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ABSTRACT

Recent fusion power reactor designs have shown a trend toward lower power, lower cost, higher mass utilization compact configurations with inherent safety, in order to improve the economic aspects of fusion and make them more competitive with other energy sources. Since the blanket thickness directly impacts the size and mass of the remaining reactor components, it is prudent to minimize its thickness while ensuring adequate neutronic and thermal performance. This paper describes the blanket for the MINIMARS compact tandem mirror fusion power reactor. The blanket which utilizes HT-9 ferritic steel structure, LiPb breeder, Be multiplier/moderator and He gas cooling is only 17 cm thick and is backed up by a steel reflector. Helium gas cools the blanket and reflector in series and the outlet temperature of 575°C gives a gross thermal power cycle efficiency of 42.7%.

I. INTRODUCTION

A primary goal in the design of the MINIMARS blanket is the achievement of the lowest cost of electricity and highest mass utilization, while maintaining credibility and emphasizing passive safety. We have found that major improvements in the central cell are possible through the use of a thin blanket which impacts the sizes of all the other components in the central cell. An important factor in the thin blanket is the use of Be metal as a moderator/multiplier, making its thickness only 17 cm. By cooling the blanket and reflector in series using the same He gas, the energy in the reflector is recovered at a high temperature with a resulting improvement in the power cycle. This improvement is achieved while maintaining a low interface temperature between the structure and the breeding material.

Finally, we have achieved passive safety in this blanket through the use of heat pipes located at the back of the shield.

II. DESCRIPTION AND MECHANICAL DESIGN

The MINIMARS blanket is a He-gas cooled design utilizing $Li_{17}Pb_{83}$ (LiPb) breeder, ferritic steel HT-9 structure and Be metal as moderator/multiplier. The high pressure He gas is contained in small tubes which are immersed in a close-packed matrix of Be balls with the voids filled with LiPb. The result is a compact blanket, in which only the tubes are operated in a stressed condition. The blanket containment structure, however, is designed to withstand a He-gas leak in one or more coolant tubes.

The question of corrosion and corrosion product transport is always present in any liquid metal system. This blanket avoids these problems in two ways. First, the maximum liquid metal/structure interface temperature is limited to < 530°C. Second, the LiPb is essentially static and is only circulated at a very slow rate for T_2 recovery.

Because the blanket is so thin, about 36% of the thermal energy is deposited in the steel reflector. By routing the He gas from the blanket to the reflector, this energy is recovered very efficiently. However, the reflector will be subjected to radiation damage which means that it will have to be replaced once in the lifetime of the reactor.

The central cell in MINIMARS has 24 blanket modules, each 3.6 m long and each supplying ~ 60 MW_{th}, of which 21.6 MW_{th} comes from the reflector. Figure 1 shows an end view and a side view of a blanket module. There are 18 toroidal cells each 20 cm wide joined together to form the 3.6 m module. There are four supply and four return elliptical He gas manifolds. Each set of two supply and two return manifolds serves alternate cells. Each set of two supply manifolds is connected to a single supply header. Each set of two return manifolds is connected to a single coupling which directs the He-gas flow into the reflector. Note that the supply headers are located on one end of the

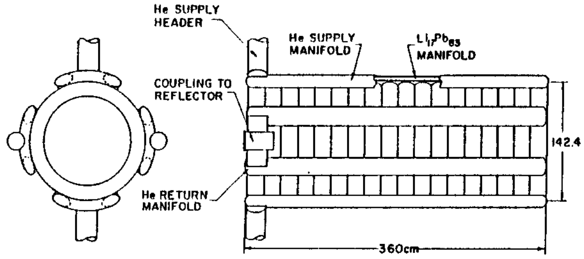

Fig. 1. End and side view of blanket module.

module to make it possible to slide out the blanket module from its respective reflector module from one end.

Figure 2 is a cross section through several cells. Note that the outer containment structure is semi-ellipsoidal which makes it capable of withstanding a He-gas leak in a cooling tube. The tubes are surrounded by a matrix of Be balls with the voids filled with molten LiPb. There are two types of cooling tubes in this blanket, outer and inner tubes. The outer tubes provide cooling for the first wall and absorb a large fraction of the nuclear heating in the front zone of the blanket. Each outer tube makes only four loops inside the cell before returning to the exit manifold. The inner tubes, of which there are three, cool the central part of the cell performing a small radius large pitch spiral and traveling the full length of a cell quadrant. All the inner and outer tubes are the same length and are therefore impedance matched to the flow of He-gas. Figure 3 is a cross section through a cell quadrant. It shows the He-gas supply manifold connected to the tubes at a manifold flange. The tubes travel one-fourth of the circumference in both directions and are then connected to a return manifold.

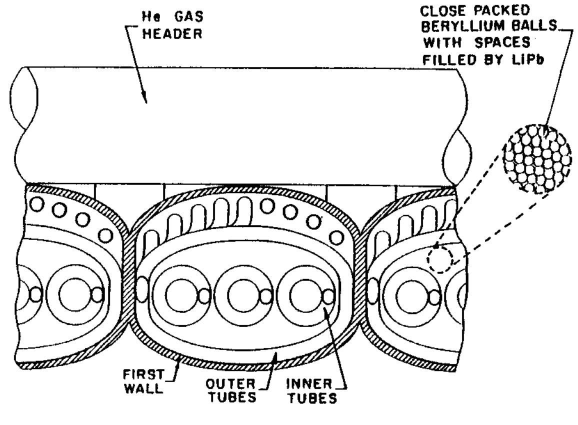

Fig. 2. Cross section through several cells.

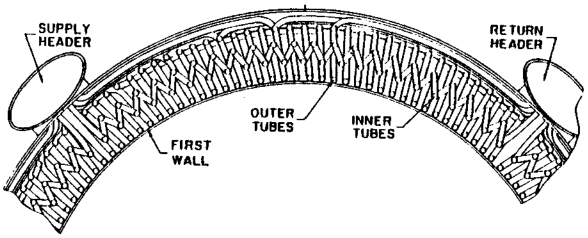

Fig. 3. Cross section through cell quadrant.

Figure 4 is an end view of the central cell at an interface between modules. It shows two supply headers attached to the blanket, two transition couplings at the blanket/reflector coolant interface and finally, two return headers coming from the back of the reflector. Also shown are heat pipes which dissipate afterheat in the event of a LOCA.

III. THERMAL HYDRAULICS

The blanket in MINIMARS is cooled with He-gas at 80 atm. Helium cooled blankets have a general reputation for requiring a high pumping power. Pumping power is a function of the volumetric flow rate and the pressure drop, and is therefore directly dependent on the pressure of the coolant. We have found that 80 atm. seems to be the pressure at which the benefits of lower pumping power begin to be offset by increased structure in the blanket. In this design the He-gas enters the blanket at 275°C, exits at 466°C, then is routed to the steel reflector and exits at 575°C.

The primary aim of thermal hydraulic analysis is to ensure that the blanket structures are adequately cooled and that the hot spots on the first wall or elsewhere do not exceed recommended design limits for the materials at those conditions. To determine the maximum temperature at the first wall it is necessary to obtain the bulk coolant temperature profile in the last outer tube in a cell quadrant. Since the He-gas circulates in a spiraling motion within the outer tubes which are in contact with the first wall, it is the coolant bulk temperature which will determine the hot spot on the first wall. We write steady state one dimensional energy balance equations for the He-gas and for the blanket materials neglecting circumferential conduction and all convection. Since the mass flow rate per tube is fixed at 38.06 g/s but the density is a strong function of temperature, the velocity in the tube varies from 69 m/s at the inlet to 92 m/s at the outlet and the heat transfer coefficients vary from 0.67 W/cm^2 K at the inlet to 0.702 W/cm^2 K at the outlet. The worst case hot spot temperature on the first wall between coolant tubes is 524°C. The maximum heat flux occurs on the inner tubes and is

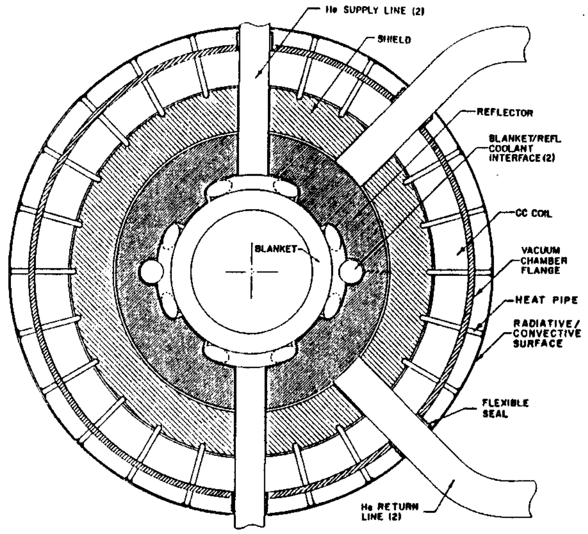

Fig. 4. End view of central cell at interface between modules.

equal to 50 W/cm^2 which gives a maximum structural/LiPb interface temperature of 529°C. Table 1 summarizes the mechanical and thermal hydraulic parameters of the blanket.

IV. BLANKET STRESSES

During normal operation the blanket outer structural shell is at a low pressure and a negligible stress. The cooling tubes themselves are constantly subjected to the high pressure and for this reason are designed with a higher margin of safety. The maximum stress in the coolant tubes was determined using thin walled pressure vessel formulae, while the maximum stress in the outer structure was determined using formulae for a semi-ellipsoidal toroidal shell. These stresses are 94 MPa and 150 MPa respectively and the recommended design stresses at maximum temperature are 160 MPa and 165 MPa[1] respectively.

Nuclear heating in the first wall is 22.4 W/cm^3 and the surface heating is 2.73 W/cm^2. This heating will produce a thermal stress in the first wall equal to ± 22 MPa. With time, thermal and radiation creep will anneal this stress out. However, when the plasma is turned off, the thermal stress returns in reverse. Under the worst condition, the combined stress at the first wall is 172 MPa. The equilibrated temperature of the wall when the plasma is turned off is 400°C and the design stress is > 200 MPa.

Table 1. Blanket Parameter List

First-wall radius (cm)	54.2
Blanket thickness (cm)	17
Reflector thickness (cm)	48.4
Shield thickness (cm)	38.5
Volumetric fraction of HT-9 (v/o)	11.2
Volumetric fraction of He + void (v/o)	21.69
Volumetric fraction of Be (90% density) (v/o)	55.14
Volumetric fraction of LiPb (v/o)	11.97
Breeding ratio	1.05
Energy multiplication	1.44
Fusion power (MW$_{th}$)	1230.8
Thermal power (MW$_{th}$)	1433.6
Stress in tubes (MPa)	94
Average heat flux (W/cm^2)	36.4
First-wall thickness (cm)	0.52
Thermal stress in first wall (MPa)	±22
He-gas mass-flow rate (kg/s)	920
Average gas velocity in tubes (m/s)	80
Power cycle efficiency (%)	42.7
LiPb circulation rate (ℓ/s)	58
LiPb pumping power (kW)	20
T_2 inventory in LiPb (g)	0.13
T_2 inventory in He gas (as T_2O) (g)	0.25
T_2 leak rate to environment (Ci/d)	$\sim$ 10
He gas pressure (atm)	80
Inlet temperature to blanket (°C)	275
Outlet temperature from blanket (°C)	466
Outlet temperature from reflector (°C)	575
Power in blanket (MWth)	914.7
Number of tubes/cell	56
ID of coolant tubes (cm)	1.0
Total length of coolant tubes in reactor (m)	82,253
Total surface area (m^2)	2816.4
Maximum heat flux on tubes (W/cm^2)	50
Hot spot temperature on first wall (°C)	524
Maximum coolant tube/$Li_{17}Pb_{83}$ interf. temp. (°C)	529
Pressure drop in the blanket (MPa)	0.11
Pressure drop in the reflector (MPa)	0.07
He pumping power for blanket (MW)	17.2
He pumping power for reflector (MW)	9.4

V. REFLECTOR GENERAL DESCRIPTION

The reflector is made of the modified 9Cr1Mo ferritic steel which has been normalized and tempered.[2] The modification is done by the addition of 0.06-0.1% Nb and 0.18-0.25% V to the original composition of 9Cr1Mo. In this composition this alloy has creep strength which exceeds that of standard 9Cr1Mo for the temperature range 427-704°C. Estimated design allowable stress values are considerably higher than the standard alloy, being a factor of two higher at 550°C.

Table 2. Nuclear Heating (MeV/Fusion)

	Nominal Section	Section through He Manifold	Overall
Blanket			
Neutron heating	10.193	9.915	10.101
Prompt γ heating	2.877	2.768	2.841
Decay heat	0.162	0.162	0.162
TOTAL	13.232	12.845	13.104
Reflector			
Neutron heating	0.712	0.696	0.707
Prompt γ heating	6.657	6.343	6.553
Decay heat	0.178	0.140	0.166
TOTAL	7.547	7.179	7.426
Total Recoverable	20.779	20.024	20.530
Energy Multiplication	1.474	1.420	1.456

The reflector is built up of concentric cylinders which have cooling channels machined into them prior to assembly. The He-gas flow path is chosen to minimize high temperature buildup and the coolant channel distribution is consistent with the nuclear heating in the reflector.

As in the case of the blanket, there are 24 reflector modules each 360 cm long. He-gas is fed into the two inlet ports, travels axially, then splits in half and travels circumferentially through the grooves. He gas temperatures are determined from energy and mass balance equations, and heat transfer coefficients are calculated using average gas properties for each zone. The maximum temperature occurs in the rear zone and is equal to 600°C.

Thermal and pressure stresses in the reflector are calculated using thick walled cylinder formulae. The maximum stress is 54 MPa and the allowable design stress is > 60 MPa.

VI. VISCOUS AND MHD EFFECTS IN THE LiPb

The LiPb is circulated at a low velocity for T_2 recovery. As it flows through the matrix of Be balls and coolant tubes, it experiences a pressure drop. Further, because LiPb is an electrically conducting fluid, it is also retarded by MHD effects. The viscous pressure drop is calculated with equations for flow through pebble beds. The pressure drop is a function of the effective Reynold's number, fluid mass velocity, viscosity, flow path length, void fraction and average particle diameter. The MHD effects in the circulating LiPb are dominated by local return currents in the Be balls; these balls have a resistivity about ten times smaller than that of the LiPb. We obtain an upper limit to the MHD pressure drop by neglecting the resistance of the current return path through the balls and LiPb near their points of contact. The total pressure drop for a residence time of 120 s is 0.36 MPa and the pumping power is 20 kW.

VII. BLANKET NEUTRONICS

Because of the soft spectrum in a LiPb system, using highly enriched lithium (90% ^{6}Li) is beneficial. Further thinning can be accomplished by using a moderator in the blanket. Beryllium has the dual advantage of acting as a moderator and multiplier. Adding 70% Be to a LiPb blanket increases TBR by 66% and M by 18%. The use of Be is superior to other moderators as it yields the thinnest blanket with largest energy multiplication for the same TBR.

Using LiPb/Be results in breeding-blanket thickness in the range 15 to 20 cm. We found that the optimum combination of breeder and Be that maximizes the TBR in such a thin blanket is 17.8% LiPb to 82.2% Be. Due to the small Li inventory in the thin blanket the depleted Li is constantly replenished in the slowly circulated LiPb. Many iterations were performed to determine the blanket thickness and composition that satisfy all requirements for neutronics, thermal hydraulics and mechanical design. The final blanket design has a breeding zone made of 12.73% $Li_{17}Pb_{83}$ (90% ^{6}Li), 58.76% Be (0.9 density factor) and 5.41% HT-9 with the balance being void and He coolant. The blanket is 15.96 cm thick with 0.52 cm thick HT-9 front and back walls. The breeding blanket is backed by a hot 9Cr1Mo reflector which consists of 90% steel and 10% He. In addition to recovering the energy of neutrons and gammas, the reflector acts as the first layer of the magnet shield. The shield optimization indicates that the steel shield should occupy 54.3% of the shield space. The winding pack of the central cell superconducting magnets has an inner-bore radius of 1.73 m which implies a reflector thickness of 48.4 cm.

The He coolant manifolds cover 33% of the area at the back of the blanket. The effective reflector thickness is reduced by 12 cm at these locations. Two neutronics calculations were performed; one at the full reflector thickness and the other at the manifolds. Weighting the results for the two sections by the corresponding area fractions, the overall TBR was determined to be 1.05. Only 0.04% of the TBR is contributed by the ^{7}Li(n,n'α)t reaction. The nuclear heating results are summarized in Table 2. The nuclear heating values calculated using the MATXS5[6] cross-section library accounts only for heating by neutrons and prompt gamma rays. Some neutron interactions produce short-lived radioactive nuclides. The decay heat from these nuclides will contribute to nuclear heating during operation. We estimated this contribution by calculating the afterheat resulting from short-lived isotopes immediately following 5 full-power years (FPY) of operation. This amounts to 0.388 MeV per fusion corresponding to 1.6% of the total recoverable energy. Neutron heating contributes 53% of the total heating. The total recoverable energy of 20.53 MeV per fusion implies an overall energy multiplication of 1.456. 63.8% of the total nuclear heating is deposited in the blanket. The peak power densities in the first wall, blanket, reflector and shield are 22.4, 23.5, 8.38 and 1.28 W/cm^3, respectively.

The peak dpa rate values in the blanket and reflector are 37 and 10.4 dpa/FPY, respectively. The corresponding peak values for helium production are 380 and 54 He appm/FPY, respectively. A 38.5 cm thick He cooled shield consisting of a front B_4C shield and a back Pb shield is used behind the steel reflector/shield. This yields acceptable radiation effects in the magnets with the peak winding pack power density behind the coolant manifolds being 0.38 mW/cm^3.

VIII. RADIOACTIVITY

We calculated activation related quantities for the central cell by using the ACTL cross-section library.[4] The induced activities of the central cell are high (approximately 2 x 10^5 Ci/cm after shutdown) and decay rather slowly (down only a factor of 2 after one year). The blanket afterheat is about 900 W/cm of central cell at shutdown and decreases a factor of ten in ~ 1.2 days. The initial afterheat in the reflector is 500 W/cm and a factor of ten reduction requires one year. The afterheat of the shield is extremely low, only 0.2 W/cm at shutdown. The biological dose rate outside the central cell after shutdown is 1.4 x 10^5 mrem/hr and its reduction with time is not enough to make hands-on maintenance possible. After one week the dose is reduced to 10^4 mrem/hr. These high dose rates mean that remote maintenance techniques or an additional 20 cm of lead shielding must be used.

The waste disposal ratings (WDR) have been calculated based on "Class C" wastes (as defined in 10CFR61) using basic waste disposal quantities as calculated by Fetter,[5] who employed 10CFR61 methodologies. The compacted blanket WDR is 9.2 while averaging over the blanket volume, the WDR is 1.2. If the module is encapsulated as a unit, the WDR drops to 0.53. This option appears to be an acceptable mode of disposal and the blanket can be considered acceptable as Class-C waste for near surface burial. The reflector will have to be replaced once in the lifetime of the reactor. After 15 full power years it will have a WDR of 5. The lifetime components such as the shield and magnets when averaged over the whole central cell region including the plasma and blanket yield a WDR of 2.8. Thus, as in the case of the reflector, they are not suitable for Class-C disposal without additional material modification.

IX. TRITIUM ISSUES

The technique selected for the recovery of the tritium from the breeder utilizes the slow circulation (0.054 m^3/s) of the liquid alloy to an external Tritium Removal System (TRS). The relatively high partial pressure,[6] 18.8 Pa, of T_2 in the liquid breeder at the exit from the blanket makes it possible to recover tritium by a simple vacuum degassing technique. At the exit from the TRS the T_2 partial pressure has been reduced to 1.0 Pa with an average tritium partial pressure in the liquid breeder of 7.1 Pa and a composition of 3.2 x 10^{-3} wt.ppm. The tritium inventory which includes the breeder, Be spheres and structural components, is only 5.63 g for the entire breeder blanket system.

Although the majority of the tritium is removed from the liquid breeder, ~ 5% of the bred tritium permeates into the helium coolant, with a high potential for permeation into the steam generator if it remains in the elemental form, T_2. The tritium partial pressure is reduced, therefore, by the addition of oxygen into the helium. Recent experiments[7] have shown that when tritium permeates a steel tube and emerges through an oxidized surface, greater than 95% of the tritium is oxidized. Additionally, oxidized metal surfaces, less than one monolayer thick, greatly retard[8] the permeation of hydrogen (tritium). These effects for the ferritic steel, HT-9, retarded the tritium permeation rates by a factor of ~ 10^3 at the T_2 pressure in the steam generator and by a factor of 10 at the T_2 pressure in the blanket, as compared to the square-root dependency of the tritium pressure. A purification system was designed to process 0.25% of the helium flow and remove both T_2 and T_2O. The steady-state T_2 pressure in the helium would cause only 10 Ci/d to permeate into the steam cycle. The steady-state inventory of T_2O would be 1.3 g in the helium coolant. A tightly constructed helium circuit[9] would release ~ 7 Ci/d of T_2O to the reactor building. During a severe accident in which the containment building was breached, the release of all the T_2O in the helium would not be expected to exceed the radiation guidelines for an individual residing 1 km from the reactor.

X. PASSIVE SAFETY

During the design of the MINIMARS blanket attention was paid to passive safety under a variety of transients and postulated accident conditions. The design basis for the blanket was the consideration of a number of serious transients; e.g. loss of flow, loss of heat sink, or a loss of off-site power. The criteria applied to the blanket was that it must maintain its overall structure without any active systems

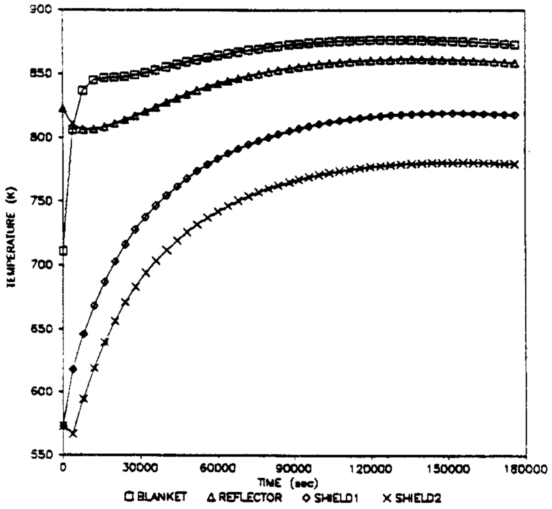

Fig. 5. Temperature response of the blanket, reflector and shield due to LOCA.

operational and that each blanket module must be replaceable as an integral part of normal blanket maintenance. Initially we considered a liquid nitrogen dewar accumulator as a passive system to accomplish these objectives. However, in the interests of achieving the highest level of passive safety we have incorporated a series of heat pipes located at the back of the shield. These passive devices have the advantage over the cryogenic accumulator of being distributed uniformly over the shield and being redundantly reliable. Based on simple heat pipe design considerations we found that a combined heat sink capability of 40 kW/m of central cell is quite capable of keeping the maximum temperatures of the blanket below damage limits (< 600 °C). Figure 5 shows the trends of a loss-of-coolant/ loss-of-heat sink transient for the MINIMARS blanket using 40 kW/m of central cell heat pipe capacity. The maximum temperature is seen to be below the damage limit for reactor components.

XI. CONCLUSIONS

In conclusion we feel the MINIMARS blanket satisfies the goals we have set for it. It has minimized the cost of the central cell thus achieving a relatively low COE (41.4 mills/kW_h) and maximized mass utilization (100 kWe/tonne) while achieving a gross thermal efficiency of 42.7% and passive safety.

ACKNOWLEDGEMENT

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REFERENCES

1. J.D. GORDON, J.K. GARNER (TRW), N.M. GHONIEM (UCLA) and J.F. PARMER (GD), "Ferritic Steel Application in the MARS High Temperature Blanket", Proceedings of Topical Conference on Ferritic Alloys for Use in Nuclear Energy Technologies, Snowbird, Utah, June 1983.

2. V.K. SIKKA, "Development of Modified 9Cr-1Mo Steel for Elevated Temperature Service", (ORNL), Proceedings of Topical Conference on Ferritic Alloys for Use in Nuclear Energy Technologies, Snowbird, Utah, June 1983.

3. R. MACFARLANE, "Nuclear Data Libraries from Los Alamos for Fusion Neutronics Calculations", Trans. Am. Nucl. Soc., 46, 271 (1984).

4. M.A. GARDNER and R.J. HOWERTON, "ACTL: Evaluated Neutron Activation Cross Section Library", Lawrence Livermore National Lab., UCRL-50400 Vol. 18 (1978).

5. S.A. FETTER, "Radiological Hazards of Fusion Reactors: Models and Comparisons," Ph.D. Dissertation Univ. of California, Berkeley (April 1985).

6. Y.C. CHAN and E. VELECKIS, "A Thermodynamic Investigation of Dilute Solutions of Hydrogen in Liquid Li-Pb Alloys", J. Nuclear Materials, 122 & 123, 935 (1984).

7. D.F. HOLLAND and G.R. LONGHURST, "Modelling and Experiments on Tritium Purification in Fusion Reactor Blankets, Fusion Technology, 8, 2067 (1985).

8. M.A. PICK and K. SONNENBERG, "A Model for Atomic Hydrogen-Metal Interactions - Applications to Recycling, Recombination and Permeation", J. Nuclear Materials, 131, 208 (1985).

9. B.G. CHAPMAN, "Design Operating Experience", in Proc. Gas-Cooled Reactor Information Mtg., Oak Ridge, TN, April 27-30, 1970, CONF-700401 (1970).