Chapter IX

TRITIUM-BREEDING BLANKET

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1. DESCRIPTION

The incorporation of a tritium-breeding blanket in the INTOR design is based on both economic and tritium availability considerations. The cost of tritium is estimated to be of the order of a billion dollars for the reactor lifetime and the availability from existing sources is questionable. Fission power reactors are the primary source of tritium and it appears that these reactors could supply only a fraction of INTOR's needs. The choice of the tritium-breeding ratio represents a compromise between economic considerations and the desire to develop a simple and reliable blanket for INTOR. From the engineering point of view it is proposed that the tritium-breeding blanket be limited to the outboard and upper regions of the machine. This will provide a 60% coverage. Since local breeding ratios of 1.0–1.3 are generally considered to be attainable, a net breeding ratio in the range of 0.6 to 0.8 can be attained with a 60% coverage. A minimum value of 0.6 was recommended for the INTOR blanket.

Since economics is the primary reason for a tritium-breeding blanket in INTOR, it is not essential that the blanket design, materials and operating parameters be reactor relevant. This permits the use of design options for INTOR which enhance tritium breeding and tritium recovery but which might not be permissible for a power-reactor blanket. The experimental test programme, however, will include testing of blanket modules which will provide simultaneous electricity production and tritium breeding.

1.1. Choice of solid breeder

Solid and liquid breeder materials were evaluated for the INTOR blanket design [2–5]. The Li_2SiO_3, Li_4SiO_4, Li_2O and $LiAlO_2$ ceramics, and the Li_7Pb_2 and LiAI intermetallic compounds were considered for solid breeder concepts; $Li_{17}Pb_{83}$, $LiPb_4Bi_5$ and lithium were considered for liquid breeder concepts.

In the blanket designs studied [2–5], the breeding ratios were higher for the liquid metals than for the solids. The methods of tritium extraction from $Li_{17}Pb_{83}$ and $LiPb_4Bi_5$ are less well developed than those for extraction from lithium; however, the lithium alloys have the advantage of lower chemical activity than pure lithium. The solid breeding materials offer the advantage of engineering design simplicity. The major question regarding the use of solid breeding materials relates to tritium recovery. The greatest uncertainty involves the possible effects of radiation on the tritium release mechanisms. Of the different solid breeding materials, the ceramic compounds are believed to offer the best potential for acceptable tritium recovery.

The superiority of a certain kind of breeder could not be determined by a comparison of the liquid and solid breeders during the Phase-One study of the INTOR design. The comparative simplicity of the engineering design was the main argument for the recommendation of the solid breeder for the present study.

The reference blanket concepts are based on Li_2SiO_3, with Li_4SiO_4 as a back-up material. Alternative blanket concepts with Li_2O and $Li_{17}Pb_{83}$ as breeding materials are presented in Section XXI.4. More detailed analyses are also presented in the individual INTOR reports [2–5].

1.2. Design description

The reference tritium-breeding blanket design developed during the Phase-One INTOR activities is discussed and analysed in the following.

The specifications for the reference tritium-breeding blanket design are presented in Table IX-1. The breeding blanket is located in the outboard and upper regions of the toroidal plasma chamber. A solid breeding material (Li_2SiO_3) was selected for the reference design and a breeding ratio of at least 0.6 was specified. A lead neutron multiplier is incorporated into the blanket to achieve the desired breeding ratio. The first wall is structurally integral with the blanket. A low-temperature water coolant is used for all blanket regions, namely D_2O for the first wall and multiplier and H_2O for the breeding zone.

The basic concepts of the blanket were determined by scoping studies. Based on more detailed neutronic, thermohydraulic and mechanical evaluations, two reference blanket designs were chosen. The primary difference between them relates to the choice of moderator and the location of the breeding material

TABLE IX-1. SPECIFICATIONS FOR THE REFERENCE TRITIUM-BREEDING BLANKET DESIGN

Number of sectors	12
Blanket location	top and outboard
Required tritium-breeding ratio	0.6
Breeder material	Li_2SiO_3
Neutron multiplier	Pb
Structural material	SS
Coolant:	
first wall/multiplier	D_2O
breeder zone	H_2O
Blanket thickness	50 cm
Coolant location	in tubes
Multiplier thickness	5 cm

with respect to the coolant. The first design, referred to as BOT/SM (Breeder Outside Tube/Solid Moderator), uses graphite as a solid moderator and the breeding material is located outside of the coolant tube (Fig.IX-1). In the second design (Fig. IX-2), referred to as BIT/LM (Breeder Inside Tube/Liquid Moderator), water (H_2O) is used as a liquid moderator and the breeding material is concentrically located inside the coolant tube. In both designs a lead neutron multiplier is placed between the first wall and the breeding region. The main parameters for the two designs are summarized in Table IX-2.

The BOT/SM concept incorporates two key features by which the blanket design can be easily adapted to the varying widths of the top region and to changes in neutron wall loading with distance from the mid-plane: (1) the use of modules which divide the blanket poloidally into a number of discrete segments, and (2) provision of flow in the toroidal direction across the sector width.

The Li_2SiO_3 is fabricated at 70% theoretical density, with lithium enriched to 30% ^6Li. The lithium silicate is formed in cylinders around the 1-cm-ID stainless steel coolant tubes. As shown in Fig. IX-1, there are three separate rows or banks of breeder/coolant-tube assemblies. The solid graphite moderator is located between these banks and in front of the rear module wall. Separate small-diameter coolant tubes are also located in the moderator region. A thin metal tube (jacket) surrounds each breeder cylinder to prevent reaction of the graphite with the breeder material. Tritium is removed from the ceramic breeder by a low-pressure (~0.1 MPa) helium purge stream. The breeder temperature is maintained at between 400 and 600°C to facilitate tritium release. A 5-cm-thick lead neutron multiplier is located between the breeding region and the first wall.

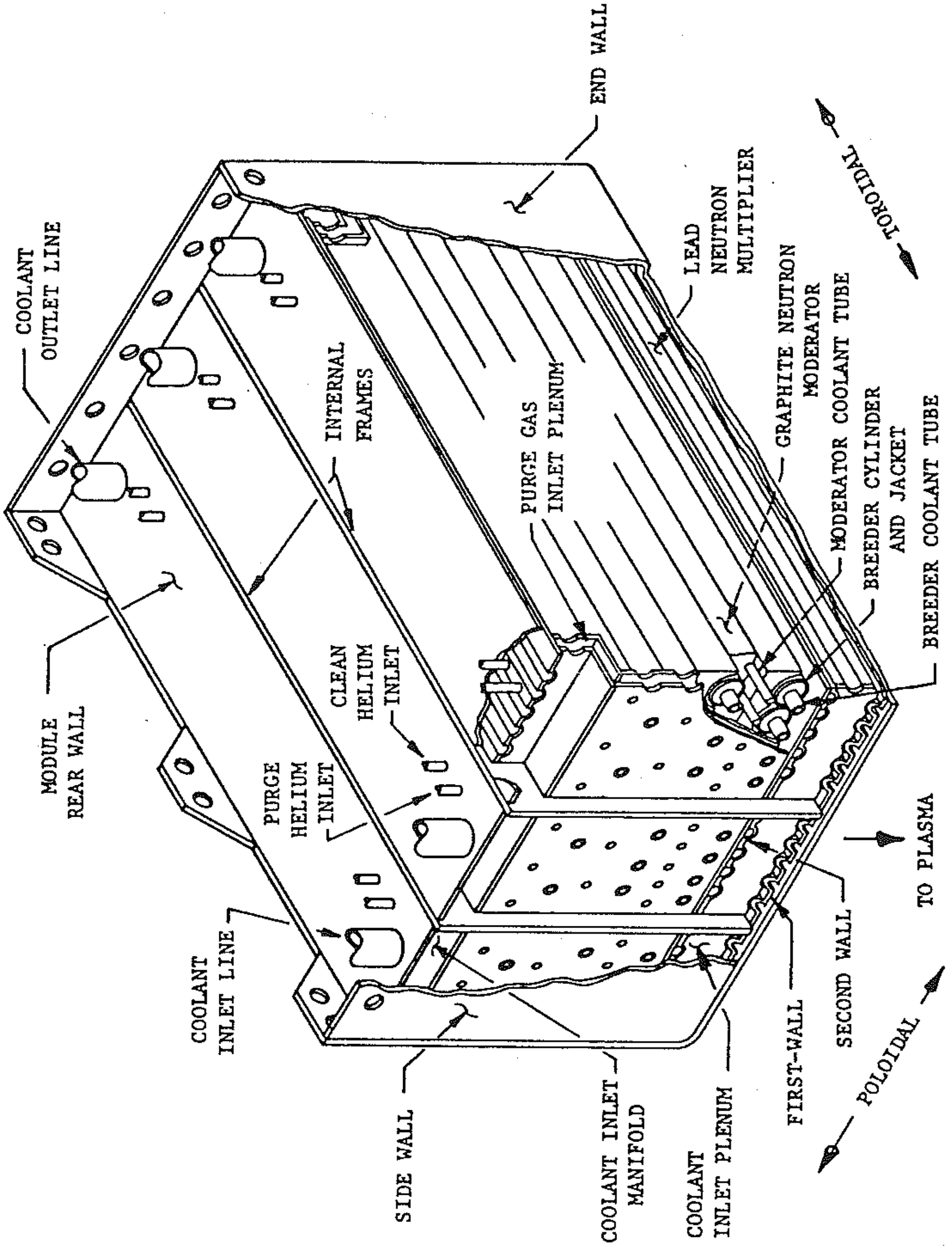

FIG.IX-1. BOT/SM reference tritium-breeding blanket design.

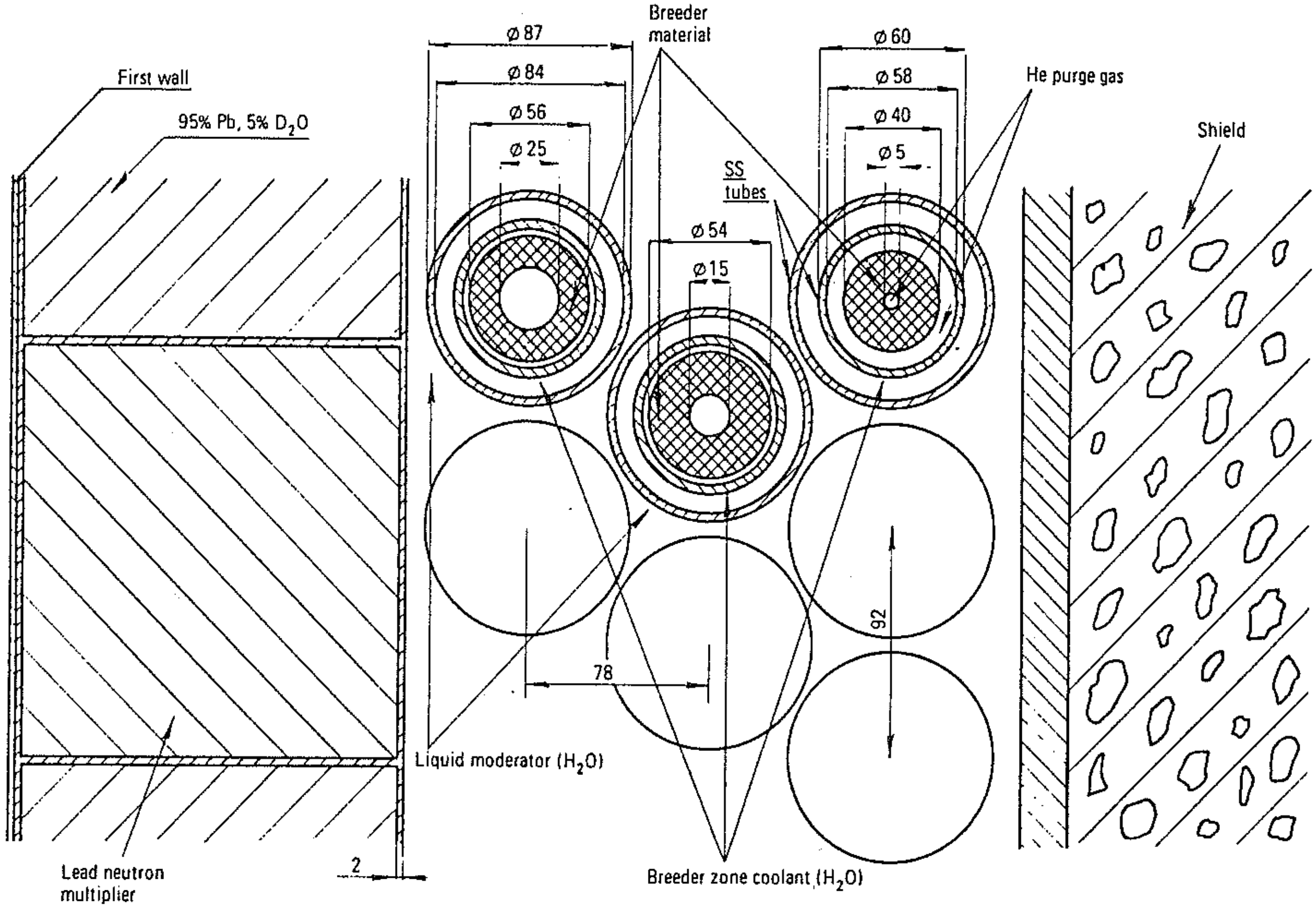

FIG.IX-2. BIT/LM reference tritium-breeding blanket design.

TABLE IX-2. REFERENCE DESIGN PARAMETERS FOR TRITIUM-BREEDING BLANKET

	Design 1 (BOT/SM)		Design 2 (BIT/LM)
Neutron multiplier			
Material		Pb	
Thickness		5 cm	
Maximum temperature		290°C	
Melting point		327°C	
Coolant	H_2O		D_2O
Breeder region			
Breeder material		Li_2SiO_3	
Breeder temperature (max./min.)		600/400°C	
Effective density		0.7	
Breeder element diameter	4–6 cm		6 cm
Enrichment of ^6Li		30%	
Tritium-processing gas		He	
Structural material		316 SS	
Maximum structural temperature		150°C	
Coolant		H_2O	
Coolant inlet/outlet temperature		50/100°C	
Coolant pressure		0.7 MPa	
Neutron moderator	C		H_2O
Breeder region thickness	43 cm		26 cm
Effective blanket coverage		0.6	
Net tritium-breeding ratio		0.65	

A water-cooled panel, which separates the lead from the breeder materials, provides cooling for adjacent regions. The lead is cooled on the front side by the water-cooled first wall which also serves as part of the blanket containment. An acceptable net breeding ratio (>0.6) is obtainable with this design.

The BIT/LM blanket concept has as its main advantages: (1) simplified fabrication of the solid breeder material, and (2) minimal breeder material inventory and blanket thickness by using a more effective moderator. This concept incorporates three rows of breeding elements behind the neutron multiplier region. Each element consists of a hollow cylindrical Li_2SiO_3 breeder encased in a stainless steel tube which is cooled externally by water coolant contained in a second, outer concentric tube. Both the inside and outside diameters of the ceramic breeder are adjusted in each of the rows to accommodate radial and poloidal variations in nuclear heating. Tritium recovery is accomplished in a similar way as in the BOT/SM design, by low-pressure (~0.1 MPa) helium flowing through the central void and annular gap surrounding the solid breeder. As before, the low density (70% of theoretical density) of the solid breeder and the breeder temperature (400–600°C) facilitate tritium recovery. The three rows of elements are surrounded by a low-temperature water (H_2O) moderator that is separate from the coolant. The water moderator and breeder elements are contained in a stainless steel vessel located directly behind the 5-cm-thick lead neutron multiplier region, which is similar to that in the BOT/SM design. A net tritium breeding ratio of ~0.65 is attainable in both designs.

2. MATERIALS

2.1. General

A solid breeder blanket concept was chosen for the reference design, primarily because of the desire for engineering simplicity of the blanket for the INTOR operating conditions. From the wide spectrum of candidate solid lithium compounds considered, Li_2SiO_3 was selected as the reference material, and Li_4SiO_4 was selected as back-up material. The important criteria used in the selection of the breeder material and the materials data base used in the development of the blanket design are summarized in this section. Table IX-3 summarizes the data base for Li_2SiO_3, Li_4SiO_4 and Li_2O. The phase diagram for temperatures above 900°C is shown in Fig. IX-3. The materials data base for the alternative Li_2O and liquid metal ($Li_{17}Pb_{83}$ and $LiPb_4Bi_5$) blankets is given in Section XXI-4 (see also Table IX-3).

Several criteria must be considered in the selection of candidate solid breeding materials for a fusion reactor blanket. The most important criteria considered in the present study are:

- tritium recovery performance
- physical and chemical stability of the compound
- compatibility of the breeder material with the structure and purge gas
- tritium-breeding capability.

Other important factors related to the design and performance of solid breeder materials include physical properties, such as thermal conductivity, effects of radiation, fabrication difficulties and residual activation. Except for data on

TABLE IX-3. MATERIALS DATA BASE FOR CANDIDATE LITHIUM COMPOUNDS

		Metasilicate	Orthosilicate	Oxide
Formula		Li_2SiO_3	Li_4SiO_4	Li_2O
Crystal structure		Orthorhombic	Low-T (LT) monoclinic High-T (HT) pseudo-orthorhombic	Tetragonal
Theoretical density (g/cm^3)		2.53	2.39	2.013
Molecular weight		89.96	119.84	29.88
Melting temperature (°C)		1201	1255	1423
Lithium atom theoretical density (g/cm^3)		0.39	0.55	0.93
Coefficient of thermal expansion (10^{-5}/°C)		1.1	1.7–4.3 (25–400°C) 0.5–4.8 (400–800°C) [4]	1.3
Thermal conductivity (W/m·K)	300°C			6 (90% TD)
	400°C	2–5.5 (60% dense)	2–5.5 (60% dense)	
	600°C	2–4.1 (60% dense)	2–4.1 (60% dense)	
	800°C			4 (90% TD)
Heat capacity (J/g-mole·K)		101 (25°C) [4] 152 (725°C) [4]	138 (25°C) [4]	54 (299 K)
Tritium diffusion coefficient at 400°C (cm^2/s)				
single crystal^a		10^{-16}	10^{-16}	10^{-16}
polycrystalline^b		$(2-5) \times 10^{-9}$	$(2-5) \times 10^{-9}$	$(2-5) \times 10^{-9}$

	Metasilicate	Orthosilicate	Oxide
Stability	Reduced solidus (939 and 1033°C) if not stoichiometric. Crystalline/amorphous transformation	Phase transformation at 667°C. Reduced solidus (1024°C) if not stoichiometric. Crystalline/amorphous transformation	Significant vapour pressure above 1200°C (sublimation)
Tritium breeding	Slightly lower than for Li_4SiO_4; lower than for Li_2O	Slightly better than for Li_2SiO_3	Neutron multiplier probably not necessary
Chemical compatibility	Chemical compatibility with SS and moist He under operating conditions was not studied	Chemical compatibility with SS and moist He under operating conditions was not studied. Decomposition in hot water	Corrosion of stainless steel and Inconel-625 alloy at 600°C and above. Considerable mass transfer in moist helium. High tritium solubility

[a] Estimated from single crystals of Al_2O_3 and BeO.

[b] Experimental data.

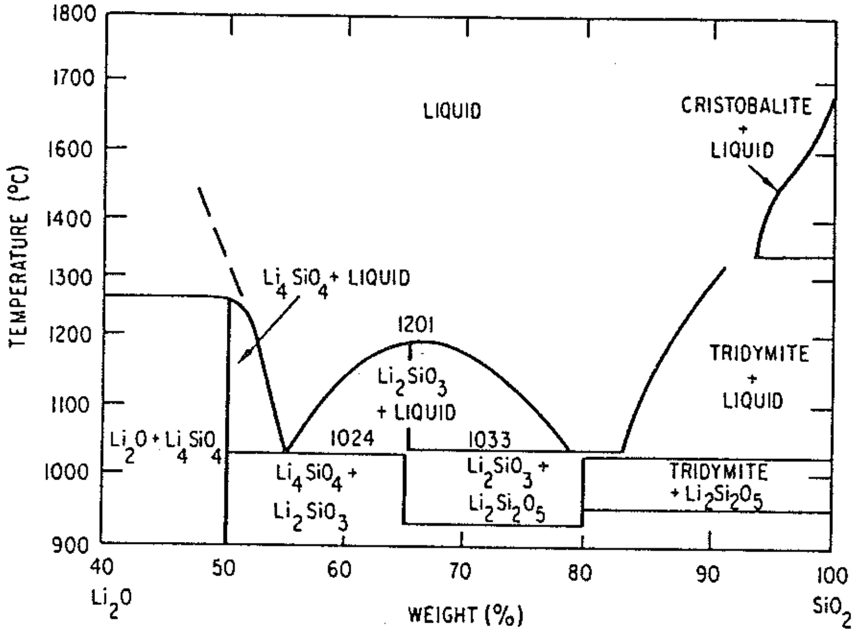

FIG.IX-3. Phase diagram for the system SiO_2-Li_2O.

residual activation (which do not differ significantly for the primary candidate breeder materials), the data base for physical properties of solid breeder materials is insufficient for making a decision as to which of the primary candidates should be preferred.

In-situ tritium recovery from the solid breeder blanket appears essential. Because of the importance of tritium recovery, this subject is treated separately in Section 7.

Li_2SiO_3 is preferred over Li_4SiO_4, primarily because it is considered to be more stable at the projected operating temperatures. The phase diagram of Fig. IX-3 shows that both silicates have the solidus for non-stoichiometric compositions at temperatures lower than the melting point. The formation of these substoichiometric compositions would reduce the temperature at which radiation-induced sintering might occur. The maximum operating temperature, ~600°C, for both silicates will be less than that for $LiAlO_2$ because of their lower melting temperatures. The operating temperature may be even lower because of the non-stoichiometry of the silicates resulting from lithium burn-up. Another major concern regarding the silicates is their well-known tendency to form an amorphous (glass) structure (see Section 2.1.1).

2.1.1. Tritium recovery performance

Tritium recovery performance has been identified as a key consideration in the selection of the primary breeding materials. Such solid compounds as LiAl and Li_7Pb_2 have relatively low melting points and low operating temperatures. Therefore, they probably cannot provide adequate tritium release in situ. Only ceramics (among solid lithium compounds) appear to have sufficient operating temperature ranges in this respect. High tritium solubility in Li_2O may lead to reduced tritium recovery, but this may be compensated to some extent by providing tritium recovery at higher temperatures.

For tritium release, a higher temperature is required for $LiAlO_2$ than for silicates. Also, the problems in connection with tritium recovery from lithium silicates await experimental examination. It is known that lithium silicates (especially Li_4SiO_4) have the tendency to form the amorphous (glass) structure that leads to reduced tritium recovery. Li_2SiO_3 has probably better tritium recovery performance than Li_4SiO_4 (see below).

2.1.2. Physical and chemical stability

To provide tritium release from the blanket, the breeding materials must operate at elevated temperatures. To keep the breeding material solid under operating conditions, its melting point and decomposition temperature must be relatively high. The vapour pressure of the breeding material and related impurity compounds must be sufficiently low.

Weight measurements on Li_2O at 1000°C and above indicate that considerable transfer of lithium in the tritium purge gas may occur. Similar experimental results are not available for lithium silicates. Most likely, a weight loss of lithium silicates in the moist helium also takes place under operating conditions. Li_4SiO_4 has a phase transition at 667°C, which is considered to be prohibitive for tritium recovery since it limits the capability for operation in excess of the recommended 600°C operating temperature.

2.1.3. Compatibility with structural materials and tritium purge gas

Compatibility of the lithium compounds with stainless steel and with other possible structural materials at high temperatures, as well as lithium weight loss resulting from chemical interactions with small amounts of moisture contained in helium, are recognized as important considerations with respect to both safety and operating limitations. Compositional variations in lithium compounds, which are a consequence of lithium burn-up and chemical interactions, make the problem more complex. The Japanese and US experiments [3, 4] have shown that severe corrosion of several structural materials, in particular of stainless steel, occurs when they are in contact with Li_2O at 600°C and above.

Also the compatibility of lithium silicates with structural materials must be studied since it is likely that corrosion of structural materials in contact with lithium silicates takes place. However, from thermochemical considerations, it is expected that the compatibility of structural materials with lithium silicates is better than with Li_2O at the same temperatures. Lithium metasilicate has better compatibility with stainless steel than orthosilicate as it contains less Li_2O.

2.1.4. Tritium-breeding capability

An adequate tritium-breeding ratio can be obtained practically with all liquid and solid breeding materials considered. For most of the solid lithium compounds, except Li_7Pb_2 and probably Li_2O, a neutron multiplier is required. The low percentage of lithium in a compound can be compensated by using larger amounts of the compound.

2.1.5. Summary of limitations and concerns

The major limitations and concerns for each of the candidate solid lithium compounds are summarized below:

Intermetallic lithium compounds: Probably an unacceptable tritium release.

Li_2O:
- (a) Tritium release uncertain
- (b) Weight loss in moist helium at high temperature
- (c) Corrosion of stainless steel at 600°C and above.

Li_4SiO_4:
- (a) Tritium release uncertain
- (b) Crystalline-amorphous transformation
- (c) Phase transition at 667°C
- (d) Microstructural and chemical changes under irradiation, deteriorating tritium release characteristics
- (e) Chemical compatibility with stainless steel and moist helium is uncertain.

Li_2SiO_3:
- (a) Tritium release uncertain
- (b) Crystalline-amorphous transformation
- (c) Microstructural and chemical changes under irradiation, deteriorating tritium release characteristics
- (d) Chemical compatibility with stainless steel and moist helium is uncertain.

Regarding lithium atomic density and melting temperature, lithium oxide is to be preferred to lithium silicates. Lithium oxide can be used for tritium breeding probably without a neutron multiplier. However, because of the above-mentioned concerns regarding Li_2O, lithium silicates were selected for the conceptual design as reference breeding materials. Li_2SiO_3 is preferred to Li_4SiO_4 because it has a larger operating margin above the recommended 600°C maximum operating temperature and is considered to be more stable at the projected operating temperatures.

The available experimental data are very limited and at present it is impossible to make a definite conclusion regarding the selection of tritium-breeding materials.

2.2. Data base for candidate breeding materials

The property data of the three candidate breeding materials Li_2SiO_3, Li_4SiO_4 and Li_2O are summarized in Table IX-3. Large discrepancies exist for transport and thermal properties (tritium diffusion coefficients, thermal conductivity, heat capacity). These discrepancies result primarily from the absence of direct experimental data on thermal conductivity and tritium diffusivity of lithium silicates. The silicate properties were estimated from data for similar ceramics with appropriate microstructure. The uncertainties may also result from differences in porosity and fabrication methods of ceramics.

Many important properties for all candidate ceramics depend on neutron fluence, for which experimental data are not available. The thermodynamic equilibria of candidate materials with T_2O should be better determined. Also, the purity of all materials should be better characterized for compatibility studies.

The low-density (60–70%) sintered product of Li_2SiO_3 was selected for the conceptual design as the reference tritium-breeding material. Its microstructure with bimodal pore distribution and a relatively high porosity should facilitate T_2O migration to the helium purge stream. Very small grain size (1 μm or less) is essential to lower the diffusion tritium inventory.

2.3. Irradiation effects

As a result of lithium burn-up under irradiation, the chemical composition of lithium compounds will be changed. A burn-up of several per cent of lithium could alter the physical characteristics of the compound and increase the chemical interaction with structural materials and impurities in the tritium purge gas.

Radiation damage in lithium ceramics will result from the highly energetic tritium and helium recoils produced by the (n, Li) reaction.

Very few radiation damage data exist for lithium ceramics. The major considerations are: possible swelling, enhanced recrystallization or sintering, and trapping of tritium by defects or cavities. Of particular concern is the potential effect of radiation-induced sintering on the tritium release characteristics.

2.3.1. *Swelling*

Swelling could occur as a result of vacancy coalescence or gas generation (He or T). The effects of the high-energy tritium and helium nuclei with recoil ranges of about 30 μm and 4 μm, respectively, are important. In contrast to metals, helium is typically more mobile than hydrogen in ceramics. Therefore, if low tritium inventories can be maintained, the build-up of helium should not be excessive. The 30% porosity of lithium ceramics should accommodate some swelling with little impact on the structural containment. Some micro-cracking of the brittle ceramic may occur and must be considered in the design.

2.3.2. *Recrystallization*

Recrystallization or sintering are believed to be extremely important since they may have a substantial effect on the tritium release characteristics. Significant thermal sintering takes place at 0.8 T_m (absolute melting temperature). In a radiation environment, enhanced sintering has been observed at lower temperatures.

Since the high-energy (MeV) tritium and helium nuclei have recoil ranges much greater than the proposed grain size, considerable ion-induced damage and intergranular sputtering are expected. The small grain size and fine pore structure desired for tritium release make the lithium compounds probably more susceptible to radiation-induced sintering than would a more coarse structure. Significant restructuring typically occurs at 0.6 T_m (for Li_2SiO_3, this temperature corresponds to 600°C).

2.3.3. *Trapping*

Radiation-induced trapping of tritium at defects has been observed in many materials and is expected to occur in Li_2O and in other ceramic breeding materials. The most pertinent data base for assessing this effect is presented by the surface effect studies conducted as part of the fusion materials development programme. Although further analyses and experiments are needed for a more accurate assessment, it can be stated that radiation-induced tritium trapping may increase the diffusive hold-up of tritium by at least a factor of 10, possibly reaching a level of a few per cent tritium in the ceramic.

2.3.4. *Stability under irradiation*

The maximum permissible deviation from stoichiometry without a great change of physical properties may be in the range of 15–20% [5].

The radiation-induced chemical reactions in lithium orthosilicate are as follows:

$$Li_4SiO_4 \rightarrow Li_2SiO_3 + Li_2O$$

$$Li_2O \rightarrow LiO + Li$$

$$LiO \rightarrow Li + O$$

$$Li_2SiO_3 \rightarrow Li_2O + SiO_2$$

$$SiO \rightarrow Si + O$$

Chemical decomposition reactions will take place under conditions of the combined influence of irradiation, burn-out of lithium and thermal annealing.

Tritium resulting from a nuclear reaction is stabilized in the crystal lattice as an atom, to form OT groups in the presence of oxygen ions. These groups are the primary product of tritium stabilization. Therefore, tritium is extracted mainly as water during thermal annealing of lithium compounds containing oxygen.

2.4. Breeder fabrication methods

Three present-day methods can be used for fabrication of lithium metasilicate ceramics: sintering, slip casting and vibratory compaction.

2.4.1. Sintering

Sintering of the breeder involves pressing the material (cold or hot) into the desired shape and then firing to achieve the desired density. The sintering temperature should range between 900 and 1050°C, depending upon the desired density. Hot pressing will help provide microstructural control; however, there is the added risk of contamination of the powders by the die at elevated temperatures.

2.4.2. Slip casting

The fine particle size of Li_2SiO_3 powder is conducive to its suspension in a liquid (aqueous or organic) to form a slip. The slip can then be cast in "near net" shapes (i.e. shapes requiring little final machining) to fit within the module. The two approaches involved in this technique are: (1) in-situ casting, and (2) normal slip casting.

In-situ casting involves pouring the slip into the breeder cavity and then baking to drive off the liquid (e.g. an alcohol), with body densities of 60% or less. Forming the purge channels by machining would not be feasible since the material has limited strength, making it difficult to maintain small tolerances.

Normal slip casting involves the formation of blocks, using moulds to extract most of the water, careful drying to remove the rest, and finally firing to achieve the final density and dimensions. Different breeder densities could be achieved simply by altering the firing profile or the solids content of the slip. Slip casting has been proven to add very little contamination to the finished product.

2.4.3. Vibratory compaction

Vibratory compaction of Li_2SiO_3 offers the advantage of in-situ assembly. Blanket modules complete with cooling tubes can be packed with powder and then vibrated or pulsated to achieve the desired breeder density. Since vibratory compacts have little structural integrity, it would be difficult to make small sections of compacts for eliminating non-uniformities and voids and then to stack the compacts in the blanket module. The process does not introduce contamination since there is no physical contact with any of the breeder materials, but there is an upper limit of 65% to the achievable density.

3. NEUTRONICS

This section presents the neutronic analysis of the solid breeder blanket designs, which was performed for the purpose of optimizing the tritium-breeding ratio (TBR) for blankets having the primary features described in Section 1. The results of the scoping study are presented below. The study has shown that it is possible to achieve nearly equal TBR values for several types of designs. For a choice of the best design, more detailed evaluation is required, including fabrication and reliability considerations. Two design concepts were selected as reference designs and are discussed in more detail below.

Most of the neutronics calculations were one-dimensional and were performed by the discrete-ordinate ANISN code or the Monte-Carlo BLANK code. This model does not account for:

- real configuration and composition of the three-dimensional design
- heterogeneity of the channel (tube) blanket structure
- neutron thermalization in different blanket regions.

The first point can be corrected on the basis of three-dimensional analysis, which was done using the MORSE-CG code for the reference design BOT/SM blanket (see Section 3.4). Preliminary considerations [5] show that differences in thermal neutron spectra between first-wall/multiplier and breeder regions lead to errors of about 1–2% in TBR, which is acceptable. The effect of heterogeneous structure in the breeder region has not been estimated; it will probably decrease TBR for both reference designs. Additional calculations are necessary.

3.1. Scoping study

To define the optimum neutronic parameters of the preliminary breeding blanket concepts, a scoping study was carried out using a one-dimensional cylindrical model. In this study, three different initial blanket design options were considered. The options differ in zone thicknesses and compositions, and it is difficult to compare the absolute TBR values. The scoping study aims at determining in general the dependences of TBR upon such parameters as multiplier thickness, breeder material enrichment, type of moderator, etc., rather than at determining a level of tritium-breeding ratio for a specific design.

The compositions and dimensions of the blankets considered in the scoping study are given in Table IX-4. The three different options considered were selected from Refs [4, 5 and 3] and are referred to as Cases I, II and III, respectively.

3.1.1. Effect of armour/first-wall thickness

The armour/first-wall structure consists of a relatively thick stainless steel region backed by cooling channels. Changes in armour or coolant thickness affect the tritium-breeding ratio.

Figure IX-4 shows the tritium-breeding ratios as a function of armour thickness for Cases I and II. A decrease of the stainless steel armour thickness by 10 mm results in a TBR increase of about 0.1, or approximately 1% per mm.

The dependence of TBR on first-wall water coolant thickness is plotted in Fig. IX-5 for the Case II blanket design. A water thickness increase results in a decrease of TBR at a rate of about 2.5%/mm for small thicknesses. The strong dependence of TBR upon the amount of water in the first wall is a reason for reducing the amount of first-wall water coolant in blanket designs, or substituting heavy water for light water (see Section 3.1.4).

These effects are the result of absorption of slowed-down neutrons and may depend strongly upon the lead layer thickness and the amount of moderator between lead and breeder material.

3.1.2. Effect of neutron multiplier thickness

The effect of the neutron multiplier thickness on tritium breeding is shown in Fig. IX-6 for Cases I and II and in Fig. IX-7 for Case III.

When the multiplier has no internal coolant, TBR increases steadily in the thickness range from 0 to 150 mm. This increase is about 0.3 for Case II. The use of an internally cooled multiplier for Case I leads to an optimum lead thickness of 5–7 cm. The same effect exists in Case II.

TABLE IX-4. DIMENSIONS AND MATERIAL COMPOSITIONS FOR BLANKET STRUCTURES USED FOR THE NEUTRONIC SCOPING STUDY

Component	Thickness (cm)	Composition
CASE I		
Armour	1.0	SS
First wall	1.0	50% SS + 50% H_2O
Multiplier	5.0	92% Pb + 6% SS + 2% H_2O
Blanket	43.0	10% SS + 10% H_2O + 80% Li_4SiO_4 [a]
Gap	10.0	Void
Shield	60.0	50% SS + 50% H_2O
CASE II		
First wall/armour	1.8	0.72 SS + 0.28 H_2O
Multiplier	10.0	Pb
Second wall	1.05	0.67 SS + 0.33 H_2O
Breeder (I)	1.3	H_2O
	0.28	SS
	2.28	Li_4SiO_4 [b]
	0.28	SS
Breeder (II)	3.12	H_2O
	0.28	SS
	3.03	Li_4SiO_4 [b]
	0.28	SS
Breeder (III)	3.12	H_2O
	0.28	SS
	1.41	Li_4SiO_4 [b]
	0.28	SS
	1.53	H_2O
Shield	15.0	0.5 SS + 0.5 H_2O

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[a] Density factor: 0.6.

[b] Density factor: 1.0.

TABLE IX-4 (cont.)

Component	Thickness (cm)	Composition
CASE III		
First wall (armour)	1.04	SS
First-wall (coolant)	0.9	0.65 SS + $0.35\ H_2O$
First wall support	2.0	0.09 SS + $0.16\ H_2O$ + 0.75 void
Blanket front wall	1.25	0.84 SS + $0.16\ H_2O$
Blanket front wall	0.65	0.21 SS + $0.3\ H_2O$ + 0.49 Pb
Lead multiplier	x^c	0.05 SS + 0.95 Pb (in case of $x < 5$ cm) 0.065 SS + 0.91 Pb + $0.025\ H_2O$ (in case of $x = 7$)
Partition wall	1.5	0.22 SS + $0.25\ H_2O$ + 0.53 He (1 atm(abs))
Breeder (I)	8.0	0.12 SS + $0.06\ H_2O$ + $0.57\ Li_2O$ + 0.25 He^d
Breeder (II)	8.7	0.11 SS + $0.05\ H_2O$ + $0.59\ Li_2O$ + 0.25 He
Breeder (III)	y	0.11 SS + $0.04\ H_2O$ + $0.60\ Li_2O$ + 0.25 He
Blanket end wall	0.65	0.21 SS + $0.3\ H_2O$ + 0.49 He
Blanket end wall	3.65	0.95 SS + $0.05\ H_2O$
Gap	10.0	Void
Support frame	5.0	SS

[c] $x + y = 21.66$.

[d] Li_2O: theoretical density = 0.85, packing fraction = 0.7.

It is interesting to note that the effect changes sign for Case III (lower curve in Fig. IX-7). Case III differs from Cases I and II in that Li_2O is used instead of lithium silicate and the amount of stainless steel and water located in front of the neutron multiplier is doubled. The effect of neutron reflection to the first-wall region apparently exceeds the effect of neutron multiplication in the lead region in this case. Furthermore, the presence of neutron multiplier reduces the reaction $^7Li(n,n',\alpha)$. In contrast, the use of D_2O in the Case III blanket again changes the sign of TBR dependence on lead thickness (upper curve in Fig. IX-7).

Cases I and II are closer to the reference designs selected for further study than Case III, and an optimum thickness of 5–7 cm of lead was recommended for them. Case III serves as a good example, illustrating changes in the local optimum with variations in the initial design assumptions.

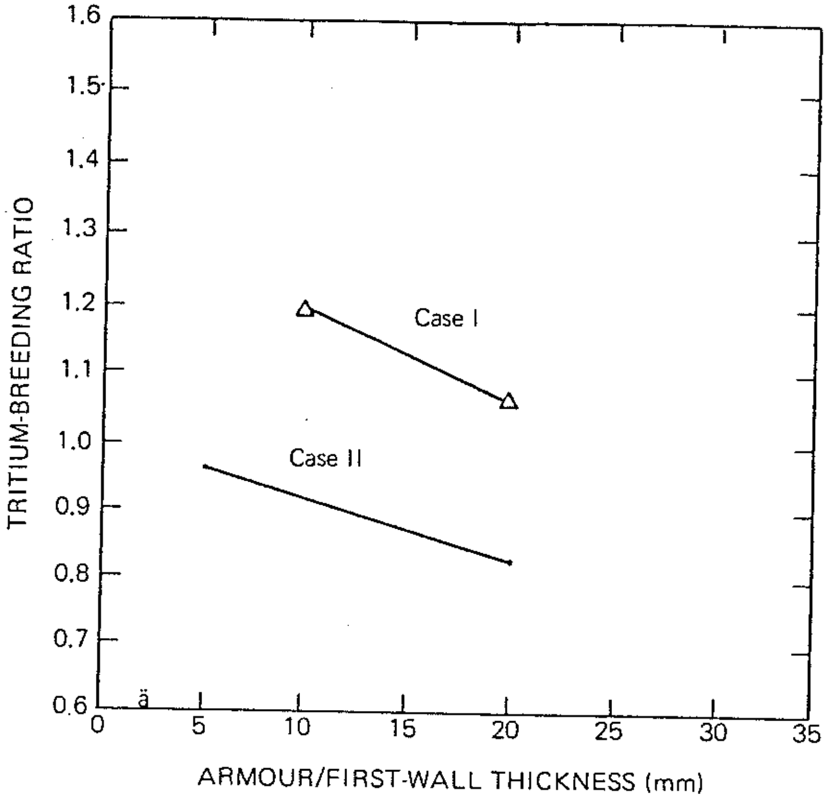


FIG.IX-4. Effect of armour/first-wall thickness on tritium-breeding ratio.

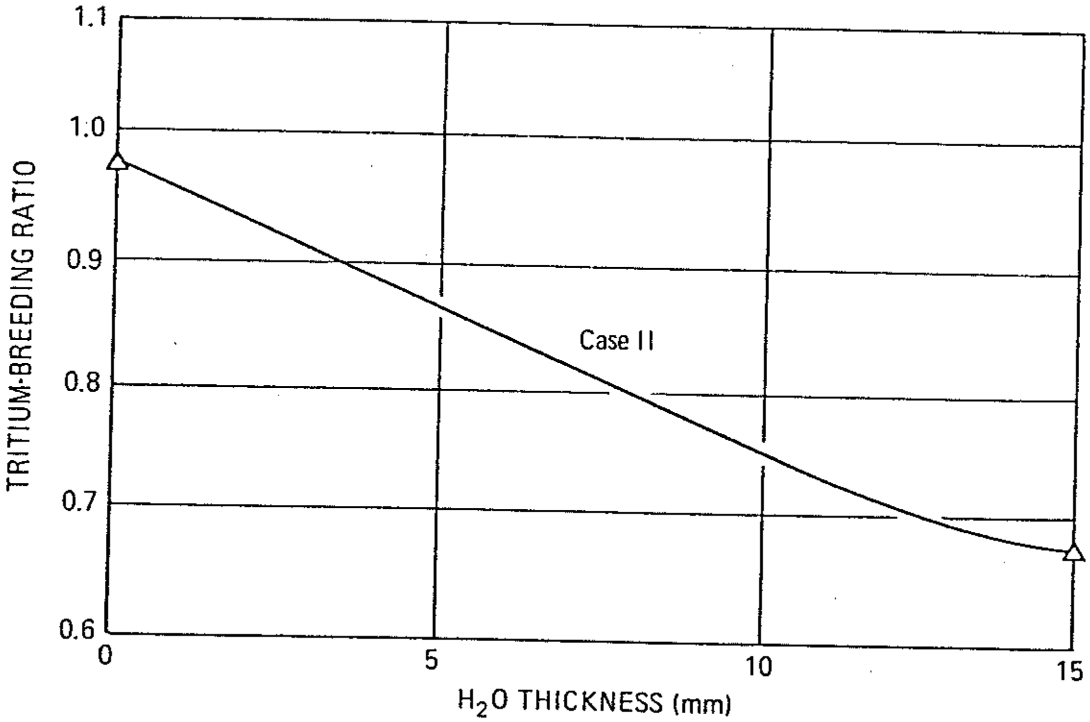


FIG.IX-5. Effect of first-wall coolant (H_2O) thickness on tritium-breeding ratio.

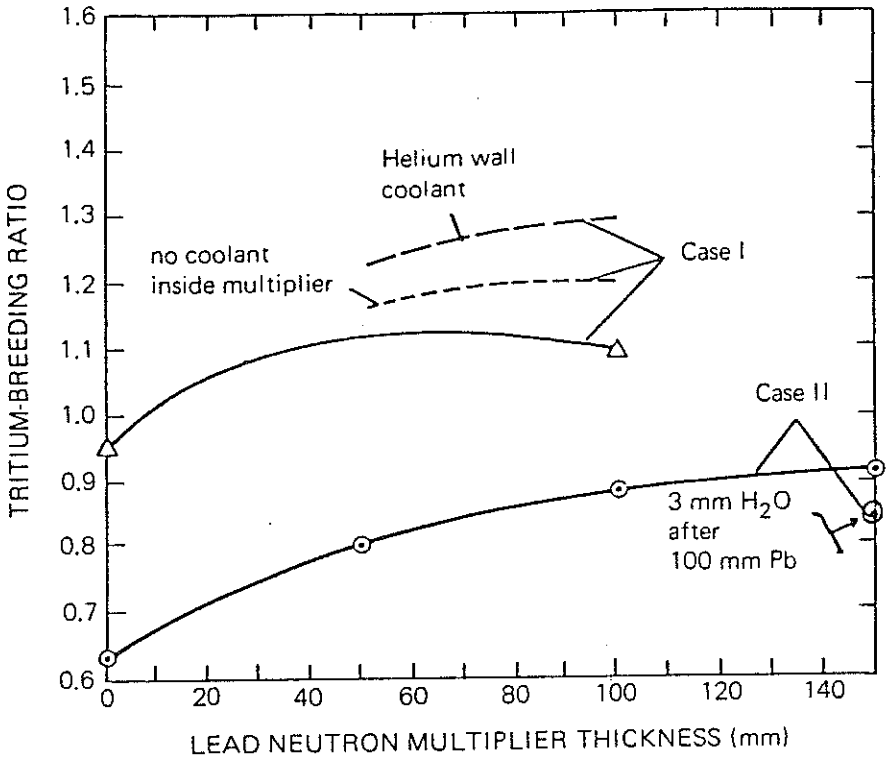


FIG.IX-6. Effect of multiplier thickness on tritium-breeding ratio. (The breeder materials are lithium silicates.)

3.1.3. *Lithium enrichment*

The dependence of TBR upon ^{6}Li enrichment is not strong for all three cases, as indicated in Fig. IX-8. The maximum variation of TBR is about 10% in the range from natural lithium (7.5% ^{6}Li) to 50% enrichment. In Case I, there is a maximum at 30%, and in Cases II and III, there is an increase of less than 3% at between 30% and 50% enrichment.

The choice of the percentage of lithium enrichment may depend more on the changes in TBR resulting from lithium burn-up than on the initial TBR value. This question is discussed in Section 3.3.

3.1.4. *Effect of H_2O and D_2O coolants*

D_2O is less effective than H_2O in neutron slow-down, and its use can decrease absorption in structural materials in the first wall and multiplier regions. As indicated in Fig. IX-7 for Case III, the use of D_2O coolant increases TBR by 0.1–0.2, depending on multiplier zone thickness and ^{6}Li enrichment in the breeding zone. Some additional results for blankets with compositions and dimensions

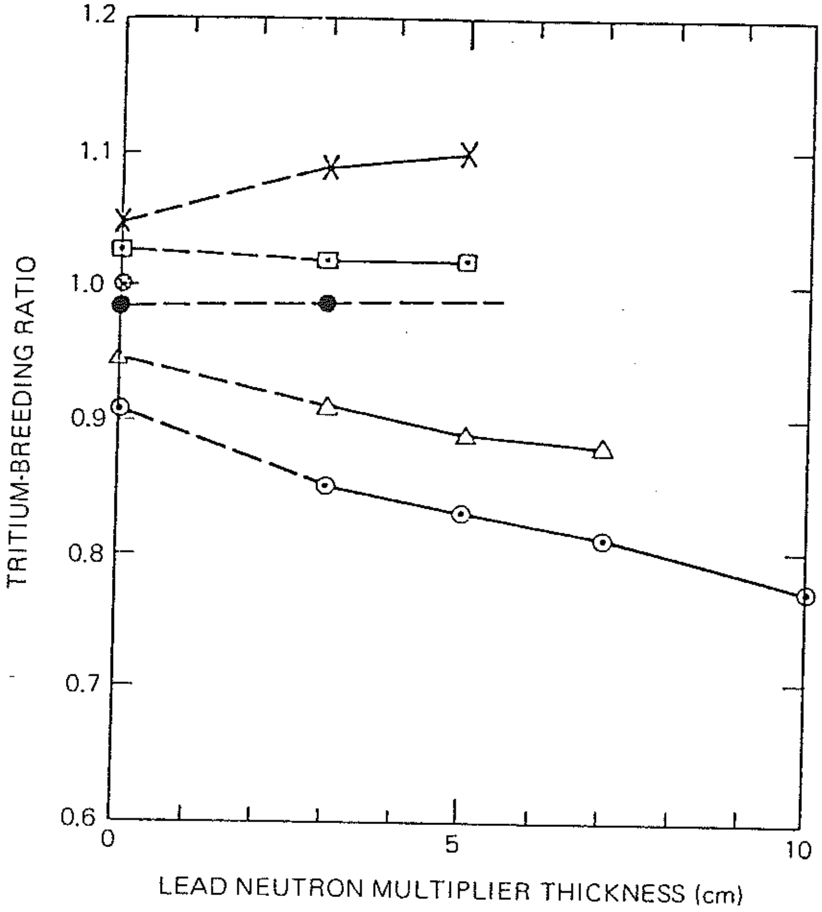


FIG.IX-7. Effect of multiplier thickness on tritium-breeding ratio for different options of Case III. (The breeder material is Li_2O.*)*
⊙ *natural lithium,* H_2O; Δ *30% enrichment,* H_2O;
⊡ *30% enrichment, first wall* D_2O, *blanket* H_2O;
X *30% enrichment,* D_2O;
⊗ *natural lithium, first wall* D_2O, *blanket* H_2O;
● *natural lithium,* D_2O.

similar to those of Cases I and II are shown in Table IX-5. Except in the case with a solid moderator, the use of D_2O increases TBR by 0.14–0.2.

In blankets with solid moderators, neutron absorption in the first wall and multiplier regions is smaller, particularly in designs with a relatively thin (5–7 cm) multiplier. The use of D_2O in these blankets leads to a smaller gain in TBR (~6%) and may not be economically profitable.

3.1.5. Liquid and solid moderators

The solid moderator design [4] was considered and a comparison of neutron performance was made using a similar liquid moderator blanket design. The

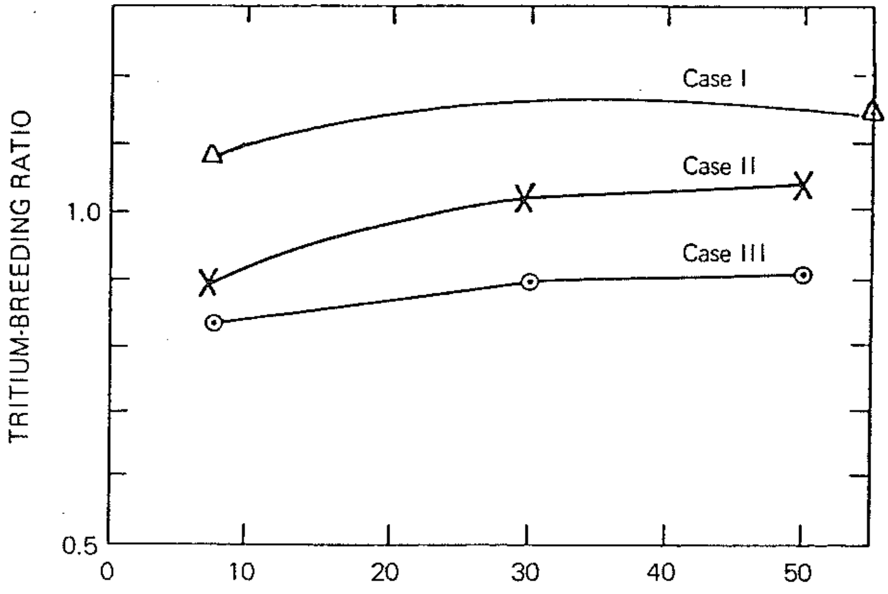


FIG.IX-8. Effect of ^{6}Li enrichment on tritium-breeding ratio.

TABLE IX-5. TBR VALUES FOR H_2O AND D_2O COOLANTS[a]

Coolant in the first-wall/multiplier region	H_2O	D_2O
1. Blanket composition with solid moderator close to that given in Table IX-6 [4]	1.06	1.12
2. Blanket design close to that shown in Fig.IX-9 [2]	0.96	1.16
3. Blanket composition for Case II, for H_2O with a slight difference for D_2O [5]	0.89	1.16

[a] Because of differences in design and composition, the three groups of TBR values should not be compared.

composition and dimensions for the BOT/SM design with a solid moderator are shown in Table IX-6. The blanket has three graphite moderator zones located in the breeding zone. The choice of material for the zone immediately behind the multiplier and second wall is very important for TBR. This region, if filled with the moderator, acts as a neutron reflector for the first-wall/multiplier region and increases parasitic absorption in the multiplier and structural material.

TABLE IX-6. DIMENSIONS AND MATERIAL COMPOSITIONS FOR BLANKET OPTION WITH SOLID MODERATOR

Component		Thickness (mm)		Composition		
Armour	Pre-blanket regions	13.4		SS		
First wall		3.0	6.0	Coolant		
		3.0		SS		
Multiplier		50.0		Pb		
Second wall		2.0	4.5	SS		
		1.5		Coolant		
		1.0		SS		
Moderator 0[a]		x_0		Moderator		
Bank-1 blanket		2.5	31.0	Void		
		5.6		Li_2SiO_3[b]		Breeder cylinder
		2.5		Void		
		1.8		SS	Coolant tube	
		6.2		Coolant		
		1.8		SS		
		2.5		Void		
		5.6		Li_2SiO_3[b]		
		2.5		Void		
Moderator 1[a]		x_1		Moderator		
Bank-2 blanket		2.7	29.7	Void		
		5.9		Li_2SiO_3[b]		Breeder cylinder
		2.7		Void		
		1.3		SS	Coolant tube	
		4.5		Coolant		
		1.3		SS		
		2.7		Void		
		5.9		Li_2SiO_3		
		2.7		Void		

---

[a] In the presence of moderator 0: $x_0 = 77$ mm, $x_1 = 80$ mm,
$x_2 = 80$ mm, $x_3 = 56.5$ mm
In the absence of moderator 0: $x_0 = 0$, $x_1 = 105$ mm,
$x_2 = 105$ mm, $x_3 = 83.5$ mm

[b] Li_2SiO_3: density factor = 0.7.

TABLE IX-6 (cont.)

Component	Thickness (mm)		Composition		
Moderator 2[a]	x_2		Moderator		
Bank-3 blanket	6.3	56.9	Void		
	13.4		Li_2SiO_3[b]		Breeder cylinder
	6.3		Void		
	0.9		SS	Coolant tube	
	3.1		Coolant		
	0.9		SS		
	6.3		Void		
	13.4		Li_2SiO_3[b]		
	6.3		Void		
Moderator 3[a]	x_3		Moderator		
Blanket jacket	15.0		SS		
Gap	30.0		Void		
Shield jacket	15.0		Fe 14Mn 2Cr 2Ni		

Table IX-7 gives tritium-breeding ratios for cases with and without moderator in the first moderator zone. When this zone is removed (i.e. no moderator between the second wall and the first breeder layer), TBR increases by 0.11. In this case the effective breeding zone is significantly shifted toward the deeper blanket region.

Removal of the first moderator zone seems to be possible in a blanket design with a solid moderator, but seems improbable in designs with a liquid moderator.

3.1.6. Blanket concept without moderator

A comparison between BIT (breeder inside tube) and BOT/NM (breeder outside tube/no moderator) designs is rather difficult because the general features of the concepts differ. Such a comparison was performed [4] for two designs with the same thicknesses, with the compositions optimized to some extent.

From the neutronics standpoint, the BIT concept analysed can be characterized by the large amount of moderator (40–50 vol.%) and the small amounts

TABLE IX-7. EFFECT OF FIRST MODERATOR ZONE UPON TBR

Coolant: H_2O
Moderator: graphite
Multiplier: 5 cm Pb
Breeder: Li_2SiO_3 (natural lithium)

A. With first moderator zone	
Bank-1 BR	0.475
Bank-2 BR	0.229
Bank-3 BR	0.139
Total BR	0.843
B. Without first moderator zone	
Bank-1 BR	0.458
Bank-2 BR	0.306
Bank-3 BR	0.187
Total BR	0.951

TABLE IX-8. COMPARISON OF THE TRITIUM-BREEDING RATIOS OF THE BIT AND BOT DESIGN CONCEPTS

Region (BIT/BOT)	Total TBR (Li_4SiO_4)	
	BIT	BOT
Bank 1/Blanket 1	0.451	0.260
Bank 2/Blanket 2	0.259	0.286
Bank 3/Blanket 3	0.118	0.212
Blanket 4	–	0.165
Blanket 5	–	0.161
Total	0.828	1.084
Homogeneous mixture calculation	1.021	1.095

of breeder (10–20%) and structural materials (~5%). The remaining volume is helium purge gas or breeder porosity for tritium extraction. In the BIT concept, the breeder tube heterogeneity is an important factor because of the relatively large tube size and the fact that every neutron to be absorbed in the breeder material must pass through two tube walls. On the other hand, the BOT/NM concept studied can be assumed to represent a homogeneous mixture because of the small size of the structural material and the small amount of water coolant. The BOT/NM blanket contains only ~3% steel and ~5% H_2O. The rest is the solid breeder material, with a density factor of 60% for this scoping study.

The breeding ratios of the BIT and BOT/NM designs are compared in Table IX-8. It is clear that for the two specific designs analysed, the BOT/NM system yields more tritium than the BIT system. The difference is ~0.25 for 100% blanket coverage. By comparing these breeding ratios with the respective calculations for the one-region homogeneous mixture system, it is apparent that the breeding performance in the BIT design is strongly affected by the system heterogeneity. Most of the effect is caused by parasitic neutron absorption in the materials located in front of the first breeder region in the BIT design.

More detailed optimization can improve TBR for the BIT design, which can be seen from the results of calculations for the reference blanket designs (Section 3.2). Nonetheless, it is clear from the comparison that heterogeneity effects strongly influence the neutronic parameters of the BIT design, and the BOT/NM option has a relative gain of ~0.1–0.2 in TBR in cases without restrictions on blanket thickness.

3.2. Reference blanket designs

Based on results of the scoping study, two reference designs were chosen for further consideration. These designs are optimized for such parameters as multiplier thickness, amount and location of coolant in the first-wall/multiplier zones, and lithium enrichment. However, the choice of coolant type and moderator in the lithium zone and the geometry of the breeder material elements cannot be done solely on the basis of neutronic and thermohydraulic calculations. For this reason, two blanket designs, with liquid and solid moderators respectively, are selected as reference designs. Further analysis is required before a choice between them can be made. The parameters for both designs are the same as those specified in Table IX-1, except for some deviations noted in Section 3.2.2.

The design with a solid moderator and breeder material surrounding coolant tubes (proposed in Ref. [4]) is referred to as the BOT/SM design. In the design with a liquid moderator (proposed in Refs [2, 5]) the breeder material is located in tubes, each of which is surrounded by liquid coolant contained in an annulus, which in turn is surrounded by a moderator. This is referred to as the BIT/LM design.

TABLE IX-9. DIMENSIONS AND MATERIAL COMPOSITIONS USED FOR THE REFERENCE BOT/SM BLANKET DESIGN

Component	Thickness (mm)		Composition		
Armour	13.4		SS		
First wall	3.0	6.0	H_2O		
	3.0		SS		
Multiplier	50.0		Pb		
Second wall	2.0	4.5	SS		
	1.5		H_2O		
	1.0		SS		
Bank-1 breeder	0.6	29.4	SS	Moderator jacket	
	8.3		Li_2SiO_3[a]		Breeder cylinder
	2.2		SS	Coolant tube	
	7.8		H_2O		
	2.2		SS		
	8.3		Li_2SiO_3[a]		
Moderator 1	0.6	126.2	SS		Moderator jacket
	62.05		C		
	0.25		SS	Coolant tube	
	0.4		H_2O		
	0.25		SS		
	62.05		C		
	0.6		SS		
Bank-2 breeder	9.7	29.3	Li_2SiO_3[a]		Breeder cylinder
	1.8		SS	Coolant tube	
	6.3		H_2O		
	1.8		SS		
	9.7		Li_2SiO_3[a]		

[a] Li_2SiO_3: density factor = 0.7, ^6Li enrichment = 30%.

TABLE IX-9 (cont.)

Component	Thickness (mm)		Composition		
Moderator 2	0.6	126.2	SS		Moderator jacket
	62.15		C		
	0.2		SS	Coolant tube	
	0.3		H_2O		
	0.2		SS		
	62.15		C		
	0.6		SS		
Bank-3 breeder	19.4	45.8	Li_2SiO_3[a]		Breeder cylinder
	1.3		SS	Coolant tube	
	4.4		H_2O		
	1.3		SS		
	19.4		Li_2SiO_3[a]		
Moderator 3	0.6	54.2	SS	Moderator jacket	
	26.45		C		
	0.2		SS	Coolant tube	
	0.3		H_2O		
	0.2		SS		
	26.45		C		
Blanket jacket	15.0		SS		
Gap	30.0		Void		
Shield jacket	15.0		Fe 14Mn 2Cr 2Ni		

[a] Li_2SiO_3: density factor = 0.7, ^6Li enrichment = 30%.

TABLE IX-10. AVERAGE NUCLEAR HEATING (MW/m^3) IN THE VARIOUS ZONES FOR THE REFERENCE BOT/SM BLANKET DESIGN

Zone No.	Component		Heating
1	Plasma		–
2	Scrape-off		–
3	Armour	SS	14.7
4	First wall	H_2O	14.1
5		SS	11.6
6	Multiplier	Pb	6.38
7	Second wall	SS	4.69
8		H_2O	7.61
9		SS	4.66
10	Bank 1	SS	4.65
11		Li_2SiO_3[a]	20.27
12		SS	4.54
13		H_2O	6.28
14		SS	4.32
15		Li_2SiO_3[a]	18.15
16		SS	4.04
17	Moderator 1	C	1.80
18		SS	2.91
19		H_2O	3.41
20		SS	2.89
21		C	1.12
22		SS	2.09
23	Bank 2	Li_2SiO_3[a]	8.33
24		SS	1.94
25		H_2O	1.73
26		SS	1.82
27		Li_2SiO_3[a]	6.31
28		SS	1.69

[a] Li_2SiO_3: density factor = 0.7, ^6Li enrichment = 30%.

TABLE IX-10 (cont.)

Zone No.	Component		Heating
29	Moderator 2	C	0.555
30		SS	1.23
31		H_2O	1.02
32		SS	1.22
33		C	0.361
34		SS	0.863
35	Bank 3	Li_2SiO_3[a]	1.68
36		SS	0.759
37		H_2O	0.527
38		SS	0.729
39		Li_2SiO_3[a]	1.07
40		SS	0.663
41	Moderator 3	C	0.198
42		SS	0.609
43		H_2O	0.391
44		SS	0.606
45		C	0.172
46	Blanket jacket	SS	0.170

[a] Li_2SiO_3: density factor = 0.7, ^{6}Li enrichment = 30%.

3.2.1. BOT/SM reference design

Table IX-9 describes the neutronic model used for analysis of the BOT/SM design. The Li_2SiO_3 breeder material was assumed to be 70% dense and enriched to 30% of ^{6}Li. The nuclear heating rate in each zone is given in Table IX-10 and the breeding calculations are summarized in Table IX-11. The one-dimensional tritium-breeding ratio is 1.08, which makes it possible to achieve the required TBR of 0.6 after adjustment to three-dimensional analysis (assuming 60% blanket coverage).

TABLE IX-11. TRITIUM-BREEDING RATIO FOR THE REFERENCE BOT/SM BLANKET DESIGN

Coolant: H_2O
Moderator: H_2O-cooled graphite
Multiplier: 5 cm Pb
Breeder: 30% lithium-enriched Li_2SiO_3

	$^6Li(n,\alpha)t$	$^7Li(n,n',\alpha)t$	Total
Bank-1 BR	0.629	0.006	0.635
Bank-2 BR	0.319	0.002	0.321
Bank-3 BR	0.122	0.002	0.124
Total BR	1.070	0.010	1.080

The primary neutronics advantages of the BOT/SM concept, in terms of increasing TBR, are: (1) removal of neutron moderator from the region between the neutron multiplier and the first breeder layer, and (2) reduction in the thickness of steel through which the neutrons must pass before entering the breeder.

The use of D_2O instead of H_2O in the first-wall/multiplier regions of this design results in only a 5–6% increase in one-dimensional TBR. Further study and detailed design are needed before it can be determined whether the use of D_2O in the first-wall/multiplier zone results in a net economic advantage.

3.2.2. BIT/LM reference design

The dimensions and material compositions used for the BIT/LM reference design are given in Table IX-12. The breeder material is Li_4SiO_4. The geometry of the design is presented in the blanket cross-section of Fig. IX-2. The first wall and lead multiplier are cooled with heavy water. Three rows of breeding elements are located behind the lead multiplier and are cooled with light water.

The results of neutronic calculations are presented in Table IX-13, and the distribution of the nuclear heating rate in the blanket is summarized in Table IX-14. The resulting tritium-breeding ratio is 1.16. However, it must be mentioned that for this design the lead multiplier thickness is 126 mm, deviating from the 50 mm thickness specified in Table IX-1.

Another alternative to the reference BIT/LM design (considered in Ref. [2]) is shown in Fig. IX-9. In this design the lead multiplier is located inside stainless steel tubes with non-uniform thickness and is cooled by heavy water. A TBR value of 1.16 was calculated for this design [2].

TABLE IX-12. DIMENSIONS AND MATERIAL COMPOSITIONS USED FOR THE REFERENCE BIT/LM DESIGN

Component	Thickness (mm)		Composition
Armour	11.0		SS
First wall	8.0		0.5 SS + 0.5 D_2O
Multiplier	126		0.92 Pb + 0.03 SS + 0.05 D_2O
Breeder 1	4.2	57.2	SS
	14.8		H_2O
	1.0		SS
	21.4		Li_4SiO_4[a]
	1.0		SS
	14.8		H_2O
Breeder 2	4.4	59.0	SS
	14.8		H_2O
	1.0		SS
	23		Li_4SiO_4[a]
	1.0		SS
	14.8		H_2O
Breeder 3	4.4	51.6	SS
	14.8		H_2O
	1.0		SS
	13.4		Li_4SiO_4[a]
	1.0		SS
	14.8		H_2O
	2.2		SS
Shield	150		0.5 SS + 0.5 H_2O

[a] ^{6}Li enrichment in Li_4SiO_4 is 30%.

TABLE IX-13. NEUTRON BALANCE FOR THE REFERENCE BIT/LM DESIGN

Neutron multiplication	1.53
Total absorption	0.31
first wall	0.11
multiplier	0.06
lithium zone structure and coolant	0.11
shield	0.06
Tritium-breeding ratio	1.16

TABLE IX-14. AVERAGE NUCLEAR HEATING (MW/m^3) IN THE VARIOUS ZONES FOR THE REFERENCE BIT/LM BLANKET DESIGN

Region	Material	Heating
Armour	SS	12.8
First wall	D_2O	13
	SS	10.7
	D_2O	12.5
Multiplier	Pb	5.2
	H_2O	4.9
Breeder 1	SS	4.3
	H_2O	3.7
	SS	3.4
	Li_4SiO_4	10.7
	SS	2.8
	H_2O	0.7
Breeder 2	SS	2.3
	Li_4SiO_4	4.5
	SS	1.5
	H_2O	0.2
Breeder 3	SS	1.2
	Li_4SiO_4	2.5
	SS	1.0
	H_2O	0.1

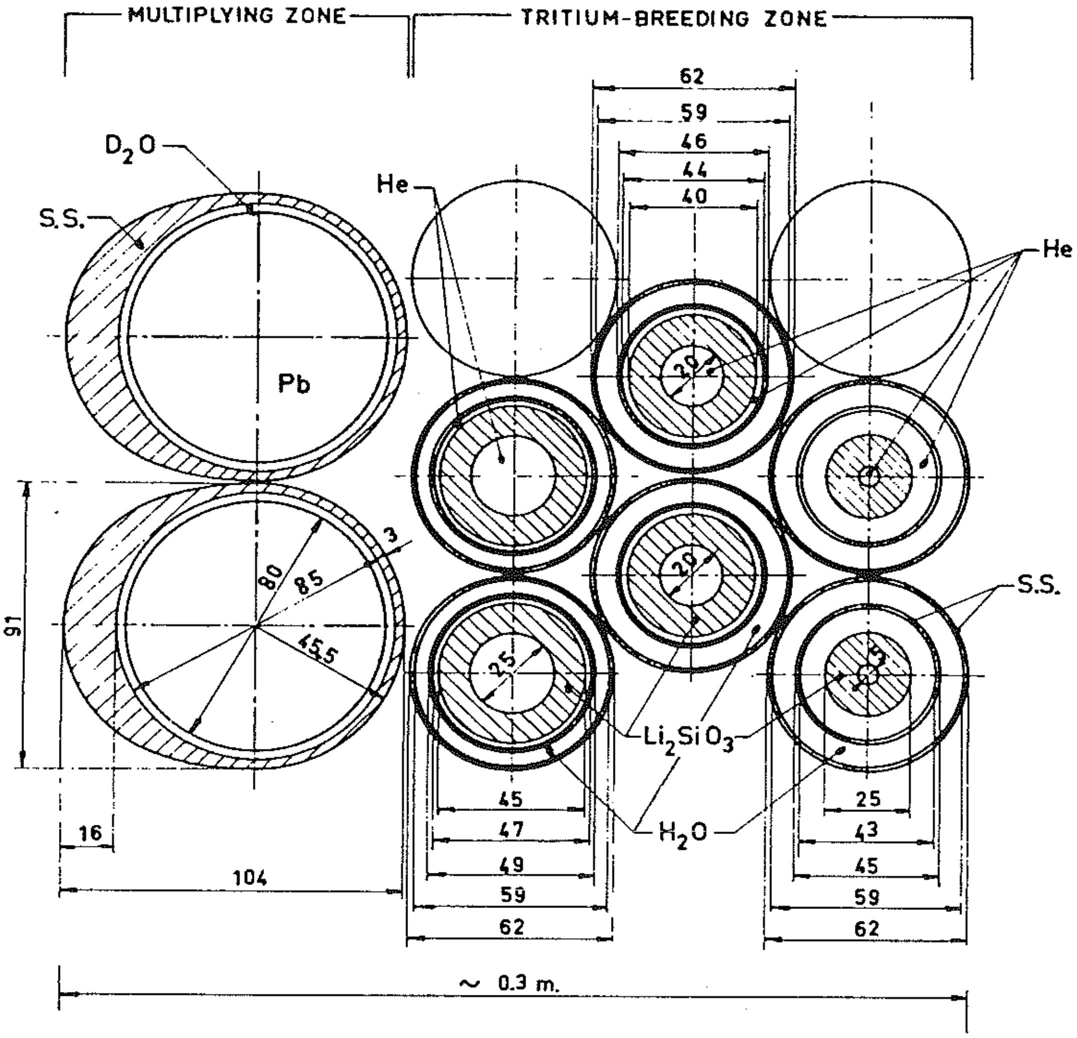


FIG.IX-9. Breeding blanket with solid breeder.

In both these liquid moderator designs, with heavy water coolant in the first-wall/moderator region, TBR appears to be high enough to achieve the required net value of 0.6 (assuming 60% coverage), according to a one-dimensional scale.

3.3. Time-dependent breeding ratio

Both the BIT/LM and BOT/SM reference designs contain a limited amount of breeder material. The high ^{6}Li burn-up in this material may lead to a decrease of TBR with operating time. The effect depends on both the level of lithium enrichment and the method used to confine the breeder. Breeding calculations were performed for the BOT/SM reference design for cases of natural and 30% enriched lithium silicate; the results are compared in Table IX-15. The breeding

TABLE IX-15. IMPACT OF ^{6}Li BURN-UP ON TRITIUM-BREEDING RATIO

Coolant: H_2O
Moderator: C
Multiplier: 5 cm Pb
Breeder: Li_2SiO_3

	Integral neutron wall load ($MW \cdot a/m^2$)		
	0[a]	2.3[b]	4.6[c]
(A) Natural lithium case			
Bank-1 BR	0.458	0.414	0.362
Bank-2 BR	0.306	0.298	0.281
Bank-3 BR	0.187	0.190	0.193
TOTAL BR	0.951	0.902	0.836
(B) 30% ^{6}Li enrichment case			
Bank-1 BR	0.553	0.543	0.533
Bank-2 BR	0.311	0.311	0.311
Bank-3 BR	0.179	0.180	0.181
TOTAL BR	1.043	1.034	1.025

[a] At start-up.
[b] 38% ^{6}Li burn-up for natural lithium, 15% ^{6}Li burn-up for 30% enriched lithium.
[c] 62% ^{6}Li burn-up for natural lithium, 27% ^{6}Li burn-up for 30% enriched lithium.

ratio in the natural lithium system deteriorates substantially at the end of the INTOR lifetime, while the 30% enriched system appears likely to maintain the initial breeding ratio. For this reason, 30% ^{6}Li enrichment was chosen for both reference designs.

Figure IX-10 shows the space-dependent tritium production rate in each tube bank of a BIT design [4]. The results for the heterogeneous treatment indicate the breeding degradation with depth inside the breeder tubes, which is significant owing to the self-shielding effect by ^{6}Li. The degree of non-uniformity of tritium production within the tubes is in contrast to the relative uniformity shown for the homogeneous treatment of the same blanket design.

The high local tritium production rates near the outer surface of the breeder tubes can lead to locally high ^{6}Li burn-up rates. This effect is seen in Fig. IX-11 for natural lithium in the BIT/LM concept. At the end of the reactor life of 6 $MW \cdot a/m^2$, the ^{6}Li burn-up rate reaches 80% (6% of the total lithium).

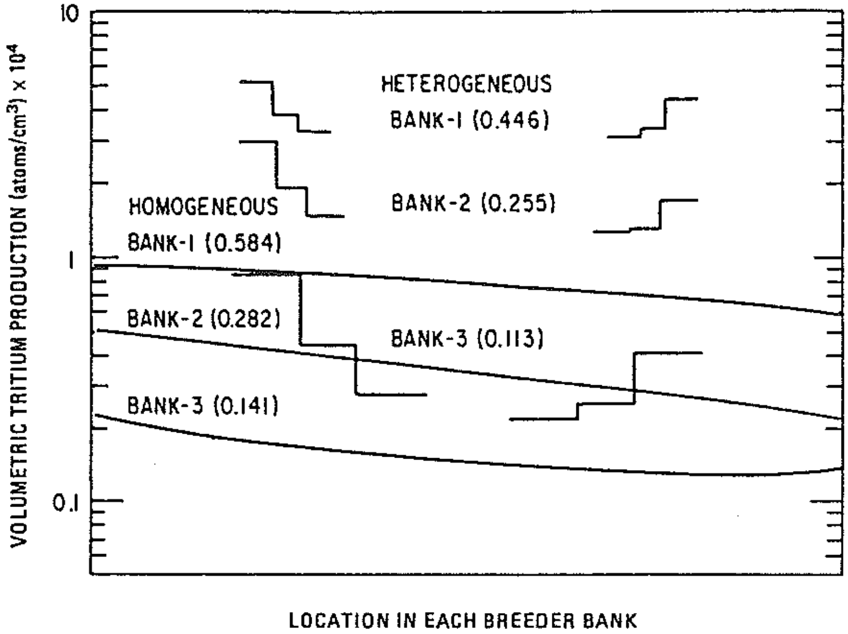


FIG.IX-10. Volumetric tritium production for BIT/LM design.

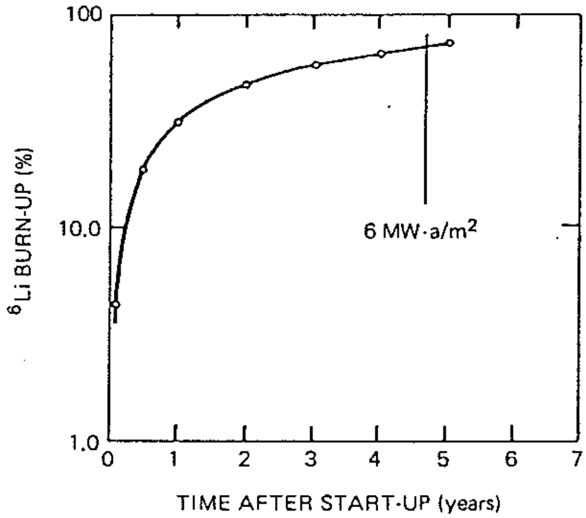


FIG.IX-11. Maximum local ^{6}Li burn-up for BIT/LM design. (Neutron wall load is 1.3 MW/m^2, plant availability is 100%, maximum burn-up at $t = 0$ is 0.0006 $cm^{-3}\cdot s^{-1}$, initial ^{6}Li concentration is 2.164×10^{21} atoms/cm^3 at 60% of theoretical density.)

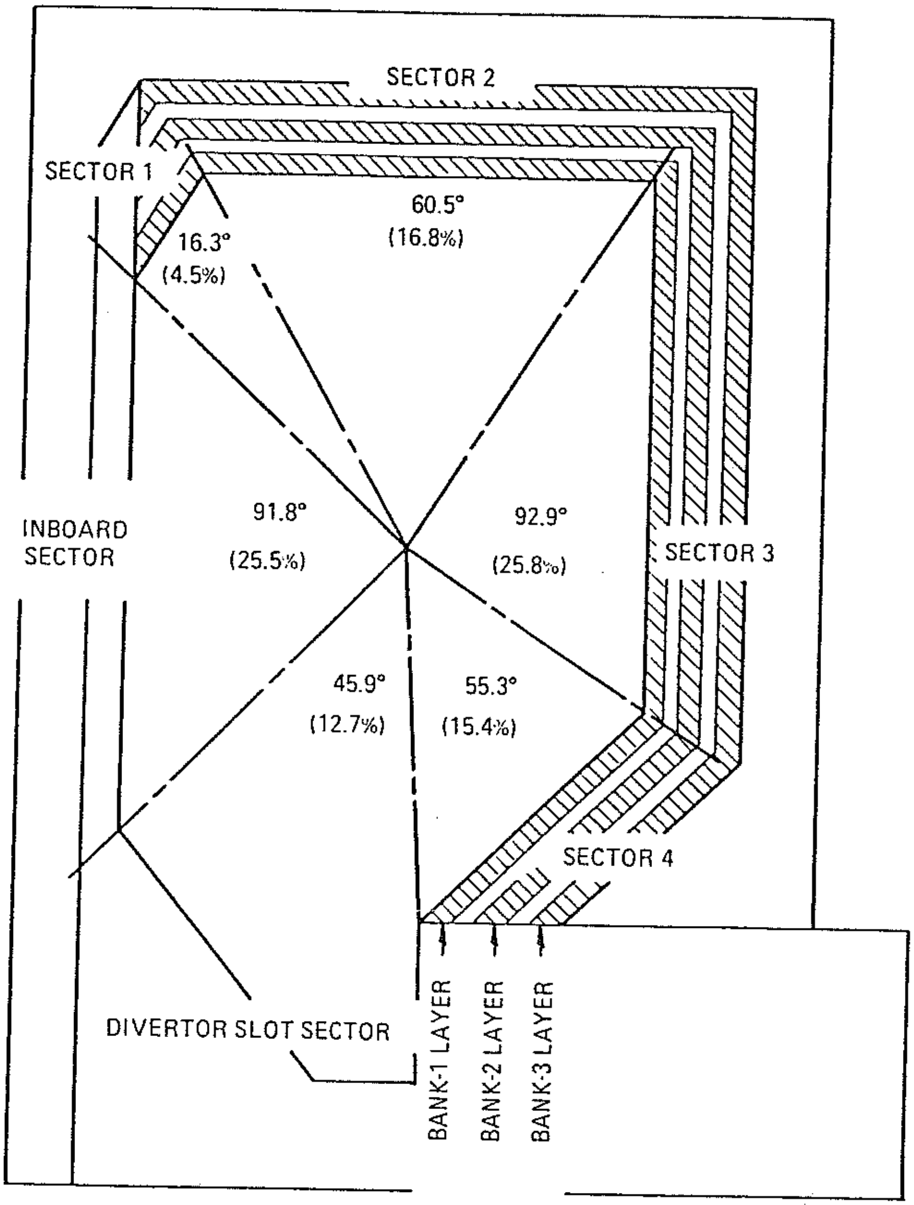


FIG.IX-12. Schematic diagram of model for Monte-Carlo analysis.

The other point of concern is the allowable local lithium burn-up, which was shown in Ref. [5] to be 15–20%. The microscopic ^{6}Li destruction rates were estimated to be 6.6×10^{-9} 1/s and 2.1×10^{-9} 1/s for natural and enriched lithium, respectively. Both cases appear to meet the design criterion. However, concern was expressed and further study is necessary.

The tritium-breeding ratio is also affected by the erosion of the first wall during reactor operation. A decrease of the first-wall thickness by 10 mm at the end of the lifetime may increase TBR by ~10% from its initial value. However, the effect of material re-deposition on the first-wall surface is unknown, and thus the possibility of TBR increase due to first-wall erosion requires further investigation.

3.4. Three-dimensional analysis

This section presents a three-dimensional tritium-breeding analysis [4] of the BOT/SM reference design based on a Monte-Carlo method. Figure IX-12 is a schematic diagram of the model used for the analysis which was carried out by the MORSE code. The spatial distribution of the neutron source accounting for the plasma MHD shift is represented as

$$f(r) = \left[1 - \left(\frac{r}{r_m}\right)^2\right]^2$$

where r is the source point distance measured from the shifted plasma centre, $r_m = R_m + S_m$, R_m is the magnetic axis major radius of 5.3 m, and S_m is the source shifting distance of 15 cm. The computation was performed for a one-sixth segment of the torus ($\theta = 0$ to $60°$). This segment contains: (1) one neutral beam duct with a rectangular opening dimension of 1.2 m (vertical) × 1.0 m (toroidal) at $\theta = 30°$; (2) one divertor slot opening with a rectangular opening dimension of 0.5 m (vertical) × 1.3 m (toroidal) at $\theta = 30°$; and (3) two one-half portions of divertor slots with the same dimension at $\theta = 0°$ and $\theta = 60°$.

The blanket region where the breeding material is placed is indicated in Fig. IX-12. The breeding zone is divided poloidally into four subzones (sectors 1, 2, 3 and 4). Each sector has been further divided into three layers of bank-1 (inner), bank-2 (middle) and bank-3 (outer) regions. The outboard material compositions and radial dimensions used are based on the reference BOT/SM design described in Table IX-9. The inboard blanket has a stainless steel armour of 1.5 cm, followed by a 0.6-cm-thick first-wall zone (same as in the outboard wall design). A 16.4-cm-thick inboard blanket with a material composition of 90% SS + 10% H_2O follows the first wall. In order to improve the statistics of the Monte-Carlo analysis, each blanket subzone of breeder or moderator region is homogeneously mixed, which does not change the one-dimensional TBR values.

Table IX-16 summarizes the breeding ratios of the individual zones, together with those of the sectors and bank layers. A comparison is also made with the one-dimensional analysis case. The numbers in parentheses stand for the statistical standard deviations as estimated by MORSE, with 20 000 neutron histories. Within an error estimate of ~1%, the net breeding ratio for the reference BOT/SM design is ~0.66, which is close to that anticipated from the one-dimensional analysis for a blanket coverage of ~60%. The actual ratio of the 3-D BR to the 1-D BR results in about 61% coverage.

TABLE IX-16. TRITIUM-BREEDING ANALYSIS BY MONTE-CARLO METHOD FOR THE REFERENCE BOT/SM DESIGN[a]

Zone breeding ratio		Sector breeding ratio		Layer breeding ratio		1-D layer breeding ratio
Sector 1/Bank 1	0.0199 (±4%)	Sector 1	0.0261 (±4%)	Bank 1	0.3890 (±1%)	0.6348
Bank 2	0.0053 (±8%)	Sector 2	0.1843 (±2%)	Bank 2	0.1908 (±1%)	0.3218
Bank 3	0.0008 (±25%)	Sector 3	0.3007 (±1%)	Bank 3	0.0795 (±2%)	0.1237
Sector 2/Bank 1	0.1077 (±2%)	Sector 4	0.1482 (±2%)			
Bank 2	0.0543 (±3%)					
Bank 3	0.0222 (±5%)					
Sector 3/Bank 1	0.1714 (±2%)					
Bank 2	0.0894 (±2%)					
Bank 3	0.0400 (±3%)					
Sector 4/Bank 1	0.0899 (±2%)					
Bank 2	0.0419 (±4%)					
Bank 3	0.0164 (±6%)					
Total:	0.6592 (±1%)		0.6593 (±1%)		0.6593 (±1%)	1.0803
T_6:	0.6520 (±1%)					
T_7:	0.0072 (±2%)					

[a] Number of neutron histories = 20 000.

TABLE IX-17. BREEDING RATIOS WITH AND WITHOUT INBOARD LEAD MULTIPLIER

	Case 1 Without multiplier[a]	Case 2 With multiplier[a,b]
Bank 1	0.309	0.368
Bank 2	0.142	0.163
Bank 3	0.050	0.054
NET	0.501	0.585

[a] Based on a one-dimensional ANISN calculation in a slab geometry.

[b] A 5-cm-thick lead zone is inserted between the inboard first wall (immediately behind the armour) and the inboard blanket.

The difference between 1-D and 3-D TBRs depends mainly on the interference between blanket sectors and inboard sector and the leakage through the divertor slot sector. This difference was assumed to be the same for the BIT/LM blanket design too.

The effects of neutron exchange between inner non-breeding and outer breeding parts of the blanket are demonstrated by a one-dimensional slab geometry analysis of a system configuration around the reactor mid-plane. On one side of the plasma region, the reference outboard BOT/SM blanket is placed, and the inboard non-breeding blanket described earlier is placed on the other side of the plasma. As a result, the breeding blanket coverage is exactly 50% of the total. Case 1 in Table IX-17 shows the breeding ratio based on this slab geometry analysis. The breeding ratio is less than that expected from the physical coverage (1.080 X 0.5 = 0.540, compared with 0.501 actually obtained). The effective coverage in this case results in only ~46%.

The reduction of system neutron amplification due to the absence of lead in the inboard blanket significantly degrades the breeding performance in the outboard blanket. The degradation is caused primarily by the relatively large neutron loss in the inboard section. In Case 1, the total neutron loss in the inboard section is 0.593, compared with the total system neutron multiplication of 1.36. In Case 2, an inboard lead multiplier is placed between the inboard first wall and the inboard blanket. The lead thickness is 5 cm, as in the outboard blanket. The breeding performance in the outboard blanket is improved with respect to Case 1. The major improvement is observable in the significant breeding enhancement in the first bank that is affected by the inboard blanket. Because of the softening of the neutron spectrum and the increased number of neutrons caused by the inboard lead multiplier, parasitic neutron absorption also increases to 0.611.

However, the multiplication gain of 0.138 in the lead reduces the net neutron loss in the inboard blanket to only 0.474, compared with 0.593 in Case 1. In fact, a large fraction of this difference (0.593 – 0.474 = 0.119) is effectively used for the breeding enhancement in the outboard blanket. The breeding ratio of 0.585 in Case 2 implies that the effective coverage for the slab geometry is raised to ~55%.

The above results suggest that an inboard neutron multiplier should be used for the INTOR design in order to enhance tritium production. The actual inboard blanket coverage is only ~25%, and thus the percentage gain would not be as large as in the cases discussed, but a moderate increase in breeding ratio is expected.

4. THERMOHYDRAULIC ANALYSIS

Thermohydraulic analysis includes calculations of temperature distribution in two regions, namely the first wall/multiplier and the breeder. Water coolant was chosen for both regions, but no interaction was assumed and each of them can be considered to be cooled by a separate circuit. For both the BOT/SM and BIT/LM reference designs the lead multiplier thickness is 5 cm, and in both designs the multiplier is sandwiched between the first wall and the second wall. The multiplier is assumed to contain no internal coolant channels, so the volumetric nuclear heat is removed by the first-wall and second-wall coolant panels. The differences in D_2O and H_2O cooling are negligible, and the thermohydraulic parameters are the same for both reference designs. In the breeder region the difference in temperature distribution in the breeder elements depends on the inner cooling of the elements in the BOT/SM design and on the outer cooling of the elements in the BIT/LM design. The results will be presented in parallel.

4.1. First wall and multiplier zone

The lead multiplier is located between the first- and second-wall coolant channels. The contacts between channels and lead may not be ideal, so a possible gap conductance was assumed between these regions.

Thermohydraulic calculations were carried out, based on the following heating rates:

Armour plate SS	15.6 W/cm^3
First-wall SS	13.6 W/cm^3
First-wall H_2O	14.0 W/cm^3
Multiplier	14.2–5.4 W/cm^3
Second-wall SS	4.9 W/cm^3
Second-wall H_2O	6.5 W/cm^3

A maximum lead temperature of 300°C was chosen, which is below the melting point. The coolant inlet and outlet temperatures were assumed to be 50°C and 100°C, respectively.

For a 70 mm lead multiplier segment, assuming a gap conductance of 4540 $W/m^2 \cdot K$, the maximum temperature exceeds the melting point of lead (327°C).

For the second set of calculations. the multiplier thickness was reduced to 50 mm, and the calculations were carried out with the same gap conductance. For this case, the maximum temperature of the multiplier was found to be 289°C, which is appreciably below the melting point of lead. Hence, this design was found to be acceptable. The assumed thermal conductance value can be obtained for a lead/steel interface at nominal mechanical pressure in the presence of gaseous helium. Even if perfect (infinite) thermal conductance were obtained at the interface, the maximum thickness of lead that could be cooled by a first wall and a second wall – for $T_{max} < 327°C$ – is only 70 mm.

For a design option in which the coolant channels near the first wall can be developed in the lead itself with only a thin protective cover [5], the permissible thickness of the multiplier without internal cooling increases up to 10 cm. However, the channels in this design can be damaged through a loss-of-coolant accident, and the design with a corrugated first-wall panel was therefore chosen. The neutronics optimization of the multiplier thickness of 5–7 cm applies only for the case of a light water coolant, as was shown by the neutronics analysis. In the case of a heavy water coolant, internal coolant channels are tolerable and the tritium-breeding ratio can be increased with increasing lead thickness. Further optimization is therefore necessary for the case with a heavy water coolant.

For the first-wall and second-wall coolant channel dimensions and the coolant temperature rise (50 K) used in these analyses, the required coolant velocity is 1 to 2 m/s for segments of the first and second wall. Hence, the pressure drop between the inlet and outlet of the coolant channels will be modest and is not a problem for the design.

4.2. Breeding blanket region

The breeding blanket region for the BOT/SM and BIT/LM designs is cooled by water with an outlet temperature of 100°C. To maintain the breeder material in the desired temperature range for operation, thermal conductance between the breeder and a structural tube is needed. In both designs a separate helium gas gap was considered for this purpose. The difference between these designs is in the location of the coolant tubes. In the BOT/SM design, the coolant is located in an inner tube surrounded by breeder material, with a thin-walled tube between the breeder and the moderator. In the BIT/LM design, the breeder is located inside the inner tube of an annulus filled with water coolant. The liquid moderator is located outside the outer tube.

TABLE IX-18. NEUTRON HEATING RATES AND DIMENSIONS OF BREEDER CYLINDERS AND COOLANT CHANNELS FOR BOT/SM BLANKET DESIGN

Row	Coolant tube diameter (inner)	Coolant tube diameter (outer)	Breeder radius (outer)	Neutron heating rate
1	10.0 mm	12.5 mm	19.0 mm	19.2 W/cm^3
2	10.0 mm	12.5 mm	21.5 mm	9.9 W/cm^3
3	10.0 mm	12.5 mm	34.0 mm	2.6 W/cm^3

4.2.1. BOT/SM reference design

It was assumed that the moderator and the breeder contain their own coolant systems in this design. The breeder itself consists of three separate regions, which can be considered as three rows of breeder elements with different geometries. To simplify the analytical calculations, only one-dimensional thermohydraulic calculations were performed. Based on the results of neutronics analyses, the thermophysical properties of the material and coolant flow conditions, the dimensions of the various regions were calculated and are given in Table IX-18.

One of the important considerations in estimating the breeder dimensions has been the temperature limitations on the Li_2SiO_3 solid breeding material for in-situ recovery of tritium. These temperature limits, in conjunction with the thermophysical properties of the breeder and the coolant inlet and outlet conditions, present severe thermohydraulic problems in breeder blanket design. To keep the temperature distribution in the breeder between 400°C and 600°C, with coolant inlet and outlet temperatures of 50°C and 100°C respectively, appropriate temperature gradients must be maintained between the coolant tubes and the breeding blanket regions. To minimize the adverse effects of any thermal insulator on the tritium-breeding ratio, the thickness of the thermal insulator must be small. For this study, a separate helium gas gap between the coolant tubes and the breeding blanket was assumed. The estimated thickness of the helium gap for the three regions is shown in Table IX-19.

The differences in the gap thicknesses at the coolant inlet and outlet are due primarily to the 50°C difference in the coolant temperature. However, it may not be practical to fabricate breeder and coolant tubes providing a precise gaseous helium gap, because the manufacturing tolerances will almost certainly exceed the differences in the gap thickness values shown.

From the viewpoint of blanket temperature control during reactor operation, it would be desirable to vary the thermal conductivity across the gap. One method studied was to vary the pressure of the insulating gas layer. It has been reported [6]

TABLE IX-19. REQUIRED WIDTH OF BREEDER-TO-TUBE HELIUM GAP FOR THE REFERENCE BOT/SM BLANKET DESIGN

Row	Gas gap thickness (mm)	
	Coolant inlet end	Coolant outlet end
1	0.43	0.39
2	0.56	0.51
3	0.65	0.60

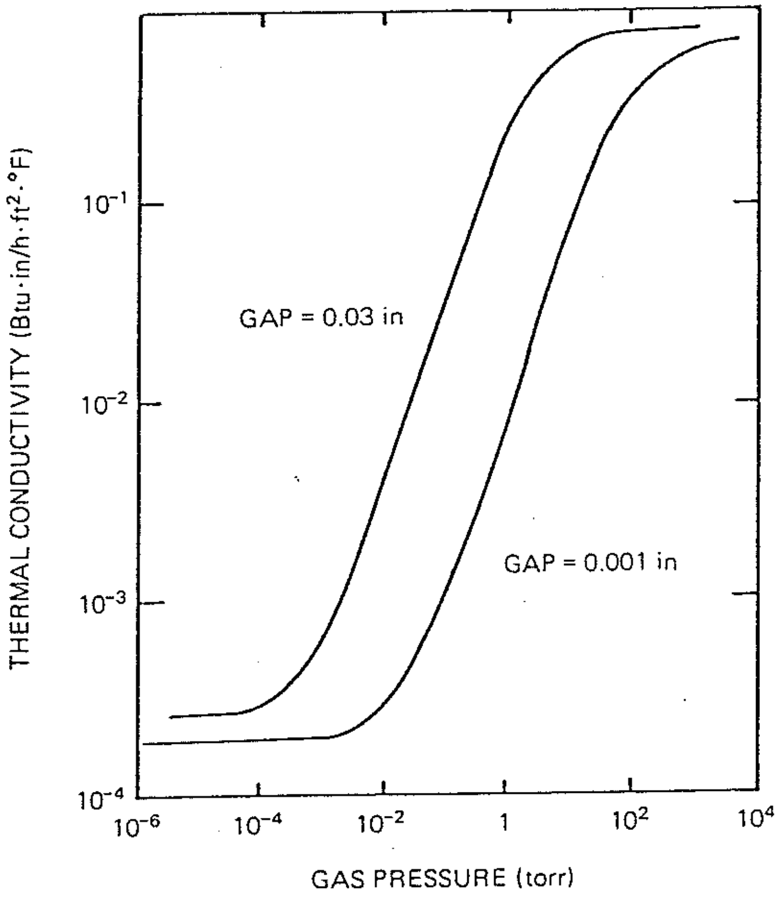


FIG.IX-13. Theoretical effect of helium gas pressure on thermal conductivity.

TABLE IX-20. PARAMETERS OF BREEDER AND MODERATOR COOLANT TUBE FOR THE REFERENCE BOT/SM BLANKET DESIGN

	Breeder			Moderator
	Region 1	Region 2	Region 3	All regions
Velocity (m/s)	0.59	0.46	0.39	0.1
Pressure drop (kPa)	7 (1 lb/in^2(abs))	7	7	negligible

TABLE IX-21. TEMPERATURE DISTRIBUTION IN LITHIUM CHANNELS

Row		r_0	r_1	r_2	r_3
1	Dimensions (mm)	20	28	29	30
	Temperature (°C)	590	430	44	38
2	Dimensions (mm)	14	27	29	30
	Temperature (°C)	607	476	35	33
3	Dimensions (mm)	5	26.5	29	30
	Temperature (°C)	611	442	34	32

that the thermal conductivity of gases is independent of pressure above 1 torr for heavy gases, and above 20 torr for light gases. A typical set of data from Ref. [6], shown in Fig. IX-13, indicates drastic changes in the thermal conductivity values, of between 10^{-4} torr and 1 atmosphere. These data indicate that it may be possible to control the gap conductance by controlling the pressure. However, the data are based on operating conditions near cryogenic temperatures. The question of the control of breeder temperature distributions by alternative means should be explored further during subsequent studies.

For the BOT/SM concept, the tritium barrier is a thin steel jacket which surrounds the breeder cylinder. To reduce tritium permeation through the jacket, its temperature should be kept below about 400–450°C. Since the breeder cylinder outer surface temperature is 600°C, achieving a temperature lower than 600°C for the jacket requires that the temperature gradient be positive from the interior of the moderator to the jacket. This, in turn, requires that the interior of the moderator be cooled by small-diameter coolant tubes which extend through the module and connect to the inlet and outlet plenums at the module sides.

Low temperatures for the jacket are ensured by the introduction of low-pressure "clean" helium into the moderator cavity (as for the multiplier cavity) in order to obtain good thermal conductance at the coolant/tube moderator and moderator/jacket interfaces. For the reference blanket design, the small temperature rise across these two gaps, combined with the low volumetric heating and good thermal conductivity of the graphite neutron moderator, result in an estimated jacket temperature of 450°C.

Cooling of the moderator does not present any serious problems and can be achieved with an additional set of coolant tubes in the moderator region. The coolant velocities for the moderator and blanket regions are less than 1 m/s and the pressure drop is quite small. Table IX-20 summarizes the coolant tube parameters for the breeder and moderator regions.

4.2.2. BIT/LM reference design

The lithium region in this case consists of three rows of water-cooled channels. The nuclear heating rates are different in the rows and they also change along the length of the channels. Appropriate channel dimensions were chosen to maintain the operating temperature of the breeder material in the range of 400–600°C.

The lithium elements are hollow cylinders with radii r_0 and r_1 (see Fig. IX-2) and a height of 30 mm; they are located in series in stainless steel tubes (r_3, r_4). The gap between r_2 and r_3 is filled with helium at 0.1 MPa pressure, which provides the required thermal conductance. It is possible to change the breeder material temperature by changing the gap thickness. The stainless steel tube is cooled from outside by water with a temperature of 30°C. It is desirable to increase this temperature up to 100°C at the outlet, to reduce the size of the heat exchanger. However, heat transfer across the moderator/coolant interface should be analysed. The breeder temperature can easily be compensated by increasing the helium gap.

The optimized dimensions of the lithium channels and the calculated temperature distributions within these channels for three rows of channels are given in Table IX-21. Nuclear heating corresponds to that given in Table IX-14.

5. ELECTROMAGNETIC CONSIDERATIONS

The electromagnetic forces in the breeder and moderator regions are small as compared with coolant pressure, and the two reference blanket designs are adequate to withstand them. However, as indicated in Ref. [3], the neutron multiplier cannot be fabricated as a solid layer unless it is supported by additional structural material (SS) of 1–2 cm total thickness. This additional material decreases the blanket tritium-breeding ratio. Its use can be avoided by subdividing the multiplier zone into smaller elements without electrical connections, but in

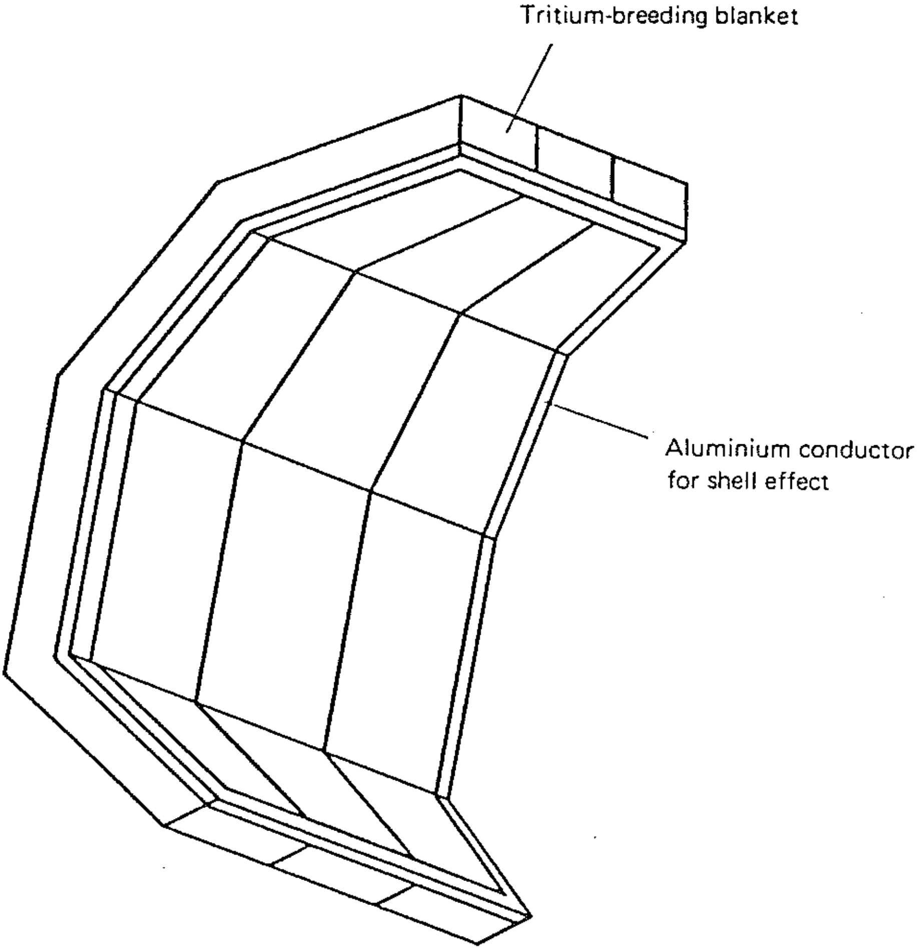


FIG.IX-14. Aluminium conductor circuit for shell effect.

this case an additional electrical circuit should be installed in the first-wall/ multiplier region.

The main concern for electromagnetic effects in the blanket is due to the requirement for a 50 ms shell time for plasma stabilization. The first-wall/blanket region should contain a passive shell for this purpose. Stresses resulting from plasma disruptions as well as maintenance considerations do not permit the lead multiplier to be used for this purpose. One possible solution [3] is the installation of an electrical circuit in the blanket (Fig. IX-14). The maximum electromagnetic force on the circuit during plasma disruption was estimated to be 2 MPa. The electrical circuit, made from aluminium, is encased by stainless steel and supported by the blanket vessel side-wall and the blanket sector support structure. The electromagnetic forces on the conductor are transmitted to the support structure of the blanket through its side-walls.

Another option has been developed where the neutron multiplier is arranged inside tubes (Fig. IX-9). (Ref. [2] should be consulted for details of electromagnetic considerations.) In this case, two pairs of lead rods (top and bottom) are replaced by aluminium bars, water cooled and clad in stainless steel as the other multiplier rods. These two pairs of bars are connected by two flat-plate aluminium conductors, one at each end of the blanket segment, to form a rectangular conducting loop.

6. STRESS ANALYSIS

6.1. Blanket internal structure

The general structural arrangement and the mechanical stresses in the structure for the two reference blanket designs were not studied in detail, and only general considerations are discussed. The preferred design approach for the first wall, neutron multiplier and second wall for the two concepts is to integrate them structurally, as well as to provide for their coolant requirements through a common system. This approach is considered the most efficient method of withstanding electromagnetic and gravity loads.

The stresses due to internal pressure of the blanket vessel for the BOT/SM concept (0.1 MPa) can easily be accommodated by the vessel walls. The specified coolant pressure in the blanket region for this concept (0.7 MPa) is well within the stress limits for the selected wall thickness of 0.125 mm.

An evaluation of the requirements for the breeding zone internal structure of the BOT/SM concept indicated that the best approach was to use internal frames, connected to the second wall behind the multiplier and to the rear wall of the breeding zone. The plane of the frames should be perpendicular to the first wall and should extend toroidally, i.e. the frames should be parallel to the breeder and coolant tubes. If the frames are also aligned with and connected to the structural elements in the multiplier zone, and are connected to the module sidewalls, the resulting module structure is inherently rigid, yet efficient in its use of steel structure.

6.2. Coolant tubes in the breeder region

For the BIT concepts, the coolant is contained in an annulus formed by two tubes extending over the width of the module. The inner tube is subjected to a uniform coolant pressure on its outer surface, which acts to buckle (collapse) the tube. Although the breeder cylinder may contact the tube inner surface, the breeder cylinder should not be used as a structural element in the design. Instead, the tube should be fabricated with longitudinal stiffening ribs equally spaced circumferentially. External ribs are preferred since internal ribs would complicate breeder cylinder installation in the tube.

If solid moderators are used for the BIT or BOT concepts, the support of the coolant tube next to the moderator is provided by the moderator itself. Thus, adjacent tubes are not required to be connected, which considerably simplifies the breeder zone internal structure.

A nominal wall thickness of 1.25 mm was adopted for the 10-mm-ID coolant tube in the reference BOT/SM design. Even though the hoop stress due to pressure is lower than the value set by S_m limits by a factor of about 50 for the present INTOR coolant pressure (0.7 MPa), the wall thickness was not reduced. The reasons for this are: (1) reduced wall thickness could lead to problems in welding the tubes to the plenums, and (2) the present wall thickness can easily accommodate any future change in INTOR coolant pressure.

A thickness of 1 to 2 mm was assumed for the coolant inner and outer tubes in the BIT/LM design. A nominal wall thickness of 1.25 mm meets the S_m limits for these tubes only to a design pressure of 4.1 MPa. If the coolant pressure should be increased, up to as much as 15 MPa (which is considered for some power reactors), the tube thicknesses must also be increased, which would result in a reduction of the tritium-breeding ratio.

6.3. Module walls

In the two reference designs the liquid coolant of about 0.7 MPa is contained within tubes. The solid moderator region of the BOT/SM concept is pressurized with ~0.1 MPa helium for good thermal conductance between breeder jacket and graphite moderator. Calculations show no design difficulties at this pressure level. The module walls must be sized either as thick plates (up to several centimetres thick, depending on the plate areas) or as rib-stiffened thin-wall plates.

The BIT/LM concept will also have a low internal pressure, and thus module walls similar to those of the BOT/SM concept can be used if the coolant outlet temperature is kept well below 100°C or if the liquid moderator surrounding each coolant is contained by a tube instead of by the module walls. If the coolant outlet temperature in the reference BIT/LM design (Fig. IX-2) approaches or equals 100°C, a higher pressure level may be required inside the module to prevent local boiling of the moderator at the surface of the higher-temperature end of the coolant tubes.

7. TRITIUM RECOVERY

7.1. General considerations

Tritium recovery from solid tritium-breeding materials has been identified as a key factor in establishing the viability of the solid-breeder concept and an important consideration in the selection of the primary candidate materials. In-situ tritium recovery from blankets is the most desirable method.

Tritium recovery from the blanket should take place at tritium concentrations of 0.1 – 10 ppm (wt) in the Li_2SiO_3. The most reasonable temperature of recovery is 400 – 600°C, and a grain size of less than ~1 μm is required.

The emphasis on the characteristics of the microstructure of the solid breeding materials selected and the concern about radiation-induced sintering arise primarily from the tritium recovery requirements. Also, the blanket design concepts are greatly influenced by the constraints imposed by the tritium recovery schemes.

In the proposed INTOR blanket concepts, the tritium generated in the solid breeder is removed by a low-pressure helium purge stream circulating through narrow gaps in the breeder cylinders. Tritium recovery can be performed continuously.

7.1.1. Continuous tritium recovery

For continuous tritium recovery it is necessary that all the breeder elements are kept at a temperature above the minimum tritium recovery temperature limit of 400°C. The upper temperature limit is determined by the necessity to secure long-term stability of the material. The continuous mode of recovery was chosen as a reference case.

7.2. Kinetic mechanism of tritium recovery

The bred tritium must undergo five steps in the tritium recovery process for the INTOR blanket concept:

(a) Tritium bulk diffusion in grains
(b) Recombination of OT (OH) groups, with formation and desorption of T_2O (HTO) at the grain surface
(c) Migration of water (HTO or T_2O) through the interconnected grain boundary pores to the particle surface
(d) "Percolation" through the pores in the packed bed of particles
(e) Convective mass transfer out of the blanket in the helium processing stream.

Determination of the process limiting the removal of tritium will permit to evaluate the optimum operating conditions for lithium material in the lithium zone of the blanket, and to select the structure of a lithium element and the temperature conditions of irradiation.

Investigations have shown that post-irradiation tritium recovery from irradiated lithium compounds can be accomplished. For low-temperature (50–100°C) irradiation to levels of 10^{16} to 10^{18} T/cm^3, approximately 99% of the tritium was recovered after a one-hour anneal to 600°C [7].

The tritium recovery kinetic mechanisms can be considered in terms of solid acidic and basic inorganic lithium compounds. Further investigations at higher temperatures and higher fluences are required to demonstrate the tritium release kinetics from ceramic breeding materials under the INTOR conditions. In Refs [7–9], the irradiation effects were discussed.

7.3. Radiation effects on tritium recovery

Radiation-induced microstructural changes in the solid breeding materials may substantially alter their tritium release characteristics:

(a) Tritium trapping in grains
(b) Helium trapping in grains
(c) Sintering leading to pore closure
(d) Restructuring and grain growth.

7.3.1. Tritium trapping

Tritium trapping at radiation-induced defects such as cavities may be substantial. Evidence for trapping of hydrogen isotopes in various materials is obtained from ion-bombardment studies. An increase in the minimum blanket temperature may be required to overcome trapping.

7.3.2. Helium trapping

Helium trapping at nuclear-induced reaction sites may be substantial. An increase in the minimum blanket temperature may be required to recover helium and to prevent helium trapping.

7.3.3. Radiation-induced sintering

Radiation-induced sintering could lead to pore closure, which would severely affect the gas-phase tritium transport, i.e. grain boundary migration or percolation. The effects of radiation on the sintering characteristics of the candidate breeding materials have not been investigated. However, the thermal sintering characteristics of stable oxides are generally similar to those of the candidate materials. Although temperatures in excess of $0.6 - 0.8\ T_m$ are required before significant thermal sintering occurs, neutron radiation typically enhances the sintering characteristics and lowers the temperatures at which sintering is observed.

7.3.4. Restructuring and grain growth

Since the calculated diffusive tritium inventory varies as the square of the grain size, significant grain growth would lead to higher tritium inventories. However, grain growth is expected to occur predominantly in the highest temperature regions (0.6 T_m or greater) where the diffusive tritium inventories should be lowest.

7.4. Tritium inventory in the blanket

In addition to the contribution of the kinetic mechanisms listed in Section 7.2, the tritium inventory in the solid breeder is dependent upon the tritium solubility in the grains at the equilibrium T_2O pressure in the gas phase. Two ideal limiting cases determine tritium inventory. In one method it is assumed that the tritium inventory is diffusion-controlled. Since the tritium concentration at the grain edge is usually assumed to be zero, the calculated tritium inventory is obviously lower than the true one.

Another method assumes chemical equilibrium, with fixed tritium for T_2O pressure in the gas phase, and uniform tritium concentration throughout the blanket. Since this model does not account for concentration gradients, the tritium inventories are underestimated. The tritium inventory is assumed to be the sum of a diffusive component and an equilibrium or "solubility" component.

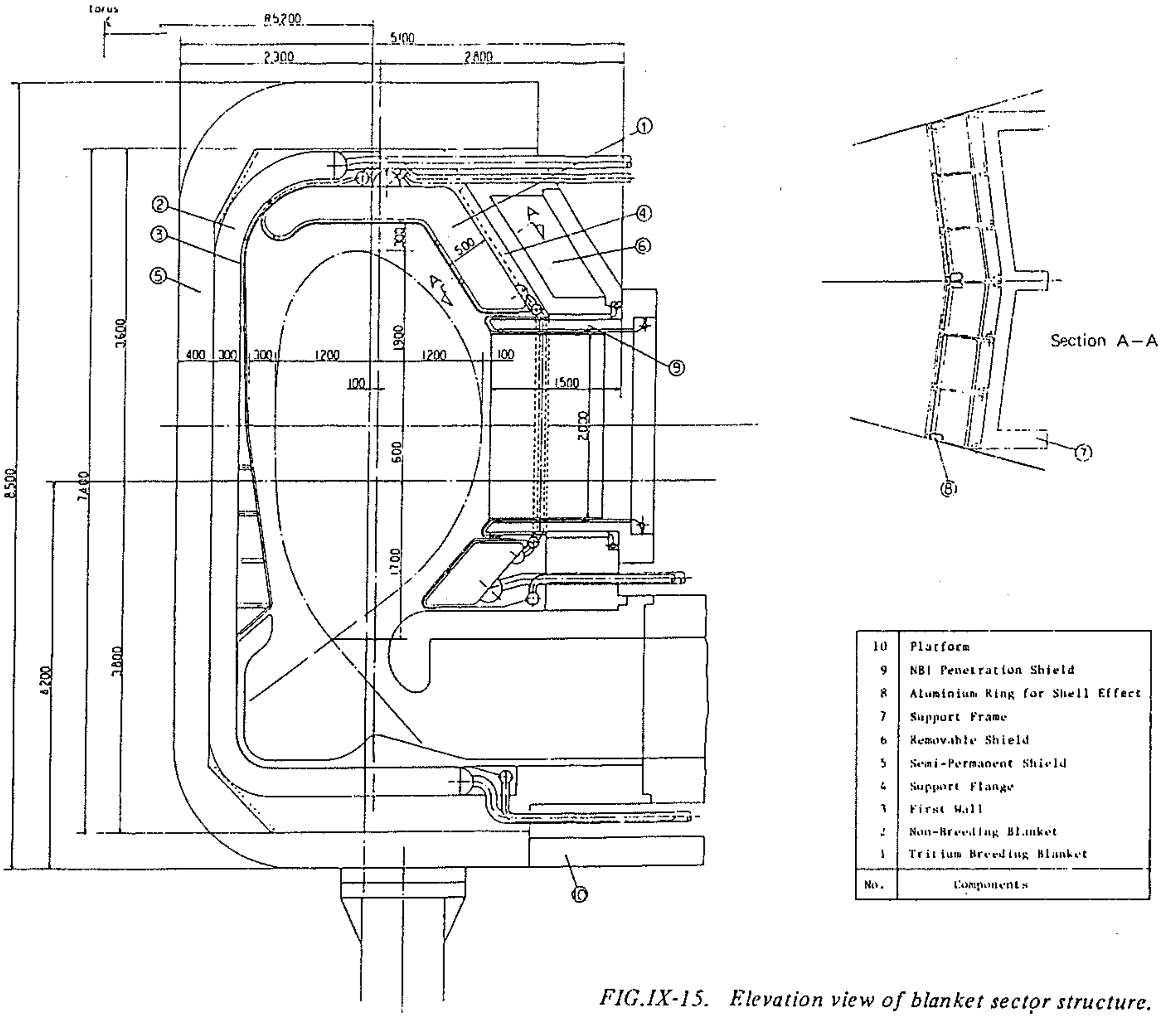
The total blanket tritium inventory (not taking into consideration radiation effects) was assumed to be up to 200 g. Theoretical estimates have shown that the total blanket tritium will be increased by radiation effects to values of the order of 0.5–1 kg.

8. MECHANICAL DESIGN

The mechanical designs for the two reference tritium-breeding blanket concepts were developed on the basis of results and evaluations discussed in the previous sections. An alternative design of a breeding blanket using Li_2O without a moderator [3] is described in Section XXI-4.

8.1. General arrangement

The blanket was assumed to occupy the outboard and top parts of each of the twelve sectors. It was assumed that all penetrations, including injector ports, test modules and stations, require some chamber surface in the blanket region, but do not change the local blanket parameters. Each of the twelve blanket sectors can be individually installed in or removed from the reactor. The effective



No.	Components
10	Platform
9	NBI Penetration Shield
8	Aluminium Ring for Shell Effect
7	Support Frame
6	Removable Shield
5	Semi-Permanent Shield
4	Support Flange
3	First Wall
2	Non-Breeding Blanket
1	Tritium Breeding Blanket

FIG.IX-15. Elevation view of blanket sector structure.

coverage of the plasma chamber was assumed to be about 60%, including the larger penetrations. As an example, an elevation view of a typical blanket design (without moderator) is shown in Fig. IX-15.

In both reference concepts the first wall and lead multiplier regions have a coolant circuit separated from the breeder region circuit. These regions are separated by the second wall located immediately behind the multiplier. The arrangement of the breeder and coolant within the breeding zone is governed by the requirement that the breeder temperature must be between 400°C and 600°C for the two reference designs.

8.2. BOT/SM reference blanket design

An isometric view of a reference BOT/SM blanket sector structure is shown in Fig. IX-1. The blanket module design integrates the structure of the first wall, multiplier and breeding zone. The stainless steel first wall consists of a thick plate and a corrugated skin which contains the first-wall coolant. The first-wall panels serve as the plasma-side containment for the neutron multiplier, and the cooling system of the panels removes part of the volumetric heat of the multiplier.

The containment at the back face of the multiplier is also an actively cooled corrugated panel (second wall), which removes the remainder of the multiplier's volumetric heat. The first wall and second wall are joined by structural elements extending through the 5-cm-thick multiplier. They act as shear webs to combine the two panels structurally into a relatively deep two-cap beam. The panels, together with the module side-walls and end-walls, form a pressure boundary around the multiplier. Low-pressure helium is introduced into this zone to provide good thermal conductance at the multiplier/coolant panel interfaces.

The lithium silicate in the breeding zone is formed in cylinders around single-wall steel coolant tubes. There are three separate rows, or banks, of breeder cylinder/coolant tube assemblies which are separated radially within the zone. The axes of the cylinder/tube assemblies extend toroidally across the full module width. The solid graphite neutron moderator is located between the banks, and between the third bank and the rear wall of the module. Separate, small-diameter coolant tubes cool the moderator.

A thin metal tube (jacket) surrounds each breeder cylinder. This jacket provides a pressure boundary between the helium purge gas flowing through the breeder cylinder and the "clean" helium filling the remainder of the breeding zone and the multiplier zone. This helium provides good thermal conductance between the moderator and its coolant tubes, and between the moderator and the jackets. As a result, the jackets are at a relatively low temperature during reactor operation and thus act as low-permeability barriers against tritium migration from the purge gas into the graphite.

The coolant inlet and outlet temperatures are 50°C and 100°C. The coolant is pressurized to 0.7 MPa (100 lb/in^2(g)). The moderator coolant tubes and breeder coolant tubes are connected to the coolant inlet and outlet plenums located at the module sides (in the poloidal plane). These plenums are also connected to the first wall and the second wall. At the rear of the blanket the coolant plenums are enlarged, to serve as manifold regions. These manifolds are connected at intervals (poloidally) to large-diameter coolant lines which extend through the bulk shield behind the module.

Helium purge gas inlet and outlet plenums are located between the coolant plenums and the breeding zone. At each breeder cylinder, the walls of these narrow plenums are welded to the end of the jacket around each cylinder and to the outer surface of the coolant tube inside the cylinder, thus completing the helium purge gas pressure boundary. The purge gas travels along the breeder cylinder through several narrow gaps extending radially through the cylinder. Oxygen of low partial pressure in the helium of ~1 atm pressure reacts with the free tritium at the breeder particle surfaces to form T_2O and HTO, which enter the purge gas stream. The purge gas plenums are connected to small-diameter lines passing through the bulk shield.

The end walls and the rear wall of the module are of a stiffened sheet metal construction, adequate to contain the 1 atm pressure of the "clean" helium in the breeding zone. They are welded to the side walls and to the first wall and second wall, forming separate pressure-tight multiplier and breeding zones. Actively cooled internal frames within the breeding zone connect to the second wall and breeding-zone rear wall. These frames are in line with the structural elements of the multiplier. All the walls, coolant panels, structural elements and internal frames in the module assembly thus form an efficient, integral structure to withstand gravity, seismic, pressure and electromagnetic loads which act on the module components.

Each module is connected to the bulk shield through lugs on the module rear wall at its four corners. This minimum number of attachments to the shield, together with the small number of coolant and helium lines from each module, simplify the removal and replacement operations to be performed by remote maintenance equipment if blanket or first-wall failure should occur. The first-wall and breeding blanket are designed to last for the full design life of the reactor without requiring renovation or maintenance.

8.3. BIT/LM reference blanket design

A cross-section of a typical BIT/LM blanket is shown in Fig. IX-2. The blanket is integrated with the first wall, but has two different coolant circuits for the multiplier and breeder zones. The lead multiplier and lithium zones are enclosed in a sealed vessel. The lead zone of each blanket segment is composed of separate units with channels for heavy water coolant. The outer wall of the blanket consists of two vertical plates, 2 mm thick, connected by a series of horizontal plates of the same thickness. The lead zone frame is attached to the shield with ties passing through the lithium zone. Inside the lithium zone, three rows of tubes are arranged which are used as channels for cylindrical breeder material elements. Each lithium channel is a circular section tube with ribs for providing gas gaps between the tube and the breeder material. Helium purge gas at a pressure of 0.05 MPa is slowly pumped through the channels. The tubes are cooled by water flowing through the inter-channel space. Water and helium lines which are formed by a tube to permit the use of pressurized water coolant are brought outside the cryostat, along the edges of the blanket sections, and pass through the shield. The lead zone consists of 10-cm-thick units with 4-mm-spaced cooling channels. The outlet temperature of the heavy water coolant is 100°C and the maximum lead temperature is 270°C. One of the possible options for the BIT/LM design was proposed in Ref. [2] and is shown in Fig. IX-9. The blanket consists of series of tubes placed in the toroidal direction. The tubes are about 1.5 m long in order to enable blanket segmentation. The blanket consists of two parts: a row of tubes facing the plasma and acting as first wall, and containing neutron multiplier; and three rows of tubes containing breeder material cooled by water, placed at the rear side of the blanket region.

The first-wall tube thickness is varying along its circumference, from 16 mm in front of the plasma to 3 mm on the opposite side. The non-uniform wall thickness takes into account the erosion of the front parts of the tubes and permits high neutronic performance. The lead rods in the tubes have a diameter of 80 mm and are cooled by heavy water in the cooling ducts between tubes and multiplier. The design of the breeder tubes with water moderator is similar to that described above for the reference BIT/LM design.

A choice between the two proposed BIT/LM designs can be made after more detailed consideration.

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PANEL PROCEEDINGS SERIES

INTERNATIONAL TOKAMAK REACTOR
Phase One

REPORT OF THE
INTERNATIONAL TOKAMAK REACTOR WORKSHOP
ORGANIZED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
AND HELD IN SEVEN SESSIONS IN VIENNA
DURING 1980 AND 1981

INTERNATIONAL ATOMIC ENERGY AGENCY
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