

MODELING OF TRITIUM TRANSPORT IN A FUSION REACTOR PIN-TYPE SOLID BREEDER BLANKET USING THE DIFFUSE CODE *

Rodger MARTIN and Nasr M. GHONIEM

University of California, Los Angeles, Mechanical, Aerospace and Nuclear Engineering Department, Los Angeles, CA 90024, USA

A pin-type fusion reactor blanket is designed using γ -LiAlO₂ solid tritium breeder. Tritium transport and diffusive inventory are modeled using the DIFFUSE code. Two approaches are used to obtain characteristic LiAlO₂ grain temperatures. DIFFUSE provides intragranular diffusive inventories which scale up to blanket size. These results compare well with a numerical analysis, giving a steady-state blanket tritium inventory of 13 g.

Start-up transient inventories are modeled using DIFFUSE for both full and restricted coolant flow. Full flow gives rapid inventory buildup while restricted flow prevents this buildup. Inventories after shutdown are modeled: reduced cooling is found to have little effect on removing tritium, but preheating rapidly purges inventory.

DIFFUSE provides parametric modeling of solid breeder density, radiation, and surface effects. 100% dense pins are found to give massive inventory and marginal tritium release. Only large trapping energies and concentrations significantly increase inventory. Diatomic surface recombination is only significant at high temperatures.

1. Introduction

A fusion reactor blanket employing a pin-type solid breeder structure has been designed for a 1034 MWe reactor with a neutron wall loading of 5 MW/m² [1]. γ -LiAlO₂ is chosen as the solid breeder due to high temperature structural stability. In analyzing tritium inventory, the bulk diffusive inventory is based on the diffusivity D , which for γ -LiAlO₂ from 400 to 700 °C is given by an activation energy of 35.8 kcal/mol/K and a pre-exponential term of 1.2×10^{-6} cm²/s [2].

STARFIRE [3] first attempted tritium transport modeling in solid breeders using an analytical solution for diffusion in a single spherical grain with zero surface concentration; intragranular diffusive inventory is given by:

$$I_g = [r_g^2/15D] \dot{g} V_g, \quad (1)$$

with \dot{g} the tritium generation rate per unit volume, V_g the grain volume, and r_g the grain radius. From blanket temperature and tritium generation profiles, the intragranular inventories can be calculated and scaled up to represent blanket unit cells, and then summed to give total blanket diffusive inventory.

Billone and Clemmer [2] extended eq. (1) to evaluate tritium inventory and diffusion in more complex solid breeder geometries for the TRIO experiment [4] and the BCSS study [5]. The following equations were derived to evaluate a cylindrical unit cell:

$$I_d = f \dot{G} r_g^2 / [15D(\bar{T})] \quad (2)$$

where

$$f = (\beta - 1)^{-1} \int_1^\beta \exp[(Q/RT)(\bar{T}/T - 1)] d\eta, \quad (3)$$

with \bar{T} the cross-sectional area-averaged temperature, $\beta = r_o^2/r_i^2$ with r_o and r_i the outer and inner radii of the unit cell, $\eta = r^2/r_i^2$ with r an arbitrary radius, R the ideal gas constant, and $T = T(\eta)$ the local temperature. The present study follows a similar approach to modeling, but incorporates a computer code which numerically evaluates the diffusion equation to obtain intragranular tritium diffusive inventories.

Other contributions to inventory arise from solubility, grain boundary diffusion, surface adsorption, and purge gas inventory. Reactor inventory includes tritium permeation into the coolant and metal structure. BCSS modeling considers grain boundary, adsorptive, and purge inventories negligible compared to diffusive. Solubility inventory is also negligible for LiAlO₂. The TRIO experimental results support these conclusions for 0.1 vol% H₂ added to the helium purge [2].

Although useful, previous modeling does not address the following:

- (1) exponential approximations are used for blanket temperature and tritium generation profiles rather than calculated profiles;
- (2) modeling of transient operation is limited;
- (3) the analytical solution presupposes zero concentration on spherical grain surfaces;
- (4) limited experimental data and no models exist on irradiation effects;
- (5) large variations exist in reported diffusion coefficients;
- (6) oxidation/reduction effects on purged tritium are poorly understood.

This research attempts to address the first four areas.

2. A Model for tritium transport in a pin-type blanket

The present modeling uses the DIFFUSE code [6] for a one-dimensional numerical solution of the diffu-

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sion equation. This code is useful for modeling tritium generation, inventory, and release in solid breeders as well as permeation.

Fick's laws govern the DIFFUSE analysis:

$$J_j(x, t) = -D_j(T(x, t)) \left[\nabla C_j(x, t) + \frac{C_j(x, t) Q^*}{kT^2(x, t)} \nabla T(x, t) \right], \quad (4)$$

and

$$\frac{\partial C_j(x, t)}{\partial t} = -\nabla J_j(x, t) + G_j(x) - \sum_i \frac{\partial C_i^j(x, t)}{\partial t}, \quad (5)$$

where the concentrations $C_j(x, t)$ and $C_i^j(x, t)$ represent the j th diffusing species and the j th species in the i th trap respectively, $G_j(x)$ the implant (generation) source term, $J_j(x, t)$ the flux, $D_j(T)$ the diffusivity, Q^* the heat of transport, k Boltzmann's constant, and $T(x, t)$ the temperature. Solutions can be obtained for slab, spherical, or cylindrical geometries. Appropriate choice of source terms simulates tritium generation.

DIFFUSE can evaluate several boundary conditions:

- (1) perfectly reflecting boundary (e.g. impermeable oxide layer);
- (2) zero concentration at the boundary;
- (3) Sievert's law (bulk solubility);
- (4) diatomic surface recombination;
- (5) simple interface between two materials.

As in previous models, bulk diffusion is assumed to dominate inventory in LiAlO_2 . Given the tritium generation rate and a representative cell temperature, a characteristic grain can be used to model each unit cell. Use of the zero concentration boundary condition by the DIFFUSE code gives the intragranular diffusive inventories which are scaled up to give the total blanket inventory. Detailed neutronics analysis provides tritium generation and volumetric heating rates.

The temperature chosen for each characteristic grain is important; two approaches are used for evaluation. The first divides each pin into five concentric zones of equal thickness. The temperature for the volumetrically averaged radial position of each zone is determined from the heat transfer profiles. Each zone is represented by one grain at this temperature and the pin generation rate. DIFFUSE gives the diffusive inventory for this grain, which is scaled up for the zone and the five zones summed for the pin inventory. This analysis is performed for a pin from each row, and extrapolated to blanket dimensions.

The second method, evaluation of pin inventory from a single DIFFUSE analysis, requires a characteristic single grain temperature representative of the entire rod inventory. Manipulation of eq. (1) gives another

equation amenable to numerical analysis, similar to eq. (3):

$$\bar{T} = Q / \left[R \ln \left[\frac{2}{r_o^2 - r_i^2} \int_{r_i}^{r_o} \exp(Q/RT) r dr \right] \right]. \quad (6)$$

Substitution of $T = T(r)$ gives \bar{T} for the single DIFFUSE analysis.

A third approach employs a derivative form of eq. (1) to numerically evaluate the diffusive inventory for each characteristic grain at an average pin temperature weighted by diffusive inventory. For uniform tritium generation, the working equation is:

$$\bar{I}_g = \frac{2r_g^2 g}{15D_0(r_o^2 - r_i^2)} \int_{r_i}^{r_o} \exp(Q/RT) r dr, \quad (7)$$

which only requires the temperature profile $T = T(r)$ obtained from thermal hydraulics. D_0 and Q are the pre-exponential and activation energy terms for diffusion, and r_i and r_o the inner and outer radii of the ceramic within the pin.

3. Steady-state inventory

Fig. 1 shows one of the 1080 modules of this blanket design. Each LiAlO_2 pin has a central channel for the helium purge and a 0.1 mm gap between the ceramic and 1 mm thick cladding of 9-C (low activation HT-9). Behind the lobular first wall are six rows of 1.7 cm diameter beryllium pins for neutron multiplication. Next are five rows of LiAlO_2 pins with purge channel radius of 0.05 cm and 0.61 cm outer radius, then six rows of larger pins of 0.135 and 1.46 cm radii. Helium coolant flows past the first wall and through the module at 50 atm pressure, with inlet and outlet temperatures of 250 and 550°C. The cladding has an oxide layer to reduce tritium permeation. The maximum LiAlO_2 temperature approaches 1150°C and the minimum 530°C. The

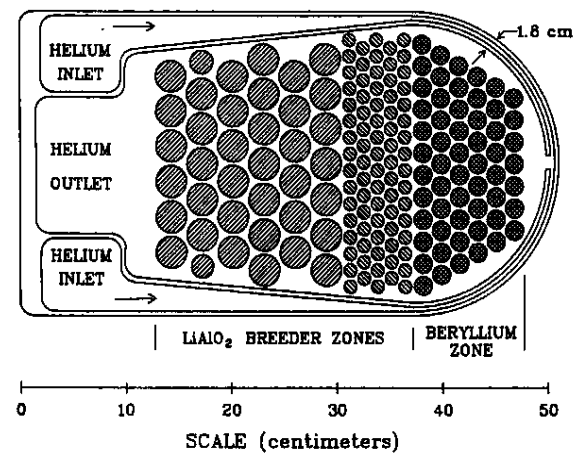


Fig. 1. Design of blanket module.

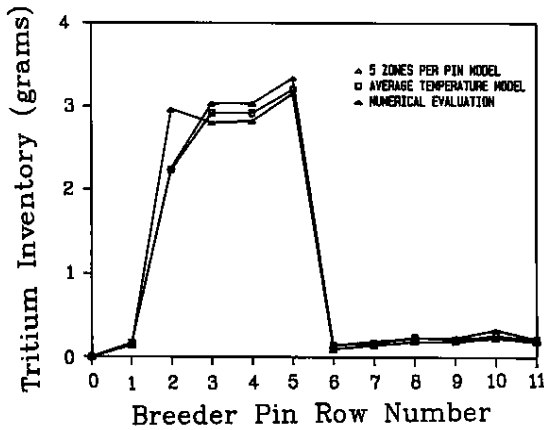


Fig. 2. Comparison of steady-state tritium inventory models.

LiAlO_2 grain size is $0.1 \mu\text{m}$, and ceramic density is set at 85% theoretical density for greater porosity and faster tritium release.

The 5-zone approach for steady-state diffusive inventory gives 12.9 g of tritium. The method of one DIFFUSE analysis per pin gives 12.6 g. The numerical evaluation gives 13.2 g. These methods show very good agreement. Inventory of 0.10 wppm in this 129 000 kg LiAlO_2 blanket compares favorably with the GA Technologies model results of 38.3 g inventory (0.073 wppm) in a 522 000 kg LiAlO_2 blanket [7].

Fig. 2 gives row-by-row inventories. The high first row temperatures reduce inventory to 0.03 wppm; likewise for rows six through eleven with less than 0.02 wppm. The cooler pins of rows two through five have inventories approaching 0.6 wppm.

With the diffusive tritium inventory only 13 g at steady-state, the major concern might be high temperature permeation through pin cladding. With an inner oxide layer on the cladding to resist permeation, these concerns are believed manageable and are not quantified in this paper.

4. Transient tritium inventory

Two different start-up conditions are modeled: full helium coolant flow through the blanket as at full power operation, and reduced helium flow. For each, a two week start-up is modeled with 3.5 days each at 10%, 20%, 50%, and 80% followed by 100% power.

With 100% helium flow, the fractional tritium generation and volumetric heating rates and the coolant temperature rise across the blanket are the same as the fractional power level. New temperature profiles across the pins are calculated and eq. (6) gives the temperature representative of each row for each power level. A sequence of five DIFFUSE runs for a single grain gives transient inventories at each power characteristic of the row.

With fractional helium flow restricted to the same fraction as the power level at 20%, 50%, and 80%, coolant temperature rise across the blanket is identical to full-power operation, giving significantly higher transient temperatures. For 10% power the helium flow is maintained at 20% of maximum, so coolant temperature rise across the blanket is only half that of full power.

Fig. 3 shows that full flow inventory builds up rapidly to several hundred grams at low power before decreasing rapidly at higher power. The first row contributes most to inventory with its high generation rates. For restricted flow the lower temperatures at 10% power give some tritium build-up but inventory decreases rapidly at 20% power.

Significant inventory will accumulate for unrestricted helium flow during start-up. Tailoring of helium flow to power alleviates these concerns. Even controlled flow gives some inventory build-up at low power testing and start-up, but coolant pre-heating would alleviate such concerns.

Two shutdown scenarios are evaluated: coolant flow at 20% that of full power, and a combination of coolant flow reduction and preheating for coolant temperatures of 470 to 500°C across the pins. Zero tritium generation and afterheat generation of 1% that at full power are assumed.

For the first scenario the temperature rise from inlet to each row of pins is 1/20 that of full power. New pin temperature profiles and characteristic temperatures are calculated. Steady-state conditions for each grain are followed by a second DIFFUSE run using temperature and generation profiles at shutdown.

Fig. 4 shows the cold shutdown scenario to give negligible reduction of inventory with time. From a steady-state inventory of 12.6 g, 12.4 g remains after two weeks, 12.1 g after 6 months, and 11.7 g after one year. With ceramic temperatures near 270°C blanket inventory will be virtually immobilized after shutdown.

In comparison, average temperatures for hot shutdown range over 200° higher with much faster diffu-

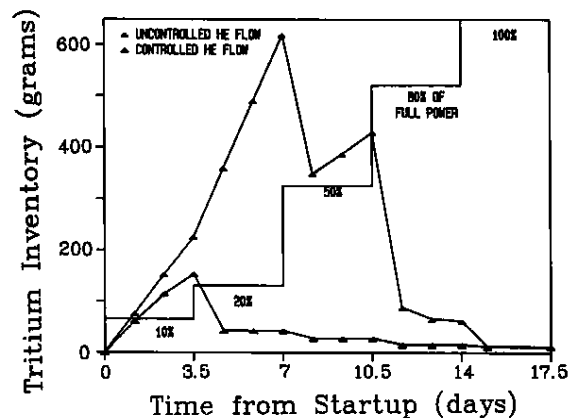


Fig. 3. Blanket inventory during start-up transients.

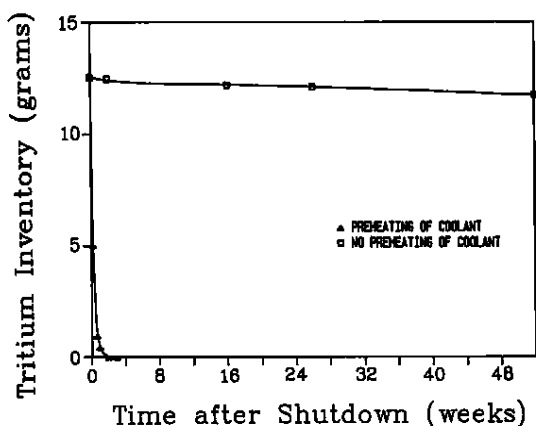


Fig. 4. Blanket inventory after shutdown.

sion. One week after shutdown, total blanket inventory drops from 12.6 to 0.45 g, and after two weeks a trivial 0.02 g remains. With coolant pre-heating, purge of diffusive inventory can be considered complete within days.

For this small inventory, the expense of coolant preheating may not be worth the benefits obtained. But if larger blanket inventory results from actual operations, blanket baking could rapidly alleviate post-shutdown inventory concerns.

5. Effects of solid breeder properties

DIFFUSE is used to study effects of density, surface phenomena, and radiation on inventory in solid breeders [8,9].

DIFFUSE analyzes the effects of 100% density for a single crystal LiAlO_2 cylinder of dimensions identical to the blanket pins. Tritium diffusion is evaluated with zero concentration boundary condition at the purge channel (i.e. hydrogen added to the helium purge gas [2]) and reflecting boundary condition (oxide layer) at the cladding. The temperature profiles calculated previously give very slow tritium diffusion through these massive grains. Over three years only 1.7% of the total generated tritium is purged from the hottest pins; the cooler pins release only a few hundredth of a percent. Huge inventories are a significant safety concern. Advantages are the possibility of batch processing of pins for tritium recovery at the end of blanket life, reduced permeation problems, and enhanced tritium breeding ratio from higher density.

Surface effects are evaluated using the diatomic surface recombination boundary condition for a typical LiAlO_2 grain. With the lack of experimental data, input values for surface properties felt to be reasonable are used. Results indicate negligible surface inventory with respect to diffusive over low to medium temperatures. Measurable surface contribution to the total inventory

only becomes apparent above 1100 K; the contribution at 1400 K is 65% that of diffusive, although uncertainties in input values make quantitative analysis very tentative.

Radiation effects are approximated using combinations of temperature, radiation-produced trap concentration, and trapping energy. Experimental uncertainties lead to use of input values which seem reasonable. For a trap concentration of one appm in LiAlO_2 , the trapped inventory is overwhelmed by diffusive inventory over a reasonable range of trapping energies. At 1273 K the trapped inventory is comparable to diffusive only at a large trap energy of 4 eV. For an assumed trap energy of 3.5 eV and a temperature of 1273 K, the trapped inventory is comparable to diffusive only at trap concentrations of 100 appm and more. Assuming a very large trap concentration of 1 at%, a comparison of inventories from 700 to 1475 K is made for trap energies of 2.5 and 3.5 eV: at 3.5 eV the trapped inventory is overwhelming while at 2.5 eV the trapped inventory is predominant at low temperatures but rapidly becomes insignificant at temperatures much above 825 K. These results suggest significant trapping requires trapping energies above 3 eV, and that effects due to low trap concentration are only significant at high temperatures while very high trap concentrations have most significance at lower temperatures.

6. Conclusions

(1) The total diffusive steady-state tritium inventory for this blanket is expected to be 13 g.

(2) For start-up power ramping, unrestricted coolant flow will rapidly lead to hundreds of grams of tritium inventory. Reduction of coolant flow can keep inventory at acceptable levels.

(3) Restricted coolant flow after shutdown will not significantly affect the residual inventories. Preheating of the coolant can lead to rapid purging of residual tritium.

(4) Use of 100% dense LiAlO_2 will lead to massive inventories over blanket life, but the marginal release rates would favorably impact permeation concerns. Post-shutdown batch processing may be feasible.

(5) At low to moderate breeder temperatures, diffusive inventory is expected to predominate. Considerable radiation-induced trap concentrations and trapping energies would be required for predominance of trapped inventory.

(6) The DIFFUSE code offers much potential in modeling tritium behavior in solid breeders under a wide range of operating conditions and phenomena.

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