TRITIUM ANALYSIS OF A WATER-COOLED SOLID BREEDER BLANKET FOR ITER*

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Abstract: This paper presents quantitative predictions for the tritium release and inventory in a water-cooled solid breeder blanket for the International Thermonuclear Experimental Reactor (ITER) obtained from the tritium transport code MISTRAL [1] recently developed at UCLA. The blanket consists of a layout assembly of solid breeder and beryllium multiplier, with two layers of solid breeder in the outboard region and one layer in the inboard region [2]. The analysis includes steady-state inventory evaluations as well as transient calculations under assumed ITER pulsed operation. Different scenarios were investigated including operation at reduced power level. Key parameters affecting the kinetics of the tritium release and the inventory evolution considered in the investigation and discussed in this paper include the solid breeder microstructure, the purge gas composition and the operating burn and dwell times.

INTRODUCTION

A water-cooled solid breeder blanket has been proposed for the ITER tritium-producing blanket [2]. The breeder is operated at high temperature based on tritium release and reactor-relevance considerations while the coolant is operated at low pressure and temperature based on reliability and safety considerations. The blanket uses beryllium for neutron multiplication and lithium-base ceramic such as oxide or orthosilicate for tritium breeding. The material forms considered for the initial reference case are sintered products for both the breeder and the multiplier with 0.8 density factor. The lithium-6 enrichment is 90 %. The blanket uses one and two thin solid breeder layers in the inboard and outboard regions, respectively. Each breeder layer is separated from the water coolant channel on each side by a thick beryllium layer providing the temperature drop between the high temperature breeder and the low temperature coolant. The blanket is divided into 32 inboard and 48 outboard segments [2]. Due to the particularly sensitive safety concern linked with the first nuclear fusion test reactor, prediction and minimization of the tritium inventory levels in ITER are important issues [3]. Cyclic operation which is anticipated for ITER creates a very complex situation for the prediction of the tritium release behavior in the breeder material which is affected by the combined effect of changes in temperature and tritium generation, and whose analysis requires the use of fairly sophisticated theoretical models and computational systems. This paper presents the results of the transient tritium release analysis for the proposed blanket which was obtained from the computer code MISTRAL [1].

ANALYSIS AND RESULTS

For the analysis, typical pulsed operation scenarios with 1000 - 3000 s burn time and 100 s dwell time with quasi-instantaneous rise and fall were assumed. The main parameters used in the transient tritium calculations are summarized in Table 1.

Table 1: Main Parameters Used for the Tritium Calculations for the Current Design of the Li_4SiO_4 (Li_2O) ITER Solid Breeder Blanket [5]

	Outboard		Inboard
	ZONE1	ZONE2	
Mass, (10^6 g)	5.57	5.57	2.13
Volume, (m^3)	3.64	3.64	1.39
Thickness, (cm)	0.8	0.8	0.9
T. Gen. Rate, (g/day)	67.7	45.1	28.5
Total Porosity, (%)	20		
Open Porosity, (%)	18		
Grain Size, (μm)	13 (20)		
BET Area S_{BET}, (m^2/Kg)	770 (85)		
Density ρ (TD), (g/cm^3)	2.39 (2.01)		
Grain Diffusion Pre-exp. Coefficient D_{go}, (m^2/s)	2.1×10^{-11} (7.94×10^{-9})		
Grain Diffusion Activation Energy E_D, (KJ/mol)	64 (77.4)		
Heat of Adsorption function of coverage Q, (KJ/mol)	*Fischer*[6]		

The transient temperature profiles were estimated from a thermal time constant [4]. In general, the temperatures of the solid breeder reach thermal equilibrium during the first burn cycle. They then drop to some minimum values (392 and 598 K for the outboard region 1 and 2 respectively, and 429 K for the inboard region) during the 100 s dwell time before returning to steady-state during the next burn time. The one exception to the above is the case of the second outboard breeder zone for 1000 s burn time for which thermal equilibrium is not obtained for all cycles. Figure 1 shows the temperature distribution at equilibrium over half the solid breeder layer thickness for the outboard zone 1.

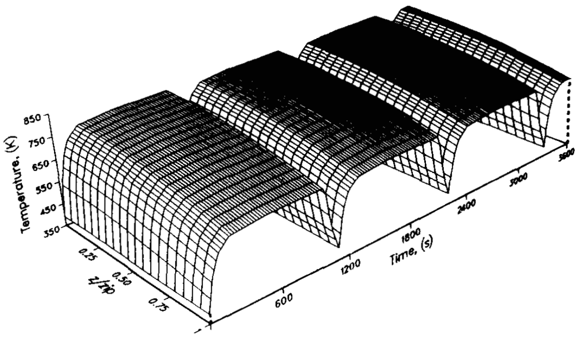

Figure 1. Temperature distribution under pulsed operation at equilibrium in the outboard zone 1 (over half the breeder layer thickness).

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Table 2 shows the different cases which were analyzed to observe the effects of the following key parameters on the tritium release kinetics: the specific surface area, the purge gas composition, the operating burn and dwell times, and the reactor power level.

Table 2. Cases Investigated for the Tritium Transient Analysis.

Cases	**A**	**B**	**C**	**D**	**E**
Material	(o)	(o)	(o)	(o)	(⋆)
(o) Li_4SiO_4					
(⋆) Li_2O					
Power Level (%)	100	100	50	100	100
% H_2 **in Purge**	1	0.01	1	1	1
Burn T (s)	1000	1000	1000	3000	1000
Dwell T (s)	100	100	100	100	100
Regions	o 1	o 1	o 1	o 1	o 1
o=outboard	o 2				
i=inboard	i				

Because of computational time constraints, the transient calculations have been limited to 10 hours. Figure 2 shows the normalized tritium release for the Case A for the outboard region 1. The figure indicates that the normalized tritium release is about 0.95 after 10 hours close to the quasi-steady state value of R/G=1. Figure 3 shows for the Case A the evolution of the different inventory components (i.e. grain, pore, surface) in the outboard region 1. It can be seen that by far the largest contribution to the total inventory comes from the surface.

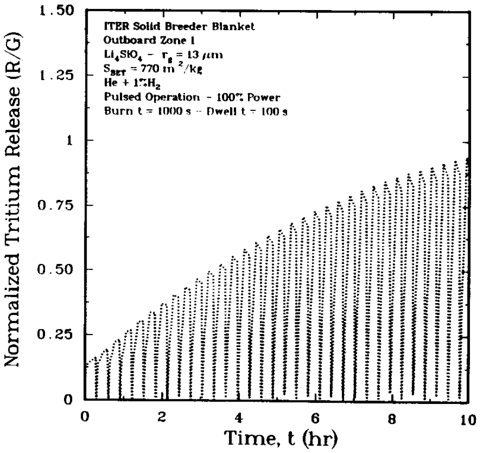

Figure 2. Case A: Predicted tritium release profile under pulsed operation.

The calculations for the Case A were carried out for the outboard regions 1 and 2 and the inboard region of the blanket. The comparison of the results for the total inventory for the three solid breeder blanket regions is indicated in Figure 4. Values of the inventory that will be reached at steady-state are also indicated. Typically the inventory build-up after 10 hours is about half of the steady-state inventory to be attained.

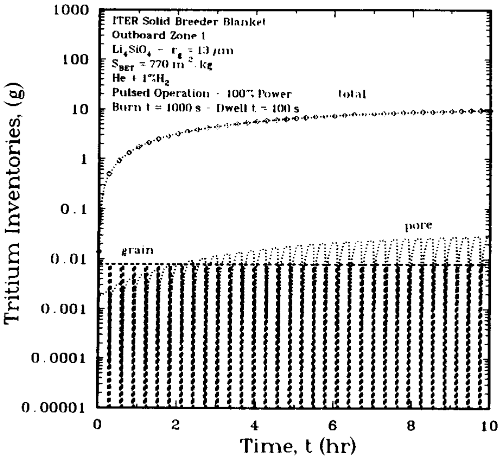

Figure 3. Case A: Predicted transient inventory profiles under pulsed operation.

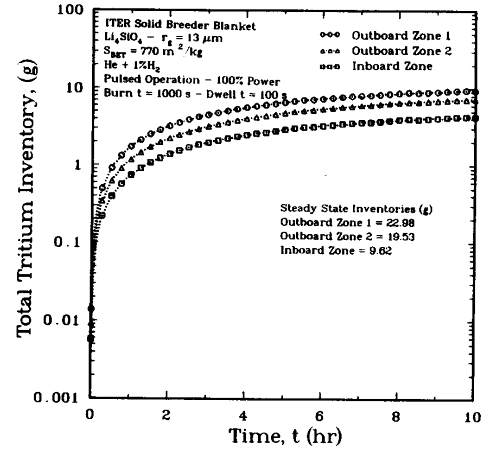

Figure 4. Case A: Comparison of the predicted transient inventory profiles under pulsed operation in the three blanket regions.

Since the results for all three regions were similar for the first case considered (Case A), calculations for the other cases were only done for the first outboard region 1 as representative of the three regions. Figure 5 (Case B) shows the effect of a lower content of protium (0.01%) as sweeping component in the purge which is known to strongly affect the kinetics of the release. For ease of comparison, the release curve obtained for a content of 1% H_2 is also indicated. The figure shows that whereas for the case with 1% H_2 in the purge the release reaches about 95% of the quasi-steady-state value after 10 hours, it only reaches about 50% for the case with 0.01% H_2. This can be explained by the surface inventory, in the latter case being significantly higher and taking a larger time to build-up to its quasi-steady state value. Figures 6 and 7 show the behavior of the release and the inventory component profiles respectively for case C with a 50% reactor power level. Note that for both cases, the tritium release has been normalized to the tritium generated at the 100% power level. Thus in Figure 6, for Case C, quasi-steady state will be reached when R/G = 0.5.

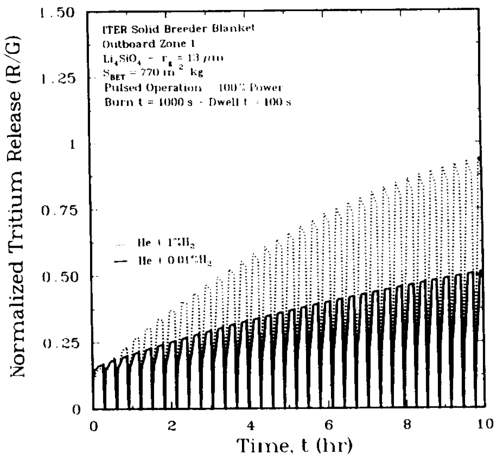

Figure 5. Case B: Predicted tritium release profile under pulsed operation.

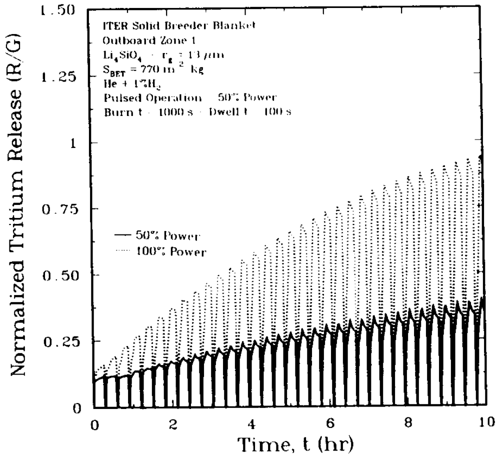

Figure 6. Case C: Predicted tritium release profile under pulsed operation.

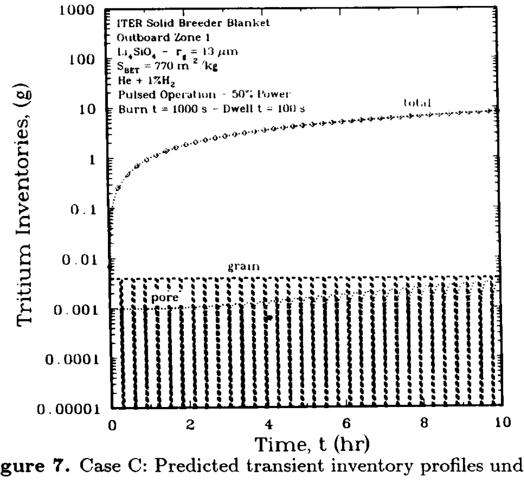

Figure 7. Case C: Predicted transient inventory profiles under pulsed operation.

The solid breeder temperature for Case C is much lower due to the reduced power level and, as indicated in the following table, the grain diffusive inventory, I_g, becomes the dominant inventory at steady-state which, because of the large diffusive time constant, t_d, is only reached after ≈100 days for Li_4SiO_4 and ≈17 days for Li_2O. At low temperature (reduced power operation), for Li_2O in particular, there is an additional inventory component due to precipitation of LiOT. This inventory component can be large but will decrease as the temperature is increased.

Table 3. Grain diffusive inventory I_g at steady-state and diffusive time constant t_d.

Power Level (%)	100	50	100	50
Average Temperature (K)	725	540	725	540
	I_g (g)		t_d (days)	
Li_4SiO_4	24	910	3.8	144.5
Li_2O	<1	120	0.22	17.8

To investigate the effect of the burn time on the kinetics of the release and the behavior of the inventory components, an analysis was performed for a longer burn time and the same dwell time. Figures 8 shows the behavior of the release and the inventory component profiles respectively for Case D with a burn time of 3000 s and a dwell time of 100 s. The transient tritium release and inventory behavior (the latter Figure not shown here) are essentially the same as for the case with a burn time of 1000 s (Case A) and it appears that it is the cumulative burn time which is of importance for quasi-steady state to be reached.

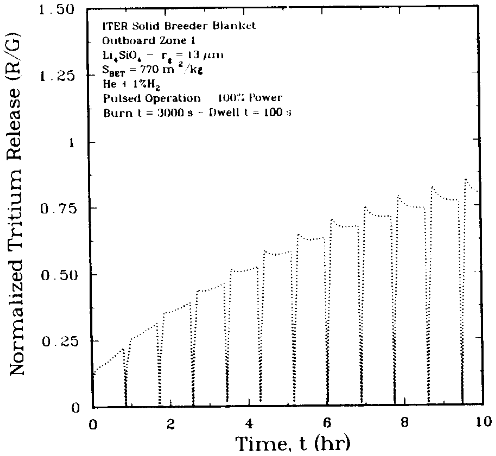

Figure 8. Case D: Predicted tritium release profile under pulsed operation.

Finally Figures 9 and 10 show the results for Case E where Li_2O is used instead of Li_4SiO_4 for conditions similar to those of the Case A. In this case quasi-steady state is reached rapidly after a few cycles. This is mostly due to the low specific surface area (S_{BET}) assumed for the Li_2O based on Ref.[5]. It should be noted that Li_4SiO_4 would show a similar behavior with the same S_{BET} since for these conditions, surface inventory is dominant.

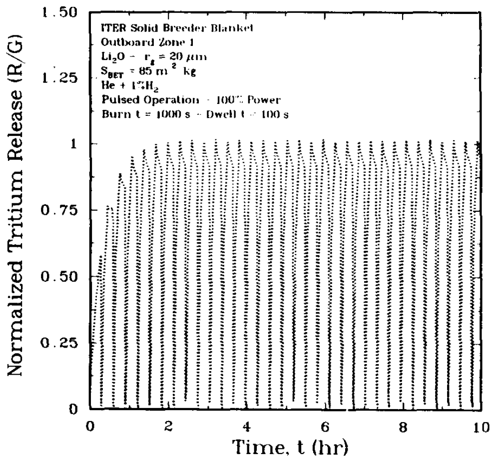

Figure 9. Case E: Predicted tritium release profile under pulsed operation.

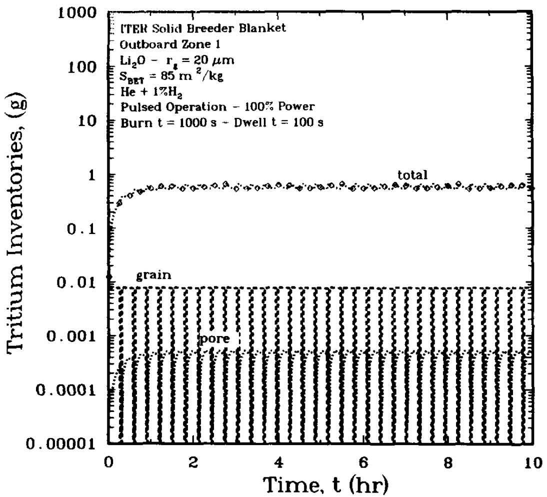

Figure 10. Case E: Predicted transient inventory profiles under pulsed operation.

SUMMARY AND CONCLUSIONS

From the analysis of the transient tritium behavior using the MISTRAL code, the following observations can be made:

1. The solid breeder temperature approaches its maximum and minimum values during pulsed operation within ≈ 100 s.
2. Tritium release approaches zero during the dwell for dwell times of about 100 s or more. Consequently, the tritium inventory is practically constant during the dwell. The tritium release results obtained for a dwell time of 100 s can then be easily extrapolated for larger dwell times.
3. The transient tritium release and inventory behavior seems to be essentially the same for both burn times of 1000 s and 3000 s. It seems reasonable to expect that for burn times of this order or higher and for dwell times of the order of 100 s and higher, the tritium inventory and release will reach quasi-steady-state essentially over the same effective period, (approximately corresponding to the product of the burn time and the number of cycles to reach quasi-steady-state).
4. Under 100% power, the surface inventory is the largest even with 1% H_2 in the purge.
5. Under 50% power (low temperature), the diffusive grain inventory increases substantially and becomes larger than the surface inventory. In addition, for the case of Li_2O in particular, there is another inventory component, due to precipitation of LiOT, which can be large.
6. The time for the tritium inventory to reach quasi-steady-state under 100% power is of the order of a day for Li_4SiO_4 and of several hours for Li_2O. Operation at 50% power would increase these times by factors of 10-100.
7. Long period of operation (days) at low power level (low temperature) would result in high tritium inventory. Subsequent operation at 100% power would reduce the inventory to its normal quasi-steady-state level in less than a day for Li_2O and several days for Li_4SiO_4.
8. Adding H_2 to the purge before instead of after start-up only has a small effect on the transient tritium release profile.

From the above sequence of considerations a key factor that emerges is the minimum operation temperature in the solid breeder which is particularly low for the cases investigated at 50% power. For this case the analysis showed that the diffusive grain inventory component increases substantially and becomes larger than the surface inventory. It is presently unclear whether such a scenario is physically realizable, but, if operation at 50% power over extended periods is anticipated, it is recommended that a mechanism for keeping the solid breeder at high temperature be incorporated in order to reduce tritium inventory. Other issues that could affect the tritium release under particular conditions and that should be considered include LiOH formation and precipitation in particular at low temperatures and radiation damage for higher fluences which may strongly modify the physical and chemical properties of the solid breeder material.

ACKNOWLEDGEMENTS

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REFERENCES

[1] A.R. Raffray, G. Federici, M.A. Abdou, "A Comprehensive Computer Model for Tritium Transport and Release in Lithium-Base Ceramic Breeders," Presented at the Second International Specialists'Workshop on Modeling Tritium Behavior in Fusion Blanket Ceramics - Indianapolis,IN April 1989.

[2] Y. Gohar et al., "Solid Breeder Blanket," Chapter III.a of the U.S. Contributions to the Homework for ITER, February/March 1989.

[3] M.A. Abdou, A.R. Raffray, Ž.R. Gorbis, M.S. Tillack, Y. Watanabe, A. Ying, M.Z. Youssef and K. Fujimura, " A Helium-Cooled Solid Breeder Concept for the Tritium-Producing Blanket of the International Thermonuclear Experimental Reactor,", Fusion Technology, Vol.15 - No.2 166-182, March 1989.

[4] M. Billone, "Estimates of Tritium Inventories in Blanket," U.S Contributions to the Homework for ITER, III.a.7 Blanket-Solid Breeder, February/March 1989

[5] M.A. Abdou, et al. "Technical Issues and Requirements of Experiments and Facilities for Fusion Nuclear Technology, FINESSE Phase I Report," University of California at Los Angeles, PPG-909/UCLA-ENG-85-39, December 1985.

[6] A.K. Fischer and C.E. Johnson, " Measurement of Adsorption in the $LiAlO_2$-$H_2O_{(g)}$ System", Fusion Technology,15 [2], 1212-1216 1988.