A Gas-Carried Li_2O Cooling-Breeding Fusion Reactor Blanket Concept

D.K. Sze, E.M. Larsen, E.T. Cheng, and R.G. Clemmer

July 1975

UWFDM-151

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

A Gas-Carried Li_2O Cooling-Breeding Fusion Reactor Blanket Concept

D.K. Sze, E.M. Larsen, E.T. Cheng, and R.G. Clemmer

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

July 1975

UWFDM-151

A Gas-Carried Li_2O Cooling-Breeding Fusion Reactor Blanket Concept

by

D. K. Sze

E. M. Larsen

E. T. Cheng

R. G. Clemmer

University of Wisconsin

Fusion Technology Program

Madison, Wisconsin

FDM-151

July 1975

This draft is preliminary and may contain errors.

Introduction

The most important functions of a blanket for a D-T fusion reactor is to remove the thermal energy and breed tritium. The mechanism of these two functions are often related. For tritium breeding, the blanket must contain either lithium or a lithium compound. To achieve a breeding ratio reasonably larger than one, beryllium is some times used as a neutron multiplier. A coolant is always introduced to the blanket to keep a reasonable blanket temperature and to transfer the heat generated to a power conversion unit.

Various coolant and breeding material combinations for conceptual fusion reactor studies have been proposed. The most frequent mentioned is to use liquid lithium both as the breeding material and as the coolant[1,2]. High pressured helium has been frequently proposed as the coolant to avoid MHD effects and the corrosion of the structure material caused by circulating high temperature lithium[3,4,5]. Potasium vapor has also been suggested as coolant for a high efficiency power cycle[6]. High melting point solid lithium compounds, such as LiAl, $LiAlO_2$ and Li_2O have been proposed as the breeding materials[3,4] Princeton design proposed to use a molten lithium salt called Flibe ($LiBeF_3$) as the breeding material[5]. However, none of the fore mentioned combinations are completely satisfactory. The problem areas of those coolants and breeding materials are summarized on Table. 1.

This study proposes to use a gaseous suspension of sub-micron sized lithium oxide particles as the coolant and the breeding material for a fusion power reactor. The thermal hydraulic characteristics, and the tritium breeding and recovery problems are investigated for a D-T fusion reactor. The results of

TABLE I COOLANTS AND BREEDING MATERIALS FOR D-T FUSION REACTOR AND THEIR ASSOCIATED PROBLEMS

COOLANTS	PROBLEMS
LITHIUM	MHD EFFECTS, CORROSION
HELIUM	HIGH PRESSURE, HIGH CIRCULATION POWER
K VAPOR	HIGH CIRCULATION POWER, APPLICABLE ONLY TO HIGH T SYSTEMS

BREEDING MATERIALS	PROBLEMS
LITHIUM	TRITIUM RECOVERY
LiAl	LOW MELTING TEMPERATURE, NEED Be
$LiAlO_2$	TRITIUM DIFFUSION, SINTERING, NEED Be
Li_2O	TRITIUM DIFFUSION, SINTERING.
FIBLE	CORROSION, NEED Be

this study show that many of the problems faced by the more conventional cooling-breeding concepts can be solved. Problem areas exist, of course, and further studies are indicated.

Thermal Hydraulics:

The thermal hydraulic behavior of a gas suspension of graphite particles have been studied as a potential coolant for a fission reactor[7,8]. The experimental work showed that the suspension had significantly improved heat transfer characteristics at a reduced pumping power. The working equations for the heat transfer coefficient and pressure drop can be summarized in the following equations:

$$Nu_m = 0.1338\ Pe_g^{0.67}[(W_s\ C_{ps}/W_g\ C_{pg}) + 1]^{0.45} \quad (1)$$

$$\Delta P_m = 0.001092\ \frac{L}{D} \cdot \frac{1}{\rho_m} \cdot G_m^{1.724} \text{ in lbs/ft}^2 \quad (2)$$

in which

Nu_m = mixture Nusselt Number = $h_m D/k_g$

D = i.D. of the tube, ft

k_g = thermal conductivity of the pure gas, BTU/hr-ft-°F

Pe_m = mixture Pectet Number = $Re_m Pr_m$

Re_m = mixture Reynolds Number = $G_m P/\mu g$

G_m = mixture mass velocity, lb/sec-ft^2

μ_g = viscosity of gas, lb/ft-hr

Pr_m = mixture Prandtl Number, $Cp_m \mu_g/k_g$

w_s/w_g = solid loading, lb solid/lb gas

Since the solid particles provide a high mixture specific heat and density compared to the pure gas, a high pressured system is not required. Since the coolant is electrically non-conducting, the MHD problems would be non-existant. For the present study, we are using lithium oxide particles instead of graphite to breed tritium. It is assumed that the thermal hydraulic behavior will be the same. The physical properties of lithium oxide is tabulated on Table 2.

A cross section of such a blanket is shown on Fig. 1. The structure consists of the first wall which is 5 mm thick. The first wall consists of a bank of tubes being cooled by pressurized helium. The main purpose of this bank of tubes is to protect the plasma chamber if a leak developes. The breeding zone is 60 cm thick and consists of 66.7% He, 31.3% Li_2O, and 2% 316 stainless steel structure, by volume. The breeding zone is divided into two regions, with 54cm before the reflector and 6 cm behind the reflector. The reflector is graphite and is 30 cm thick. The fraction of structure material is very low due to the low pressure in the blanket. The helium pressure in the blanket is only 50 psi, as compared to 750 to 1000 psi for a helium cooled blanket.

The Li_2O and helium mixture is assumed to pass once through the blanket. The mixture is supplied from the bottom of the torus and discharged from the top of the torus. The thermal hydraulic parameters of the blanket is tabulated on Table 3.

A schematic power cycle system for such a fusion reactor is shown on Fig. 2. One advantage of a gas carried Li_2O particles coolant is that the Li_2O will be carried out of the reactor and the tirtium recovery process can be simplified, as will be discussed next.

TABLE 2 PHYSICAL PROPERTIES OF LITHIUM OXIDE

FORMULA WEIGHT	29.88
DENSITY	2.013 g/cm^3
THERMAL CONDUCTIVITY	0.0173 w/cm - °C
HEAT OF FORMATION	-142.1 Kcal/mole
SPECIFIC HEAT	12.9 cal/°C-mole
MELTING POINT	1727 °C
BOILING POINT	2327 °C
LITHIUM ATOM DENSITY	$8.2 \times 10^{22}/cm^3$

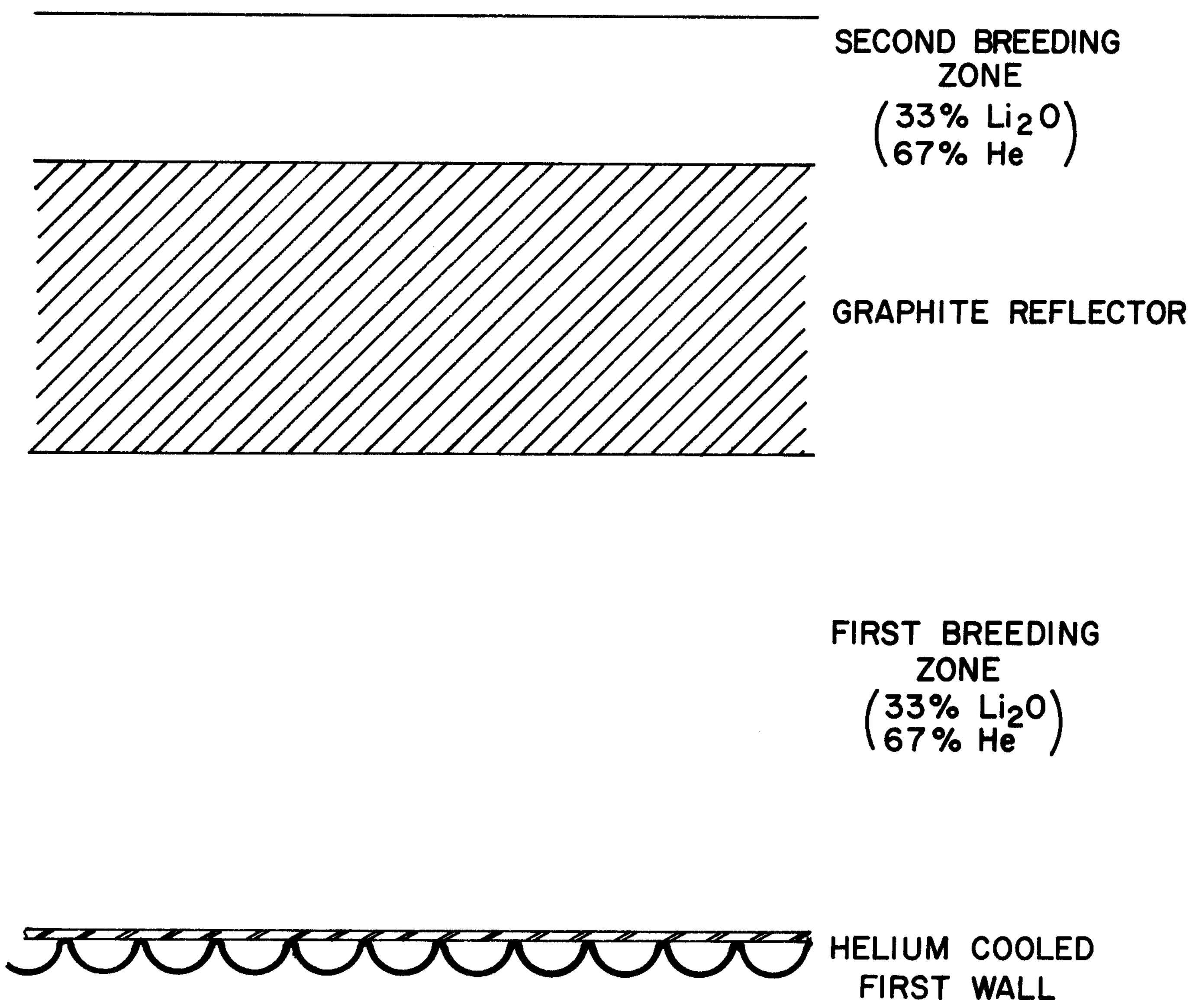

FIG. 1 SCHEMATIC DESIGN OF A GAS-CARRIED Li_2O COOLING-BREEDING. FUSION REACTOR BLANKET

TABLE 3 IMPORTANT THERMAL HYDRAULIC PARAMETERS

STRUCTURE	316 SS
COOLANT	68.1 % HELIUM 31.9 % Li_2O
COOLANT PRESSURE	50 psi
COOLANT DENSITY	.642 g/cm^3
COOLANT SPECIFIC HEAT	.432 cal/°C-g
COOLANT INLET TEMPERATURE	400 °C
COOLANT OUTLET TEMPERATURE	600 °C
COOLANT FLOW RATE	1.7×10^6 kg/hr-m^2
COOLANT VELOCITY	.75 m/sec
COOLANT PRESSURE DROP (WITHIN THE BLANKET)	6 psi
$\Delta P/P$	.12
BLANKET THERMAL POWER	4225 MW
TOTAL COOLANT FLOW RATE	4.2×10^7 kg/hr

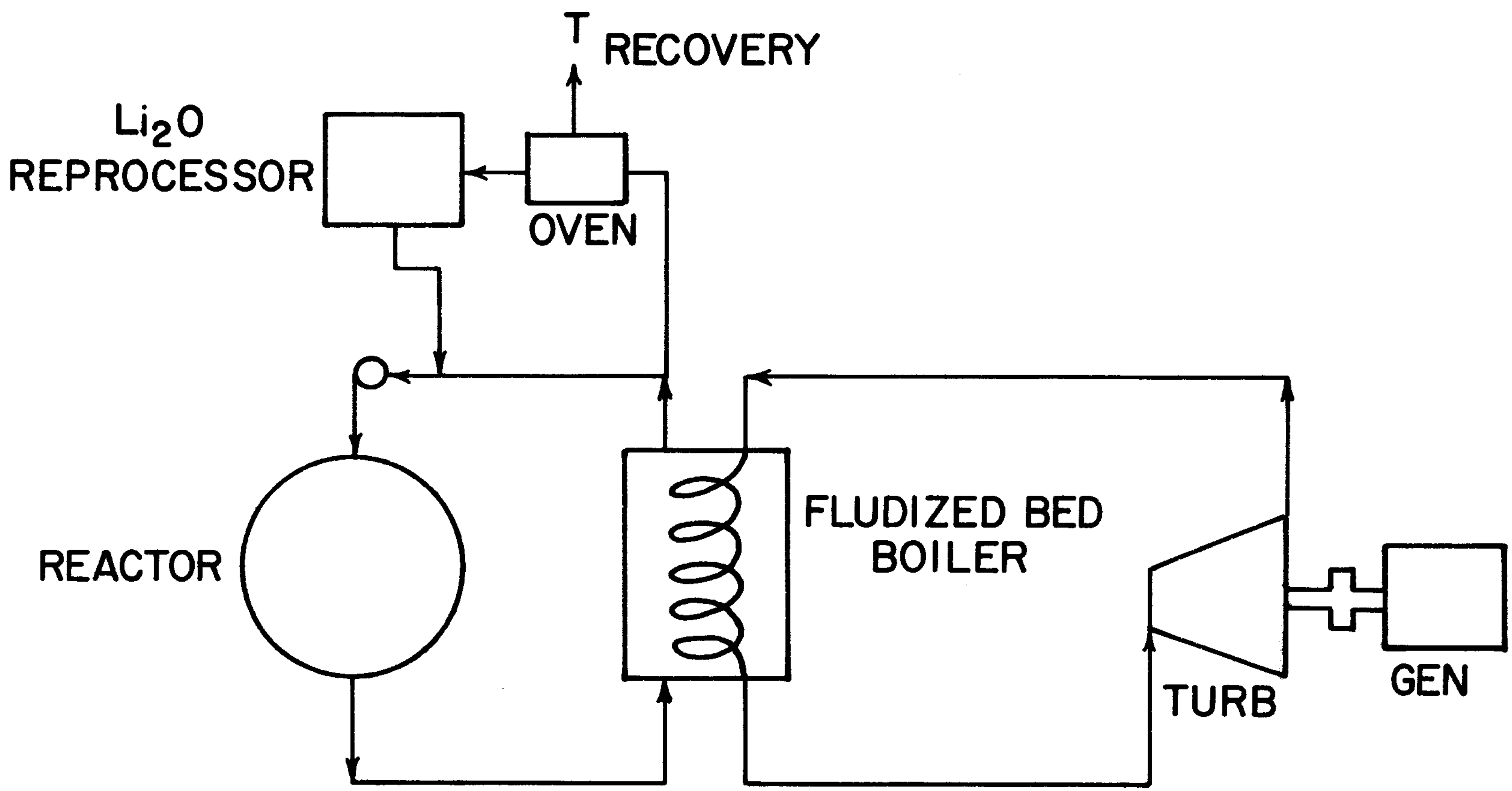

FIG. 2 SCHEMATIC DESIGN FOR A GAS-CARRIED Li_2O COOLING-BREEDING. FUSION POWER CYCLE

Neutronics

The solid breeder concept of a fusion reactor blanket has been recently discussed[3,4]. Among those lithium compounds considered, LiH or LiD is chemically unstable, Li_2C_2 and Li_3N have been shown to have tritium breeding potential that are inferior to that of Li_2O[3]. Therefore, the investigation of the tritium breeding potential for a solid blanket is restricted to the following lithium compounds, $LiAlO_2$, LiAl and Li_2O. Some neutronics calculations are performed using the above compounds as breeding materials in a bench-mark blanket. The bench-mark blanket considered consists of a 50 cm breeding zone with first wall homogenized together with structural material in this zone, and a 30 cm graphite reflector. An albedo of .3 for all groups is used to simulate the effect of the shield. The structural material is vanadium for simplicity and is set to be 10% in the breeding zone. Table 4 shows the neutronics results for the above lithium compound blankets which are calculated from ANISN code[9] for slab geometry with P_3-S_4 approximation. All the nuclear data used are the same as that described in Ref. 10.

Abdou and Conn (1974) has shown that a breeding ratio of ~1.2 is reasonable for one-dimensional calculation[10]. Therefore Li_2O is the only lithium compound which is possible to meet the tritium breeding requirement for a solid blanket with no beryllium.

An optimization calculation is carried out using the newly developed variational interpolation method[11,12]. The schematic design of a gas-carried Li_2O cooling-breeding fusion reactor blanket is shown in Fig. 1. The first wall thickness is 5 mm, the breeding zones consist of ~66.67% He, ~31.33% Li_2O and 2% basic structure. The reflector is graphite 30 cm thick. All the first wall and structural materials are stainless steel. The neutronics calculations performed here are with P_3-S_8, in cylindrical geometry. The purpose of the optimization is to determine the best distribution of thicknesses of the first

TABLE 4 CHARACTERISTICS OF TRITIUM BREEDING IN SEVERAL LITHIUM COMPOUND BLANKET

	Li ATOM DENSITY $10^{22}/cm^3$	T_6*	T_7*	TRITIUM BREEDING RATIO
LiAl	2.7	.8212	.2263	1.0475
$LiAlO_2$	2.3	.7779	.1367	0.9146
Li_2O	8.2	.9370	.4917	1.4287
Li	4.6	.9445	.5768	1.5213

* T_6 IS TRITIUM PRODUCTION FROM $^6Li(n,\alpha)$ REACTION

T_7 IS TRITIUM PRODUCTION FROM $^7Li(n,n\alpha)$ REACTION and second breeding zones when natural lithium is considered. Tritium breedings for several reference systems are shown in Table 5, where t_1 and t_2 represent the thickness of the first and second breeding zone respectively. The equi-breeding ratio contours over these two parameters, t_1 and t_2, are depicted in Fig. 3. It may be concluded that a minimum total thickness of ~60 cm breeding zones is required in the blanket and that $t_1 \geq 54$ cm is a reasonable choice.

The neutronics results of the final design with 54 cm of first breeding zone and 6 cm of second breeding zone are tabulated in Table 6.

The sensitivity of the tritium breeding as a function of % ^6Li in total lithium is estimated by the variational interpolation method using the results tabulated in Table 6 as references and is drawn in Fig. 4. We may conclude that for a gas-carried Li_2O cooling-breeding blanket as described above, the tritium breeding ratio is around 1.19. The enrichment of lithium in ^6Li is not required, although it may result in slightly increasing the total nuclear heating in the blanket system.

Tritium Recovery and Handling

The system is designed to have a low tritium inventory and a low tritium mobility, so that tritium release to the environment is minimal. The inventory of tritium is 0.6 kg, representing a concentration of 0.9 ppm. To keep the tritium in the gas phase as essentially all T_2O, a small amount of oxygen 1.0×10^{-4} torr, is added.

A. Tritium-Lithium Oxide System

The tritium generated in the solid particles will be present as tritide ions in an oxide lattice, along with the lithium ions. The solid may be described

TABLE 5 TRITIUM BREEDING OF SEVERAL Li_2O COOLING-BREEDING REFERENCE BLANKET

BLANKET SYSTEM		FIRST BREEDING ZONE		SECOND BREEDING ZONE		TOTAL TRITIUM BREEDING RATIO
t_1 (cm)	t_2 (cm)	T_6	T_7	T_6	T_7	
30	15	0.5790	0.3063	0.1400	0.0081	1.0334
45	0	0.6842	0.3593	0.0	0.0	1.0435
45	30	0.6835	0.3675	0.1275	0.0067	1.1852
60	15	0.7564	0.4024	0.0769	0.0026	1.2383

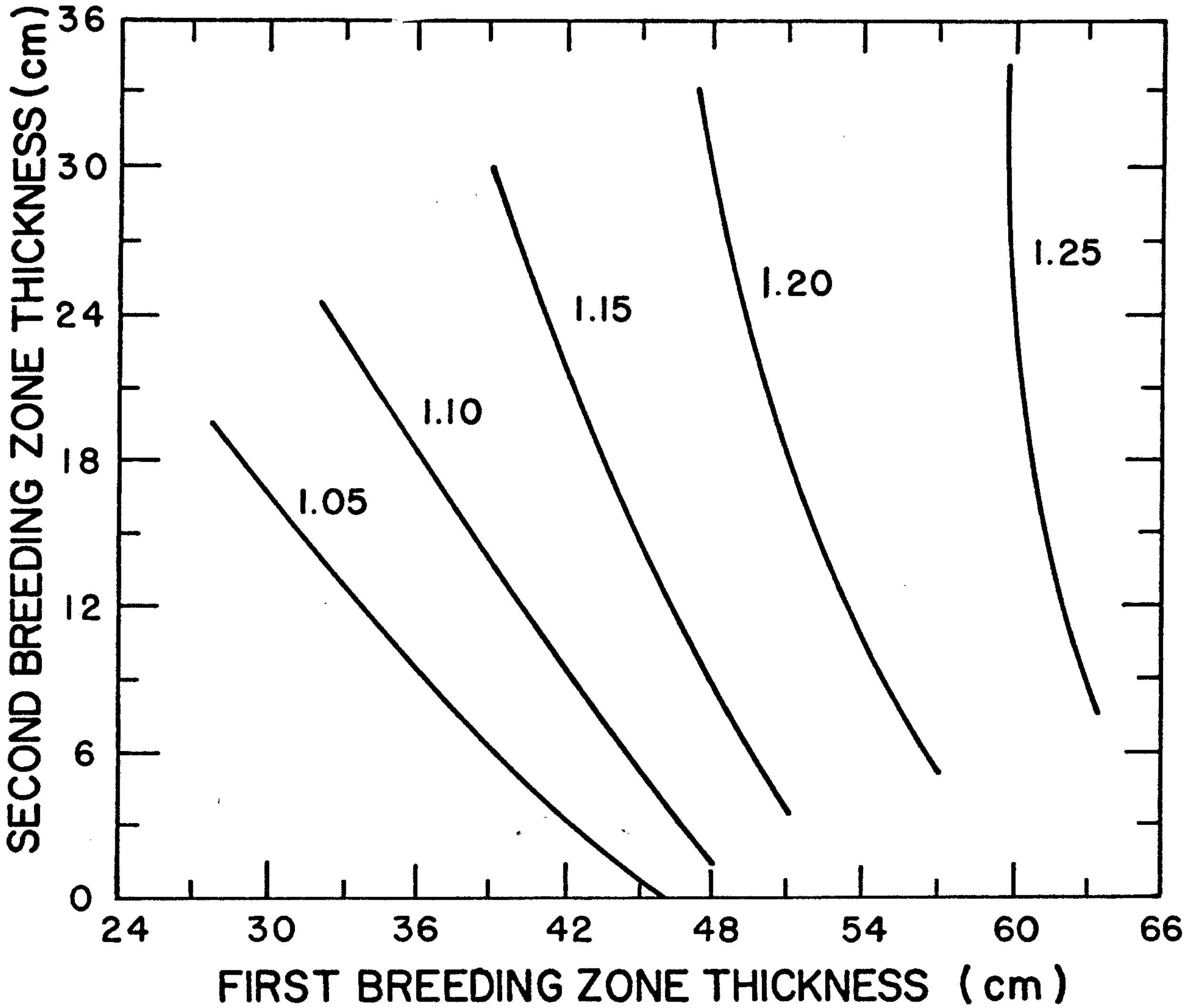

FIGURE 3 TOTAL BREEDING RATIO AS A FUNCTION OF FIRST BREEDING ZONE THICKNESS

TABLE 6 NEUTRONICS RESULTS OF FINAL DESIGN OF THE Li_2O COOLING-BREEDING BLANKET WITH 54cm OF FIRST BREEDING ZONE AND 6cm OF SECOND BREEDING ZONE

		FINAL BLANKET DESIGN	
		NATURAL LITHIUM	30% ^6Li IN LITHIUM
FIRST BREEDING ZONE	T_6	0.7285	0.8031
	T_7	0.3908	0.2891
SECOND BREEDING ZONE	T_6	0.0689	0.0503
	T_7	0.0016	0.0012
TOTAL TRITIUM BREEDING RATIO		1.1898	1.1437
TOTAL (n,2n) REACTIONS		0.0832	0.0868
TOTAL PARASITIC ABSORPTION		0.2103	0.1798
NEUTRON NUCLEAR HEATING *		11.71	12.11
GAMMA NUCLEAR HEATING		3.10	3.06
TOTAL NUCLEAR HEATING		14.81	15.17
NEUTRON ENERGY LEAKAGE TO THE SHIELD		0.126	0.124

* IN UNITS OF MeV/14.1 MeV D-T NEUTRON

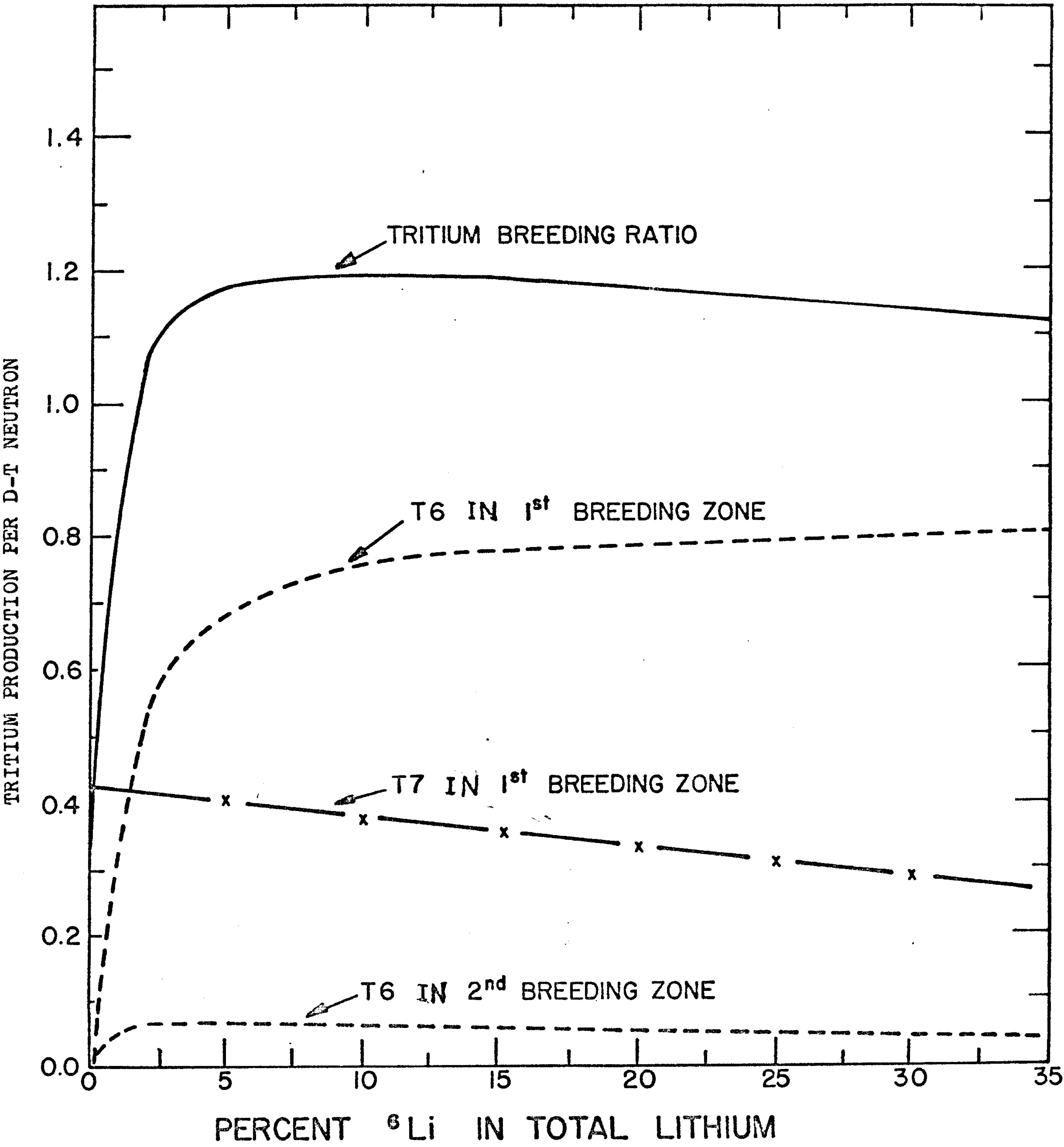
TRITIUM BREEDING RATIO
T6 IN 1st BREEDING ZONE
T7 IN 1st BREEDING ZONE
T6 IN 2nd BREEDING ZONE
TRITIUM PRODUCTION PER D-T NEUTRON
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
PERCENT 6Li IN TOTAL LITHIUM

FIG. 4

as LiOT distributed in Li_2O. The gas phase will contain in Li_2O, LiOT, T_2O, T_2, Li, O_2 and $(LiOT)_2$.

Using JANAF[13] thermochemical data for the Li-O-H system and assuming the LiOT in Li_2O behaves as an ideal solution, the concentrations of species in the gas phase can be estimated. Fig. 5 gives the estimated pressures in torr of the major gas phase species in the system.

B. Tritium Release to Environment

The major pathway for tritium to escape to the environment is by diffusion through the walls of the heat exchanger. Once the tritium diffuses into the steam side of the heat exchanger, it is no longer practicable to recover it[14]. T_2O will diffuse by decomposing to T_2 and O_2, whence T_2 will diffuse. The leak rate of tritium across a barrier is given by the expression

$$V = \frac{A}{3X} (P_1^{1/2} - P_2^{1/2}) C e^{-Q/RT} \cdot 10^{-5} \cdot \frac{1}{4.32 \times 10^{-6}}$$

V = leak rate, curies per day

A = area in cm^2

X = thickness in mm

C = permeat ion constant $(CC(STP)/hr\text{-}cm^2\text{-}atm^{1/2})$

Q = Activation Energy of diffusion = 16,100 cal/mole for S.S.

P_1 = upstream pressure (torr)

P_2 = downstream pressure (torr)

10^{-5}: converts $torr^{-1/2}\text{-}sec^{-1}$ to $atm^{-1/2}\text{-}hr^{-1}$.

$1/4.32 \times 10^{-6}$ converts CC(STP)/sec to curies/day

in this system:

$A = 8 \times 10^8 cm^2$

X = 1.5 mm

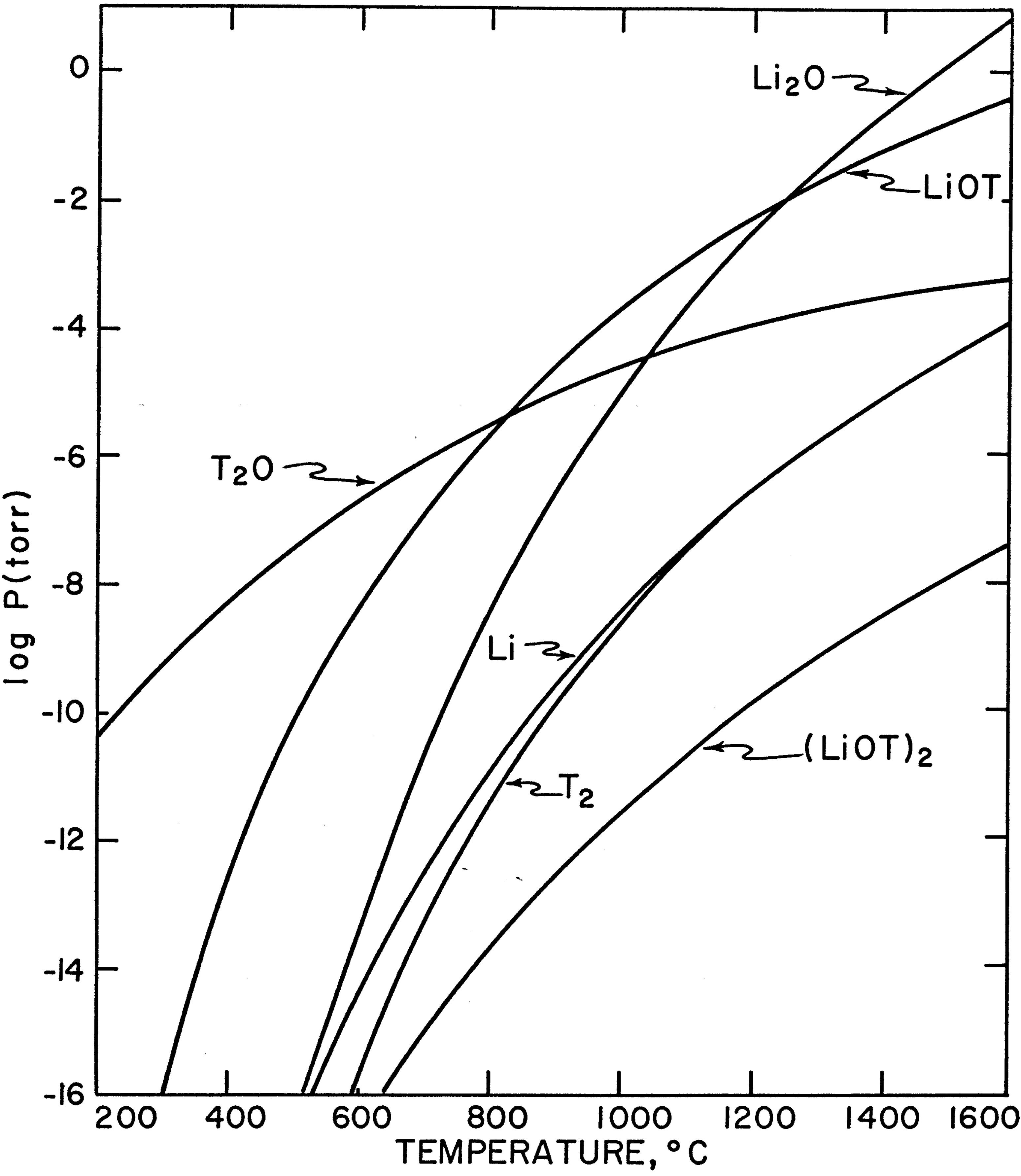

FIGURE 5 VAPOR SPECIES IN Li_2O-T_2O SYSTEM

$P_2 = 0$

$C = 850 \quad \frac{CC(STP)\text{-}mm}{hr\text{-}cm^2 atm^{1/2}}$ (Ref. 3)

$Q = 16{,}100$ cal/mole (Ref. 3)

$P_1 = 4.8 \times 10^{-15}$ at 900°K

T = Average of 400 + 600 = 500°C = 773°K

$$V = \frac{8x10^8 cm^3}{3\cdot 1.5mm} (4.8x10^{-15})^{1/2} torr^{1/2} (850) e^{-16,100/1987(773)} \cdot \frac{10^{-5}}{4.32x10^{-6}}$$

$$(.48x10^{-16})^{1/2} \qquad e^{-10.4x82}$$

$$.69x10^{-8} \qquad .0000280$$

V = .118 Ci/day

So the release of tritium is very small, being 0.12 Curies per day.

C. Tritium Recovery

A 2% stream is taken to a 1200° oven, where the tritium diffuses out of the particles.

The non-steady state solution to Fick's Law of diffusion can be solved, given the following boundary conditions:

1. The concentration at t = 0, C_o, is uniform throughout the sphere.
2. The concentration at the surface is zero.

The solution is an infinite series. The first term is taken as an approximate solution. The approximate solution is:

$$-\ln \frac{C}{C_o} = \frac{\pi^2 Dt}{r^2} \qquad (3)$$

We feel that a tritium ion in an oxide lattice will diffuse in the form of T_2O. The data for diffusion of molecular hydrogen through an oxide may not be applicable. A more realistic view of diffusion of tritium generated in an oxide solid is the data for diffusion of T_2O in solids.

The diffusion coefficient is conservatively estimated to be $1 \times 10^{-16} cm^2/sec$ at 1200°C, a value obtained by extrapolating diffusion of T_2O generated in a BeO lattice.[14]

Now Equation (3) may be solved:

Assume $\frac{C}{C_o} = .9$, $-\ln \frac{C}{C_o} = .1$ i.e., 10% of tritium diffuses out

$$D = 1 \times 10^{-16} \ cm^2/sec$$

$$t = 1000 \ sec$$

$$.1 = \frac{(10^{-16})(10^{3})\pi^2}{r^2}$$

$$r^2 = 10^{-11} cm^2 \qquad r = 3 \times 10^{-6} = 3 \times 10^{-2} \ \mu$$

The conservative diffusion coefficient used results in the conclusion that a very small particle size, $3.0 \times 10^{-2}\mu$ radius is required. If one would use the diffusion coefficients that have been used for other solid blanket designs, $D = 10^{-12} cm^2/sec$ then a much larger particle size of 3.0μ can be used.

The tritium production rate at a breeding ratio of 1.15 is 0.70 kg/day x 1.15 = 0.805 kg/day. So, 0.805 kg of T_2 must be removed per day. The Li_2O inventory is 1.4×10^6 kgs, with a flow rate of 4.2×10^7 kg/hr. A 2% stream recovering 10% of the tritium will collect .878 kg of T/day. The tritium inventory in the coolant system is 0.6 kg.

The tritium baked out of the particles escapes the surface as LiOT. At 1200°C, the gas also contains a significant pressure of Li_2O. The gas containing Li_2O and LiOT is passed to a cold trap, whence the solid mixture of the oxides is collected. The gas is cooled to 400°C, where the pressures of Li_2O and LiOT are very low and the solid collects, the gas is returned to the stream. The

TABLE 7 MAJOR PARAMETERS FROM TRITIUM CALCULATIONS

TRITIUM INVENTORY	0.6 kg
TRITIUM LEAKAGE	0.12 curie/day
Li_2O INVENTORY	1.4×10^6 kg
TRITIUM RECOVERY PROCESS	HIGH TEMP. BAKING
TRITIUM RECOVERY TEMPERATURE	1200°C
TRITIUM DIFFUSIVITY	10^{-16} cm^2/sec

tritium recovery rate is equal to the production rate, 0.805 kg/day. 15.0 kg of solid Li_2O + LiOT will be processed per day.

The solid, which is composed of approximately equal amounts of LiOT and Li_2O is then processed to recover the tritium.

The Li_2O is reprocessed and returned to the stream.

Conclusions

A new cooling breeding concept for a fusion reactor blanket is proposed. The thermal hydraulics, neutronics, and tritium recovery problems have been studied. The study shows that many difficult problems facing the conventional blanket design can be solved with this system. The design has the following advantages:

Avoid liquid lithium

No MHD problems

Low pressure blanket

No corrosion problems

No need for Be for breeding

Easy tritium recovery

Low tritium mobility

No need for IHX

No sintering problem

Various problem areas ixist. Among these are pump design, flow stability, heat exchanger design, erosion etc. However, the advantages in the area of thermal hydrulics, neutronics, tritium handling, and safety are very attractive which make this system worth additional studies.

References

1. Badger, B., et al., "UWMAK-I, A Wisconsin Toroidal Fusion Reactor Design," UWFDM-68, Vol. 1, Univ. of Wisconsin, (Nov., 1973).

2. Nishikawa, M. K. Ioki, T. Naito, N. Asmi, "On the Thermal State of the Fusion Blanket" First Topical Meeting on the Technology of Controlled Nuclear Fusion, San Diego, April, 1974.

3. Y, Seki, Sako, K., Tanaka, K. and Hiraoko, T., "Tritium Breeding in Ceramic Lithium - Compound Blanket." Ibid.

4. J. Powell, A. Arouson, P. Bezler, F. Miles and W. Winshe, "Minimum Activity Fusion Reactor Blankets" Ibid.

5. R. G. Mills, "A Fusion Power Plant" Princeton Univ. Plasma Physics Lab., Report MATT-1050, Aug. 1974.

6. A. P. Fraas, "Analysis of a Recirculating Lithium Blanket Designed to Give a Low MHD Pumping Power Requirement." DAML-TM3756, 1972.

7. Schluderberg, D. C., R. L. Whitelaw, R. W. Carlson, "Gaseous Suspensions - A New Reactor Coolant", Nucleonics, <u>19</u>, 8, p.67 (1961).

8. Hawes, R. I., E. Holland, G. J. Kirby, P. R. Waller, "An Experimental Investigation into Heat Transfer and Pressure Drop Properties of Gaseous Suspensions of Solids." United Kingdom Atomic Energy Authority Report AEEW - R 244.

9. W. W. Engle, Jr., "A User's Manual for ANISN," K-1693, Union Carbide Corp. (1967).

10. M. Abdou and R. Conn, Nucl. Sci. Eng., 55, 256 (1974).

11. E. T. Cheng and R. W. Conn, "A Multipoint Interpolation Method Based on Variational Principles for Functionals of the Solutions to Linear Equations," University of Wisconsin Report, FDM-126, May 1975. To be published in J. Math. Phy.

12. E. T. Cheng and R. W. Conn, "Application of Variational Interpolation Method to Fusion Reactor Blanket Studies," to be published in Trans. Am. Nucl.Soc. 1975.

13. JNNAF Thermal Chemical Tables, Second Ed. NSRDS-NBS37, 1971.

14. K. T. Scott, L. L. Wassell; "Diffusional Release of Tritium from Irradiation Bed." British Ceramic Society 7, 375, 1967.