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Abstract

A low technology high tritium breeding blanket concept was developed for the INTOR design. The main function of this low technology blanket is to produce the necessary tritium for INTOR operation with minimum first wall coverage. The INTOR first wall, blanket, and shield are constrained by the dimensions of the reference design and the protection criteria required for different reactor components and dose equivalent after shutdown in the reactor hall. It is assumed that the blanket operation at commercial power reactor conditions and the proper temperature for power generation can be sacrificed to achieve the highest possible tritium breeding ratio with minimum additional research and developments and minimal impact on reactor design and operation. In addition, several other factors have been considered, including safety, reliability, lifetime, fluence, number of burn cycles, simplicity, cost and development issues. A wide variety of blanket design concepts was evaluated in this study. A set of blanket evaluation criteria has been used to compare possible blanket concepts. Six areas: performance, operating requirements, impact on reactor design and operation, safety and environmental impact, technology assessment, and cost have been defined for the evaluation process. A water-cooled blanket was developed to operate with a low temperature and pressure, which simplify the design and improve the reliability. The developed blanket contains a 24 cm of beryllium and 6 cm of solid breeder (Li_2O, $LiAlO_2$, or Li_4SiO_4) both with a 0.8 density factor. This blanket provides a local tritium breeding ratio of $\sim$2.0. Also, the water coolant is isolated from the breeder material by several zones which eliminates the tritium buildup in the water by permeation and reduces the chances for water-breeder interaction. This improves the safety and environmental aspects of the blanket and eliminates the costly process of the tritium recovery from the water.

INTRODUCTION

The main function of the INTOR blanket is to produce the tritium required for the operation with a minimum first wall coverage. The INTOR first wall, blanket, and shield (FWBS) are constrained by the parameters of the reference design and the protection criteria required for different reactor components and dose equivalent after shutdown in the reactor vault. Also, it is assumed that the blanket operation at commercial power reactor conditions and the proper temperature for power generation can be sacrificed to achieve the highest possible local tritium breeding ratio (TBR) with minimum additional R&D and minimal impact on reactor operation. In addition, several other factors are considered in the FWBS study including safety, reliability, lifetime, fluence, number of burn cycles, simplicity, cost, and development issues.

A wide variety of blanket concepts was evaluated in the study. This survey and the key features for each concept are summarized in this paper. The water-cooled blanket developed to operate with a low temperature and pressure is also presented.

Tritium Breeding Criterion

The INTOR conceptual design limits the tritium breeding region to 60–80% of the equivalent first wall coverage. The 60% coverage corresponds to the outboard and top sections of the first wall assuming some allowances for testing space. The 80% coverage permits blanket coverage on the inboard section; however, any impact on shielding efficiency of the inboard section, reactor operation, or maintenance requirements must be minimized. The 60% coverage constraint requires a local TBR greater than 1.7 to eliminate the need for an external tritium source. The use of special material in the inboard and bottom sections of the first wall to multiply and reflect the neutrons to the tritium breeding blanket can reduce the local tritium breeding requirements. A thick layer 15 to 30 cm of beryllium, lead, or carbon in the front section of the nonbreeding blanket can also increase the net tritium breeding ratio by $\lesssim 0.4$. However, several design considerations discourage the use of such materials for the inboard section.

Lithium metal and lithium compounds have been considered for tritium breeding in fusion reactors.[1,2] The lithium metal has an upper theoretical limit of < 1.8 tritons per fusion neutron assuming an infinite medium. Engineering considerations dictate the use of a finite blanket thickness with a significant amount of structural materials to contain the breeder and the coolant. In all realistic blanket concepts,[3] the calculated tritium breeding ratios for a liquid lithium blanket with a steel structure are much lower than the upper theoretical limit. For tokamak reactors, the highest reported TBR is less than 1.6.[4] So, it appears that an idealized lithium blanket with a steel structure for INTOR does require external tritium source for tritium fueling unless the inboard section of the reactor or a neutron multiplier is employed to increase the net TBR.

Neutron multipliers can be used to enhance the tritium potential of the lithium blankets. Examination of the nonfissionable elements with significant (n,2n) and (n,3n) cross sections and low neutron absorption indicates that Be, Bi, Pb, and Zr have the highest potential for neutron multiplication.[5] Beryllium can produce up to 2.7 neutrons per fusion neutron (n/DTn). The corresponding number for lead is only 1.7 n/DTn. The other materials (Bi, Zr) have lower upper limits. So, blankets with the lead neutron multiplier or lithium-lead blankets have about the same tritium breeding potential. Clearly, Be is the only neutron multiplier that has the potential to satisfy INTOR requirements.

The main concerns for beryllium are the irradiation swelling produced by high helium generation rates, cost, toxicity, and the tritium inventory due to BeO (n,t) reaction. Swelling needs to be accommodated such that the induced stresses in the structural material are not excessive. The recommended approach is to use a beryllium with ~ 65 to 85% theoretical density at low temperature < 500°C

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to minimize swelling. The degradation of thermal conductivity of such a porous beryllium must be considered. However, for solid breeder blanket concepts, this effect can be used to maintain the minimum breeder temperature required for satisfactory blanket tritium inventory.

Blanket Evaluation Criteria

A set of blanket evaluation criteria has been compiled to compare possible blanket concepts. Six areas have been defined as shown in Table 1. In this section, several generic blanket concepts will be qualitatively judged according to these criteria. This approach provides an initial screening process without carrying out detailed analysis for each concept. Several blanket concepts are discussed in this section using this approach; the key points for each design are listed in Tables 2 through 6.

Water-Cooled Solid Breeder Blankets

A water-cooled blanket can be designed to operate with a low temperature (40-80°C) and pressure (0.1 - 0.5 MPa), which simplify the design and improve the reliability. Also, the water coolant can be isolated from the breeder material by several zones which eliminates tritium buildup in the water by permeation through the steel and reduces the chances for water-breeder interaction. This improves the safety and environmental aspects of the blanket and eliminates the costly process of tritirum removal from the water. At such low coolant temperature and pressure, water has a good materials compatibility, excellent heat transfer characteristics, and low operating cost. Tables 2 and 3 lists the main characteristics of these concepts. Li_2O, $LiAlO_2$, and Li_4SiO_4 are the main candidate solid breeders for this concept with a beryllium neutron multiplier.

TABLE 1
Blanket Evaluation Criteria

PERFORMANCE
- Tritium breeding capability
- Tritium inventory
- Shielding characteristics

OPERATING REQUIREMENTS
- Special startup and shutdown requirements
- Temperature, system pressure, and structure requirements
- Tritium recovery requirements
- Pumping power requirements
- Cooling requirements after shutdown

IMPACT ON REACTOR DESIGN AND OPERATION
- Reliability evaluation
- Lifetime
- Thickness and mass
- Manifolding requirements
- Maintenance requirements
- Secondary coolant loop and heat rejection system

SAFETY AND ENVIRONMENTAL IMPACT
- Vulnerable tritium inventory
- Activation product vulnerability/concentration
- Reactivity of materials
- Stored energy
- Waste management

TECHNOLOGY ASSESSMENT
- Extrapolation to commercial applications
- Low technology
- Design uncertainty
- Existing data base and R&D requirements
- Design simplicity

COST
- Materials costs
- Fabrication related costs
- Reprocessing costs
- Waste management costs

TABLE 2
Design Features of Water-Cooled Solid Breeder Blanket

1. Provides high tritium breeding ratio.
2. Can utilize low temperature (< 80°C), low pressure < .5 MPa water coolant.
3. Provides safety and reliability advantages.
4. Utilizes ceramic breeder for which data base is being developed.
5. Low temperature austenitic steel structure with low pressure coolant provides low technology system with minimum structure volume fraction.
6. Incorporate beryllium to provide high tritium breeding.
7. Low temperature beryllium reduces swelling concerns.

TABLE 3
Key Points for Water-Cooled Solid Breeder Blanket Evaluation

PERFORMANCE
- Good tritium breeding capability
- Low tritium inventory
- Good shielding characteristics

OPERATING REQUIREMENTS
- No special requirements
- Low temperature and low pressure system
- No secondary loop

IMPACT ON REACTOR DESIGN AND OPERATION
- No impact

SAFETY AND ENVIRONMENTAL IMPACT
- Satisfactory

TECHNOLOGY ASSESSMENT
- Generate data base for commercial reactors
- Low technology
- Low design uncertainty

COST
- Be dominates the blanket cost

Li_2O thermochemical data[3] show that Li_2O is very hygroscopic with the product being the low-meling (744 K), highly corrosive LiOH. For example, at a moisture partial pressure of only 34 Pa and a temperature of 683K, LiOH will form and precipitate. Lithium oxide is compatible with stain-less steels provided that its moisture content is very low. Problems are encountered if LiOH is present. For a given moisture content, the corrosion is less severe at lower temperatures. As a general rule, the temperature of the Li_2O/structure interface should be less than 744K. Vapor phase transport is a major concern for Li_2O at higher temperatures.

In this concept, the main design issues are the lower temperature limits for solid breeders based on tritium inventory due to, bulk diffusion, solubility and surface adsorption. Of the three candidates, Li_2O has the highest diffusivity and $LiAlO_2$ has the lowest. However, for Li_2O, the trapping of tritium in the form of LiOT is a major concern at the low temperatures. The temperature limit[3] of > 683 K and moisture partial pressure limit of < 34 Pa is based on LiOT precipitation.

Because of its low tritium diffusivity, $LiAlO_2$ with very small grain size must be used to achieve acceptably low tritium inventories at low operating temperatures. Such material has been fabricated and found to be quite stable in thermal and low-fluence neutron environments. Depending on the upper temperature of the breeder and the temperature distribution, minimum local operating temperatures as low as 620 K are believed acceptable. However, surface adsorption and solubility must also be considered. The presence of hydrogen is known to enhance the desorption characteristics. $LiAlO_2$ is projected to have the highest allowable operating temperature, primarily because it exhibits the highest melting temperature and thermal stability of the three ceramics.

Preliminary data on Li_4SiO_4 indicate that it might be promising as a breeding material. Its low melting point should present no concern for the non-power blanket. However, these data need to be examined with the same degree of thoroughness as the Li_2O and $LiAlO_2$ data before a valid comparison can be made.

Helium-Cooled Solid Breeder Blankets

The helium-cooled solid breeder concept exhibits many of the favorable characteristics of the water cooled concept. However, helium coolant increases the pressure, temperature, and stress level in the structural material due to poor heat transfer characteristics relative to water. Manifolding requirements represent a penalty for the design and a special attention is necessary to reduce the impact on the reactor design and operation. Neutron streaming through the helium ducts is another design problem which requires extra shielding. Radioactive waste is also increased relative to the water cooled blanket because of harder neutron spectrum. In addition, the reactor radial dimension has to increase to accommodate the extra manifolding requirements in the inboard section. Also, the first wall design will have a design limit on the surface flux because of the maximum allowable stress level.

Concerns about solid breeder materials are the same as of the water-cooled solid breeder blankets. The main characteristics of helium-cooled solid breeder blankets are listed in Table 4.

TABLE 4
Key Points for Helium-Cooled Solid Breeder Blanket Evaluation

PERFORMANCE
- Good tritium breeding capability
- Low tritium inventory
- Poor shielding characteristics

OPERATING REQUIREMENTS
- No special requirements
- High structure temperatures
- Medium pressure system
- No secondary loop
- Significant pumping power

IMPACT ON REACTOR DESIGN AND OPERATION
- Impact reactor geometry
- Large size manifolds
- Increase reactor radial buildup
- Extra shielding for helium manifolds

SAFETY AND ENVIRONMENTAL IMPACT
- Extra radioactive waste

TECHNOLOGY ASSESSMENT
- Generate data base for commercial reactors
- Existing technology
- Normal design uncertainty

COST
- Be dominates the blanket cost
- Reactor cost increased

Water-Cooled Lithium-Lead Breeder

Lithium-lead breeder has an upper limit of ~ 1.7 tritons per fusion neutron. The water coolant and the required structural material reduce this value to about 1.2. For INTOR conditions of 0.6-0.8 first wall area coverage for tritium breeding, the net tritium breeding ratio will be less than unity and an external tritium supply will be required. The TBR can be enhanced by incorporating beryllium multiplier.

The use of water coolant with liquid lithium-lead requires high pressure water to avoid phase change for lithium-lead. Also, the use of high pressure water loop next to liquid lithium-lead loop will require extra structural material, manifold volume, and cost for safe operation. Such blanket concepts will generate extra constraints on the performance and design of other reactor components. Also, it is unlikely to extrapolate to one of the leading power blanket concepts as shown in Table 5.

Self-Cooled Water/Salt Concept

This concept[6,7] provides a simple design by utilizing the same fluid as breeder and coolant. A small amount of lithium salt (LiOH or $LiNO_3$) is dissolved in the water coolant for tritium breeding. In this concept, there is both an outboard blanket and an inboard breeding shield. The outboard blanket consists of beryllium zone cooled by the aqueous breeder. A water-cooled shield system is employed as the inboard breeding shield. The combined tritium breeding ratio of the outboard blanket and inboard breeding shield is ~ 1.0. The tritium recovery from the water coolant is a well established technology but considerably more expensive (~ 20-40 M$) than that for other concepts. Also, there is a concern about the assumed tritium concentration level in the water loop (20 Ci/L) from the safety point of view. The primary critical issue with this concept relates to uncertainties associated with stress corrosion of the steel structure as shown in Table 6. The low temperature, low pressure coolant tends to reduce concerns about stress corrosion; however, the salts of

TABLE 5
Key Points for Water-Cooled Lithium-Lead Blanket Evaluation

PERFORMANCE
- Medium tritium breeding capability
- Low tritium inventory
- Good shielding characteristics

OPERATING REQUIREMENTS
- Strict constraint to avoid lithium-lead phase change
- High pressure system
- Two loop system (liquid lithium-lead and water)
- No secondary loop

IMPACT ON REACTOR DESIGN AND OPERATION
- Two loop system impacts significantly reactor design
- Extra structure to support lithium-lead breeder

SAFETY AND ENVIRONMENTAL IMPACT
- Safety concern about water/liquid lithium-lead reactivity

TECHNOLOGY ASSESSMENT
- No extrapolation to commercial concept
- Existing technology

COST
- Extra fabrication cost

TABLE 6
Key Points for Self-Cooled Water/Salt Blanket Evaluation

PERFORMANCE
- Medium tritium breeding capability
- Low tritium inventory
- Medium shielding characteristics
- Stress corrosion concern

OPERATING REQUIREMENTS
- No special requirements
- Low pressure system
- No secondary loop

IMPACT ON REACTOR DESIGN AND OPERATION
- Extra shield for inboard and outboard sections

SAFETY AND ENVIRONMENTAL IMPACT
- Relatively high vulnerable tritium inventory

TECHNOLOGY ASSESSMENT
- Existing technology
- Unlikely to extrapolate to commercial concept
- Low design uncertainty

COST
- Be dominates the blanket cost
- Relatively expensive tritium recovery system

most interest typically create stress corrosion problems.

Blanket Concept

As mentioned before, the main idea for high TBR is to use a large Be volume to multiply the fusion neutrons for tritium breeding purpose. In order to utilize these neutrons, the solid breeder has to contain a large concentration of lithium-6 isotope. A 90% lithium-6 enrichment is used. Also, the high lithium-6 enrichment reduces the solid breeder volume required in the blanket. This reduction results in a lower tritium inventory and less cost. Each solid breeder must operate in a specific temperature window for satisfactory tritium inventory. The minimum temperature required is about 350 to 400°C which does not match the desired operating temperatures of the water coolant (40–80°C). The design solution is to locate the Be multiplier between the solid breeder and the water coolant, and adjust the gap conductance to increase the lower temperature of the solid breeder. Also, the Be layer between the water coolant and tritium breeder increases the number of tritium barriers for tritium permeation from the solid breeder to the coolant.

Coolant panels or water tubes can be used to cool the blanket. The water panel consists of two corrugated panels with water flow in-between. In fact, the water panel can be viewed as a row of mechanically connected tubes for extra structure support. The water panels concept is used for the thermal-hydraulic analysis.

Carbon is used at the end of the blanket as a neutron moderator with a low absorption cross section and a thermal insulator between the water coolant panel and the solid breeder. Also, the use of carbon reduces the required Be volume and the blanket cost. The use of a heterogeneous blanket (several layers of breeder and mulitplier) was found to be essential to achieve high tritium breeding ratios. Several configurations were defined based on their tritium breeding capabilities.

Neutronics Analysis

In parametric analysis, the TBR was calculated as a function of the Be zone thickness. Table 7 gives the blanket parameters considered for the blanket configuration with one Be multiplier zone. The one-dimensional discrete ordinates code ONEDANT[8] was used to perform the transport calculations with a P_5 approximation for the scattering cross sections and an S_8 angular quadrature set. A 67-coupled group nuclear data library (46-neutron and 21-gamma) based on ENDF/B-IV was employed for these calculations. VITAMIN-C[9] and MACKLIB-IV[10] libraries were used to obtain this library. The result from this calculation is shown in Table 8. The maximum TRB is 1.4 at 10 cm Be zone thickness.

TABLE 7
Blanket Parameters for the One Beryllium Zone Configuration

Zone Description	Zone Thickness cm	Zone Composition (Vol. %)
First Wall	1	50% H_2O, 50% type 316 SS
Multiplier	X[a]	100% Be (0.8 DF)
Second Wall	0.5	50% H_2O, 50% type 316 SS
Breeder	40	5% H_2O, 10% type 316 SS, 5% He 80% Li_2O (0.8 DF)
Shield	100	20% H_2O, 80% type 316 SS

[a] X is a variable

TABLE 8
Tritium Breeding Ratio and Energy Generated per Fusion Neutron for the One Beryllium Zone Configuration

Multiplier Zone Thickness, cm	Tritium Breeding Ratio	Energy Generated MeV/DTn
2.5	1.155	8.9
5.0	1.293	20.0
7.5	1.367	21.0
10.0	1.396	22.0
12.5	1.392	22.9
15.0	1.367	23.7
17.5	1.327	24.5
20.0	1.278	25.1

The next step considered two Be zones to improve the tritium production rate. Table 9 shows a sample of the configurations considered with a tritirum breeding ratio >2. The thermal hydraulic analysis for the configurations in Table 9 suggested the used of thin breeder layers to control the temperature distribution within the required limits.

A three-beryllium zone design was developed to produce a high tritium breeding ratio using thin breeder layers. Table 10 gives the configuration for two of these designs. The total breeder zone thickness is 6 cm. Again, the thermal hydraulic analysis suggested that each of the last two coolant panels to be located within the preceding beryllium zone.

Thermal-Hydraulic Analysis

A one-dimensional heat transfer model was used to perform scoping analysis of the blanket shown in Fig. 1. The blanket has a layered structure, and the coolant channels are arranged in such a manner so that adequate cooling can be achieved in various layers of the breeder material. The following assumptions were made in the thermal hydraulic analysis: 1) no heat transfer across the coolant centerline and the breeder centerline, thus, adiabatic boundary conditions are assumed at these centerlines; 2) the average nuclear heating rate is used in the breeder and the multiplier over a finite region in the blanket; and 3) the thermal conductivities of the breeder and multiplier are constant (temperature independent). Since nuclear heating rate varies significantly with radial position, it was necessary to perform calculations for various regions in the blanket separately.

TABLE 9
Tritium Breeding Ratio and Energy Generation Per Fusion Neutron for two beryllium zone configurations.

Zone Thickness, cm						
First Wall[a]	Be^b Multi.	Li_2O^c Breeder	Be^b Multi.	Li_2O^c Breeder	TBR	Energy MeV/DTn
1	1	1	20	35	2.039	22.0
1	2	1	20	35	2.047	22.2
1	3	1	20	35	2.048	22.4
1	4	1	20	35	2.044	22.6
1	5	1	20	35	2.034	22.8

a First wall consists of 50% H_2O, 50% Type 316 SS
b 100% Be (0.8 DF)
c 5% H_2O, 10% Type 316 SS, 5% He, 80% Li_2O (0.8 DF)

TABLE 10
Configuration and Tritium Breeding Ratios for Three-Layer Beryllium Design

Zone Material	Design A Zone Thickness cm	Design B Zone Thickness cm
First wall (50% H_2O, 50% Type 316 SS)	1.0	1.0
Be (0.8 DF)	4.0	4.0
Type 316 SS	0.1	0.1
Li_2O (0.8 DF)	1.0	1.0
Type 316 SS	0.1	0.1
Be (0.8 DF)	15.0	20.0
Water coolant (50% H_2O, 50% Type 316 SS)	0.5	0.5
Li_2O (0.8 DF)	2.0	2.0
Type 316 SS	0.1	0.1
Be (0.8 DF)	5.0	10.0
Water coolant (50% H_2O, 50% Type 316 SS)	0.5	0.5
Li_2O (0.8 DF)	3.0	3.0
Type 316 SS	0.1	0.1
Carbon[a]	30.0	30.0
TBR	1.889	1.979

[a]carbon zone thickness can be reduced without impact on the blanket performance.

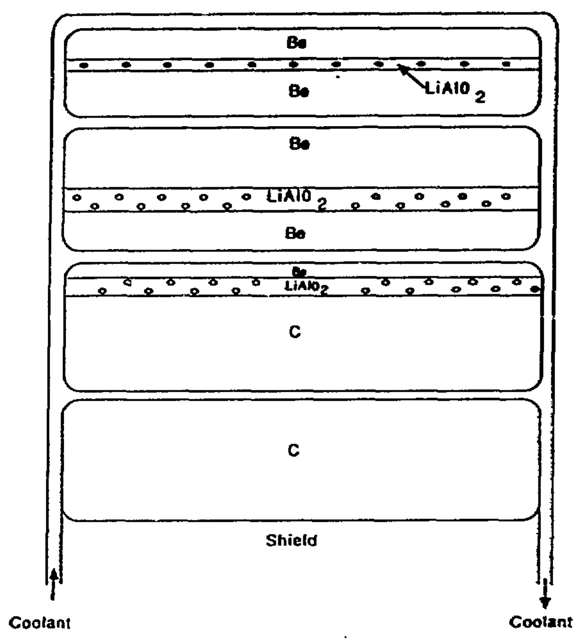

Fig. 1 Schematic View of the Blanket Coolant Configurations

The key parameter for the heat transfer analysis are: Gap conductances between breeder and stainless plate (h_{BS}), between multiplier and stainless steel plate (h_{MS}), and between multiplier and the coolant pipe (h_{MC}). The thermal analysis uses $LiAlO_2$ breeder material since the nuclear heating is about the same for the different breeder materials (Li_2O, $LiAlO_2$, Li_4SiO_4) and its thermal conductivity is the lowest. The energy release from $^6Li(n, \alpha)t$ reaction dominates the nuclear heating.

The thermal conductivities for the breeder ($LiAlO_2$), the multiplier (Be), and the reflector (graphite) are 1.6, 100, and 30 W/m-K, respectively. The $LiAlO_2$ is assumed to be 80% dense, sintered material and the thermal conductivity is estimated at 1000 K. The beryllium is assumed to be 80% dense and the thermal conductivity is estimated at 573-673K. Different values of the gap conductances (h_{BS}, h_{MS}, and h_{MC}) are used at various locations in the blanket. The reason for doing so is to maintain the breeder temperature within acceptable levels. For $LiAlO_2$, the allowable minimum and maximum temperatures are 350°C and 900°C, respectively. Table 11 is a list of the values for gap conductance used in the calculations. Region 1 refers to the first breeder region (closest to the first wall) which, incidentally, has a thickness of 1 cm. Region 3 refers to the last breeder region which has a thickness of 3 cm. Region 2 is the second breeder region in the middle. Since the breeder is cooled on both sides, there are two sets of gap conductance in each region (front and back) as shown in Table 11. The gap conductance depends on a number of factors, such as surface roughness, gap width, gas temperature and pressure, hardness, thermal conductivities of the materials, etc. Gap conductances of 10,000 - 20,000 $W/m^2 \cdot K$ have been measured for marginally closed (5-10 μm) VO_2/He/Zr gaps with very small interface pressure.[11] Thus, the high values for the fusion materials in Table 11 are considered reasonable. A detailed analysis of the gap conductance showed that in order to achieve a gap conductance of ~ 500 W/m^2-K with atmospheric helium, a gap width of ~ 0.6 mm may be required. A corrugated plate is needed to maintain such a gap.

Table 12 gives the key calculated temperature values in the blanket. The coolant inlet temperature is assumed to be 30°C. It can be observed that the temperature gradient in the breeder is very sharp

TABLE 11
Values for Gap Conductance h_{BS} (Breeder/Stainless Steel), and h_{MS} (Multiplier/Stainless Steel), and h_{MC} (Multiplier/Coolant Pipe) at Various Locations in the Blanket

Location	Gap Conductance W/m^2-K	h_{BS}	h_{MS}	h_{MC}
Region 1	Front	3,000	17,000	13,000
	Back	3,000	17,000	13,000
Region 2	Front	3,000	17,000	13,000
	Back	1,000	3,000	2,000
Region 3	Front	500	700	600
	Back	3,000	17,000*	13,000*

* Between graphite and stainless steel

TABLE 12
Key Temperature Values in the Blanket

Material	Minimum Temperature°C	Maximum Temperature°C
Breeder ($LiAlO_2$)	355	860
Neutron multiplier (Be)		<400
Structure (steel)		<200
Coolant (H_2O)	30	50

(~ 50 °C/mm) compared to that in the multiplier (~ 3°C/mm). This is the result of relatively high nuclear heating rate and low thermal conductivity in the breeder. In the first breeder region (the one closest to the first wall), the maximum breeder temperature is ~ 860°C and the minimum breeder temperature is ~ 455°C. Thus, the maximum temperature is the more limiting factor in this region. In the third breeder region, the maximum breeder temperature is ~ 725°C and the minimum breeder temperature is ~ 355°C. Thus, the minimum temperature is the limiting factor in the third breeder region. This is the reason why the gap conductances in Region 3 (front) have such low values (~ 500 W/m^2-K). It is needed to increase the heat transfer resistances and maintain the minimum breeder temperature above 350°C. The beryllium temperature is below 400°C everywhere in the blanket.

The maximum and minimum breeder temperatures do not occur at the same axial (coolant flow direction) location. The minimum occurs at the inlet while the maximum occurs at the outlet. In the calculations, the axial length of the coolant channel was assumed to be 0.5 m and the coolant velocity was assumed to be 1.0 m/s. This resulted in a heat transfer coefficient of 8,630 W/m^2-K. The coolant outlet temperature varies slightly for different coolant channels since the amount of heat generated varies with the radial location and composition of the blanket. The average coolant temperature rise in the breeding zone is ~10°C, which is small compared to the temperature gradient in the breeder and the multiplier. Thus, the coolant velocity and channel axial length can be varied over a wide range without having significant impact on the maximum and minimum breeder temperatures.

In summary, by properly selecting the locations of the coolant channels, the various thicknesses of the breeder and the multiplier zones, and the gap conductances between various interfaces; the maximum and minimum temperatures of the breeder can be maintained within the acceptable levels. However, it is the result of a few iterations between the neutronic and the thermal-hydraulic analyses and does not represent the optimized conditions for the blanket. For example, if the thickness of the first breeder region is reduced from 10 mm to 9 mm, the thickness of beryllium behind the breeder can be increased from 6 cm to approximately 8 cm. In other words, a reduction of one mm in $LiAlO_2$ can result in a gain of 2 cm in beryllium in the first breeder region without exceeding the temperature limits of the breeder.

Tritium Inventory Calculations

The model developed in Ref. 12 was used to calculate tritium inventory in the breeding zones and levels of uncertainty for the INTOR blanket. The operating conditions include the average tritium generation rate, in wppm/s, for each breeder region and the temperature distribution. Assuming that each breeder material operates within its temperature windows (T_{min} to T_{max}).

The first-wall surface area for INTOR is 380 m^2 with 230 m^2 (60%) coverage by the blanket. The total thickness of the breeder layers is 60 mm, giving a breeder volume of 13.8 m^3. Assuming the breeder is at 80% of its theoretical density gives mass of 28.9 Mg for $LiAlO_2$ (22.3 Mg for Li_2O and 26.7 Mg for Li_4SiO_4). The minimum generation rate for tritium self-sufficiency is 94 g(T)/day (1.09 x 10^{-3} g/s). If it is assumed that all of this tritium comes from the breeder, then the average $\dot{G}$ over the whole breeder (e.g., $LiAlO_2$) is ~ 3.8 x 10^{-5} wppm/s. The assumed generation rates for each of the three blanket regions are 6.2 x 10^{-5} wppm/s for region 1 (closest to plasma), 4.4 x 10^{-5} wppm/s for region 2, and 2.5 x 10^{-5} wppm/s for region 3 (furthest from the plasma).

It remains to specify a breeder microstructure and perform the calculations. The breeder is assumed to be 80% dense. The starting grain diameters are assumed to be 0.2 μm for $LiAlO_2$, 10 μm for Li_2O, and 26 μm for Li_4SiO_4. The reason for the large grain diameter Li_4SiO_4 is because this is the only size for which any reasonable data exist. The complicated model proposed for Li_2O requires the specification of other parameters. The pore-solid surface area is assumed to be 0.05 m^2/g, and the particle surface area is taken as 0.1 m^2/g. The grain boundary surface area is assumed to be 0.5 m^2/g and the tortuosity factor is assumed to be ε=3 with an effective particle diameter of 50 μm. The HTO partial pressure is assumed to be 3 Pa for solubility calculations which is ~ 1/10 of the limit for avoiding LiOT(H) precipitation.

The results of these calculations are presented in Table 13. For $LiAlO_2$, with its very low effective diffusivity at low temperatures, an inventory of 540 g (~ 0.5 kg) is calculated. Because a somewhat pessimistic diffusivity was used, the uncertainty factor ascribed to this result is only 2. This is primarily due to uncertainties in extrapolating the data to lower temperatures. For Li_2O, while there are uncertainties in the model parameters for grain boundary diffusion, even three orders of magnitude increase in grain boundary diffusion would not affect the overall tritium inventory very much. For the assumed HTO partial pressure of 3 Pa, 40 g (1.8 wppm) of dissolved tritium is predicted. A nominal uncertainty of 2 is used here. For Li_4SiO_4, only 15 g of tritium are predicted for the inventory. The factor of 10 uncertainty is assigned rather arbitrarily to reflect the absence of any reliable release data below 550°C. In extrapolating from 550°C to 350°C, there is at least a factor of 10 uncertainty.

Conclusions

The main results from the study show that a low technology high tritium breeding concept based on the water-cooled solid breeder concept is a very promising option for the near-term fusion reactor. The blanket option developed during this study used low first wall coverage and provides adequate tritium for fueling without the need for an external tritium source.

TABLE 13
Summary of Tritium Inventory Calculations for Proposed INTOR Solid-Breeder Blankets. The Be Multiplier is Assumed to Operate Within the Temperature Limits of 100-500°C and all Ceramics are Assumed to be 80% Dense.

				INVENTORY, g					
Material	Grain Diameter, μm	T_{min} °C	T_{max} °C	Diffusion Lattice	Diffusion Grain Bndy.	Surface	Solubility	Total	Uncertainty Factor
$LiAlO_2$	0.2	350	900	540	-	-	-	540	2
Li_2O	10	400	800	7.34×10^{-4}	2.44×10^{-3}	4.12×10^{-3}	40	40	2
Li_4SiO_4	26	350	730	15	-	-	-	15	10
Be	30	100	500	4×10^{-2}	-	-	-	~0	5

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