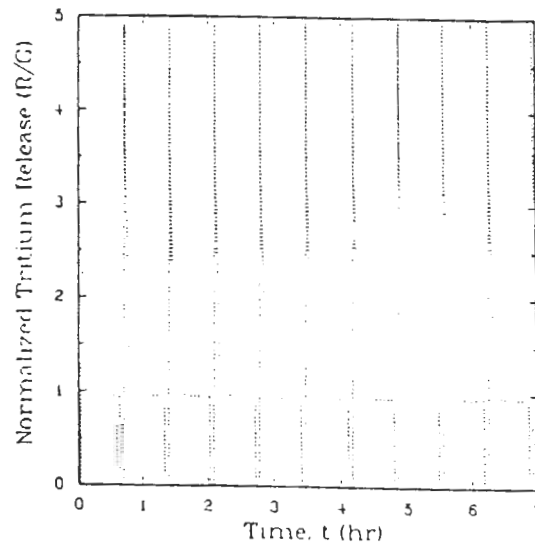


Fig. 4 Tritium Release History for the Outboard Li_2O Region 1 During the Technology Phase with a 20 Pa Tritium Partial Pressure in the Purge ($f_{dp} = 1$)

The tritium inventory in the outboard region 1 for the case of $f_{dp}=1$ is shown in Figure 5. The inventory is dominated by the surface coverage whose plot in the figure coincides nearly exactly with that of the total inventory. It oscillates between maximum and minimum values of about 0.3 and 0.05 g. The bulk (grain) inventory is quite low

because LiOT precipitation does not occur during the burn time for the temperature and moisture pressure operating conditions. Figure 6 shows the moisture pressure history at the mouth of the pore. The critical moisture pressure above which LiOT occurs is always higher than the calculated moisture pressure during the burn time. Because of the sharp drop in temperature during the dwell time, the critical moisture pressure decreases to below the moisture level. However, since there is no tritium generation and no tritium release during the dwell time, because of very slow diffusion at low temperatures, LiOT precipitation does not affect the overall tritium release and inventory behavior. It should be noted here that since LiOT precipitation occurs during the dwell time and LiOT dissociation during the burn time, the assumptions of instantaneous precipitation and dissociation require in effect for the results to be valid that at least one of these conditions exist: (i) the time constant for dissociation is much smaller than the burn time which will give time for any precipitated LiOT to dissociate; and/or (ii) the time constant for precipitation is much longer than the dwell time so as to prevent significant precipitation over the total operating time.

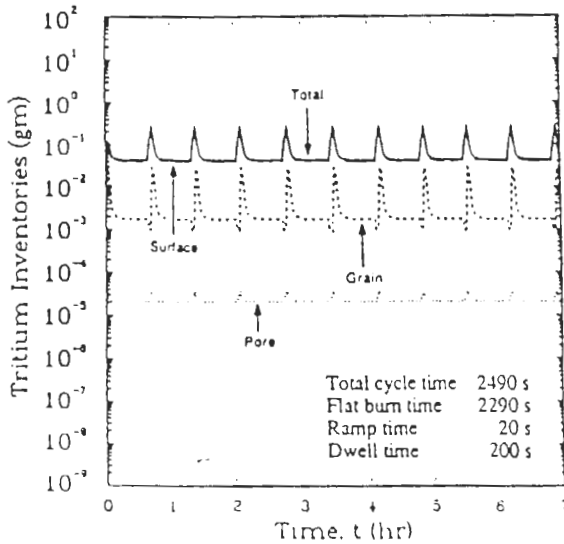


Fig. 5 Tritium Inventory History for the Outboard Li_2O Region 1 During the Technology Phase with a 20 Pa Tritium Partial Pressure in the Purge ($f_{dp} = 1$)

The tritium release results for zero tritium partial pressure in the purge for the reference pore diffusion coefficient are shown in Figure 7. The tritium inventory in this case was found to be extremely low (oscillating about 0.02 g), resulting in lower tritium release peaks.

The normalized tritium generation and maximum temperature histories for the Physics Phase [1] are shown in Figures 8 and 9. The tritium release for the case with a 20 Pa tritium partial pressure in the purge is shown in Figure 10 for $f_{dp}=1$. The results are similar to those of the Technology Phase. The peaking at the outset of the burn time is higher

than that of the Technology Phase because of the higher temperature in this case (see Figure 9). Again, reducing f_{dp} to 0.1 did not make a significant change to the tritium release behavior.

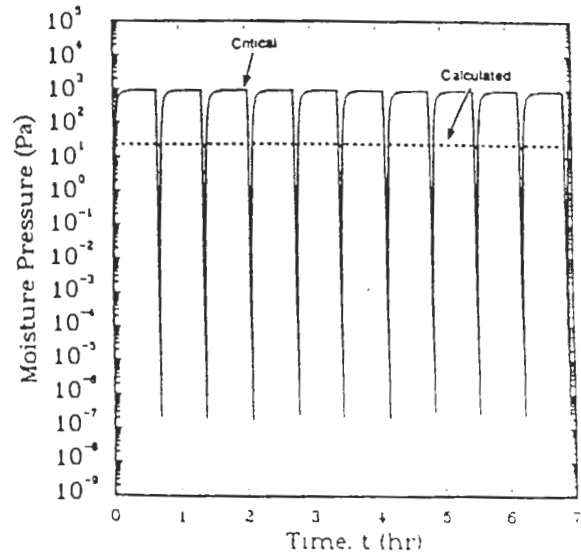


Fig. 6 Critical and Calculated Moisture Pressure Histories at the end of the Pore in the Li_2O Outboard Region 1 During the Technology Phase with a 20 Pa Tritium Partial Pressure in the Purge ($f_{dp} = 1$)

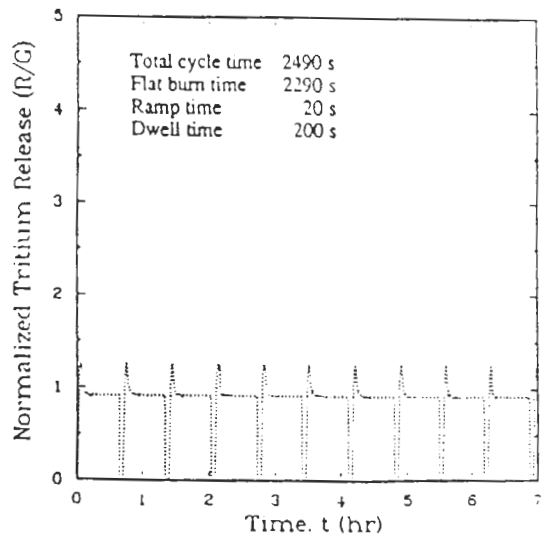


Fig. 7 Tritium Release History in the Li_2O Outboard Region 1 During the Technology Phase with Zero Tritium Partial Pressure in the Purge ($f_{dp} = 1$)

The tritium inventories are shown in Figure 11 for the same case (with $f_{dp}=1$). The total inventory is still dictated by the surface and oscillates with maximum and minimum values of about 0.2 and 0.03 g, slightly lower than for the Technology Phase because of the higher operating temperature and lower tritium generation rate.

$$P_{T_2} = \frac{1}{2} P_{He} \frac{G V_b}{Q} \tag{9}$$

where P_{He} is the helium pressure in the purge (Pa), G is the tritium generation rate (atoms/m³ s), and V_b and Q are the volume of the breeder material (m³), and helium purge flow

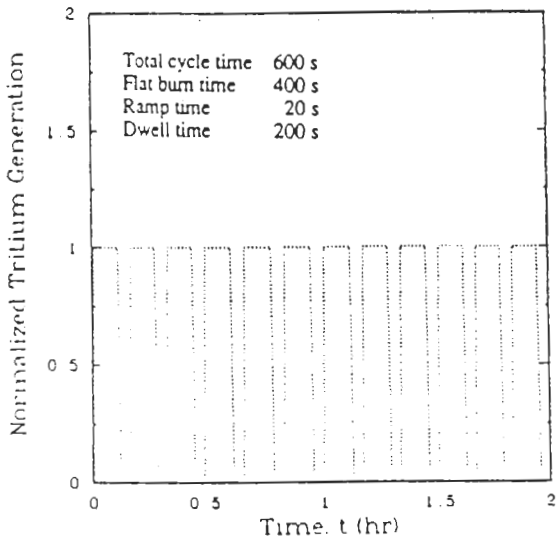


Fig. 8 Normalized Tritium Generation History During Physics Phase

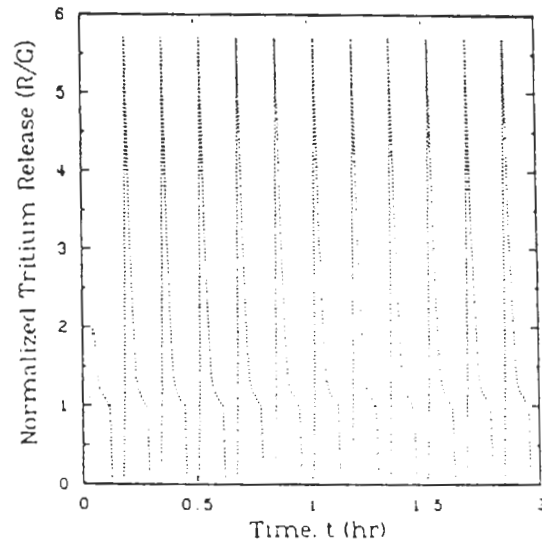


Fig. 10 Tritium Release History for the Outboard Li₂O Region 1 During the Physics Phase with a 20 Pa Tritium Partial Pressure in the Purge ($f_{dp} = 1$)

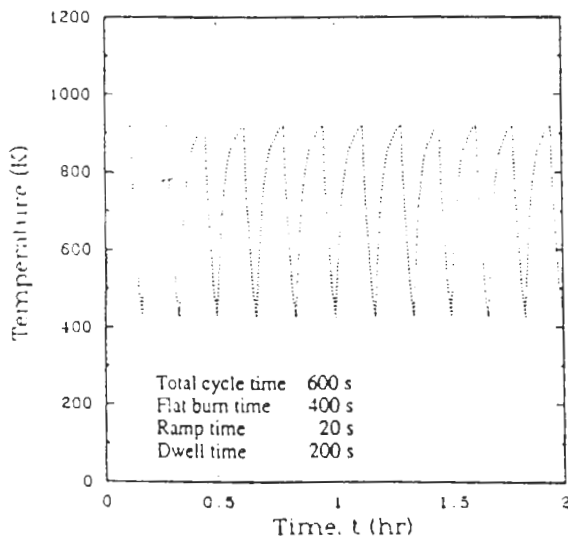


Fig. 9 Maximum Li₂O Temperature History for the Outboard Li₂O Region 1 for Physics Phase

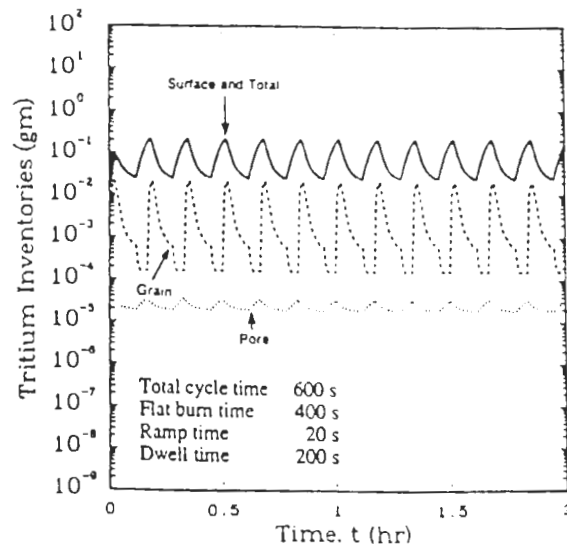


Fig. 11 Tritium Inventory History for the Outboard Li₂O Region 1 During the Physics Phase with a 20 Pa Tritium Partial Pressure in the Purge ($f_{dp} = 1$)

2. STEADY STATE

At steady state, the tritium inventory was calculated for different effective tritium partial pressures in the purge, P_{T_2} , which is related to the helium purge flow rate by:

rate (atoms/s), respectively, for the solid breeder region of interest. It should be noted that this value of P_{T_2} is the maximum spatial value of the effective tritium partial pressure occurring at the helium purge outlet.

The total pressure drop, ΔP , between the inlet and outlet of the blanket, was calculated using the following equation [1]

$$\Delta P = \frac{N R T \mu L}{k_c A (P_0 + \Delta P/2)} \quad (10)$$

where N is the helium molar flow rate (mole/m³ s), R is the universal gas constant (J/mol K), T is the temperature (K), μ is dynamic viscosity (N/m² s), L is the path length (m), k_c is the effective permeability of the medium (m²), A is the cross-sectional area of the material perpendicular to the flow path (m²), and P_0 is the outlet pressure (Pa).

The results are summarized in Figure 12 for the Technology Phase. The results for the Physics Phase are similar, except that the tritium inventory tends to be slightly lower due to the higher solid breeder temperature and lower tritium generation rate. The major inventory components in all the cases is the surface coverage. It is interesting to note that the tritium inventory varies virtually in direct proportion with the tritium partial pressure in the purge (or indirectly with the purge flow rate), except at partial pressures of about 1 Pa or lower where the inventory becomes less sensitive to changes in the tritium partial pressure. For the chosen solid breeder operating temperature range, the inventory is low enough that the purge flow rate can be set to a very low value without the inventory becoming a major concern. For example, for a low flow rate corresponding to a tritium partial pressure of the order of 100 Pa, the total inventory would probably still be of the order of 10 g which is acceptable. However, the concern is that at lower temperature a correspondingly high moisture pressure could cause the critical moisture pressure for LiOT precipitation to be exceeded, resulting in most of the tritium being trapped as

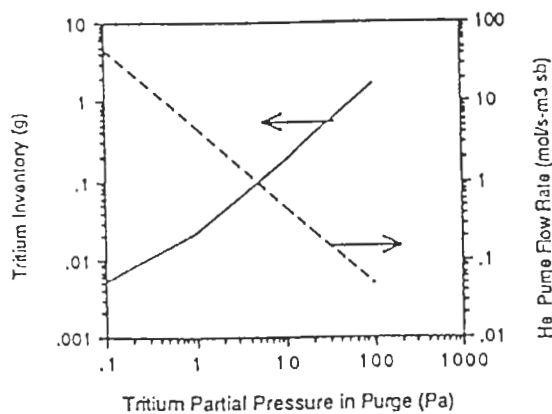


Fig.12 Tritium Inventory and Helium Purge Flow Rate vs. Tritium Partial Pressure in the Purge for the Outboard Region I During the Technology Phase

LiOT. This could result if for some reason the solid breeder operating temperature is noticeably lower than the design value. To guard against such an eventuality, it would be better to keep the design value of the tritium partial pressure in the purge to the order of 10 Pa or lower.

SUMMARY

An analysis of the tritium release and inventory in the US-ITER solid breeder blanket was performed, based on the MISTRAL code in which the effect of LiOT precipitation was included. The analysis was carried out for both the Physics and Technology Phases, for steady state and transient conditions. The results from the analysis, based on the given operating conditions and assumed property data, can be summarized as follows:

1. Both the Physics and Technology Phases exhibit the same tritium behavior. The tritium inventory, however, is lower in the Physics Phase, due to the higher operating temperature and lower tritium production rate.
2. In all the transient cases there is an initial tritium release peak at the start of the burn time due to the combined effects of the generation rate starting and the temperature rising. This is followed by a return to a normalized release of 1 during the rest of the burn time. The release falls to zero during the dwell time.
3. In all cases the tritium inventory is dominated by the surface coverage.
4. No significant change in the tritium inventory occurs when the pore diffusion coefficient was changed from its reference value to one tenth of this value.
5. The critical moisture pressure above which precipitation occurs is always greater than the calculated moisture pressure during the burn time. It becomes less than the calculated pressure during the dwell time due to the temperature drop. This, however, does not result in a change in the overall tritium inventory, since there is no tritium generation and no tritium release during this period because of very slow diffusion at low temperatures.
6. The tritium partial pressure in the purge is seen to affect the inventory significantly. However, in all cases the inventory was less than 10 g, which is acceptable. It is recommended, though, that the tritium partial pressure in the purge be kept at about 10 Pa or lower, to minimize the possibility of LiOT precipitation in the solid breeder in case the actual operating temperature is much lower than the predicted design value.

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