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CONVERTIBLE SHIELDING TO CERAMIC BREEDING BLANKET

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Four concepts have been studied for the ITER convertible blanket:

- -Layered concept
- -BIT(Breeder-Inside-Tube)concept
- -BOT(Breeder-Out of-Tube)concept
- -BOT/mixed concept.

All concepts use ceramic breeder and beryllium neutron multiplier, both in the shape of small spherical pebbles, 316SS structure, and H_2O coolant(inlet/outlet temperatures:100/150℃, pressure:2 MPa). During the BPP, only beryllium pebbles (the primary pebble in case of BOT/mixed concept) are filled in the blanket for shielding purpose. Then, before the EPP operation, breeder pebbles

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This work was conducted as an ITER Technology R&D and this report corresponds to the 1994 ITER Comprehensive Task Agreement for Design Task(Task No.G16TD12, ID No.D73, Title:Convertible Shielding to Ceramic Breeding Blanket)

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will be additionally inserted into the blanket. Among possible conversion methods, wet method by liquid flow seems expecting for high and homogeneous pebble packing. Preliminaray 1-D neutronics calculation shows that the BOT/mixed concept has the highest breeding and shielding performance. However, final selection should be done by R&D's and more detail investigation on blanket characteristics and fabricability.

Required R&D's are also listed. With these efforts, the convertible blanket can be developed. However, the following should be noted. Though many of above R&D's are also necessary even for non-convertible blanket, R&D's on convertibility will be one of the most difficult parts and need significant efforts. Besides the installation of convertible blanket with required structures and lines for conversion will make the ITER basic machine more complicated.

Keywords:ITER, Blanket, Convertible Blanket, Ceramic Breeding, Layered Concept, Pebble Bed, BIT Concept, BOT Concept, BOT/mixed Concept

コンバーティブルブランケット設計

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(1995年4月20日受理)

ITERでは，構造体を交換することなく非増殖から増殖に移行できる互換性のあるブランケット（"コンバーティブル・ブランケット"）の検討を行っており，その候補概念として，以下の4つのコンセプトの検討を実施した。

- 増殖材／増倍材分離層状型
- 増殖材／増倍材分離BIT（Breeder − Inside − Tube）型
- 増殖材／増倍材分離BOT（Breeder − Out of − Tube）型
- 増殖材／増倍材混合BOT型

これらはすべて増殖材としてセラミックス及び増倍材としてベリリウムをいずれも小球状ペブルとして使用する。また，構造材及び冷却材は316ステンレス鋼及び軽水（入口／出口温度：100／150℃，圧力2MPa）である。いずれのブランケットもBPP (Basic Performance Phase) ではベリリウムペブルのみ充填して遮蔽性能を確保して，EPP (Expanded Performance Phase) に望んで増殖材ペブルを追加充填してトリチウム増殖を行う。ブランケット容器への増殖材の充填方法としては湿式（液体によるペブル輸送）が，出来るだけ高くまた均一な充填率を得るという点で期待できる。1次元核解析の結果ではBOT法が遮蔽及び増殖性

本作業は，国際熱核融合実験炉（International Thermonuclear Experimental Reactor）の工学設計活動として，1994年設計作業契約（Task No. G16 TD12, ID No. D73）に基づいて実施した。

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能に優れているが，最終的にはブランケットの特性との整合及び製作性の点から詳細な検討を行って決定する必要がある。また，上記非増殖／増殖移行方式についても，作動流体と増殖材の共存性及び輸送・充填状況に関するＲ＆Ｄ等により各方式を比較して決定する必要がある。互換性のあるブランケットの設置に対しては，BPP後の増殖材充填に必要となる系統の設置等，ITER炉本体への影響についても考慮しなければならないので互換性のないブランケットとはいえ上記Ｒ＆Ｄを行う必要がある。なかでも非増殖／増殖移行に関する技術開発は最も困難なものの一つであり，ブランケット自身及び炉本体構造の複雑化が生じることに十分留意する必要がある。

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1. Blanket Concept

Four concepts have been investigated for the convertible blanket: (1) layered concept, (2) BIT (breeder-inside-tube) concept, (3) BOT (breeder-out of-tube) concept, and (4) BOT/mixed concept.

All concepts use ceramic breeder and Be neutron multiplier in the shape of small spherical pebbles. In the layered concept (Fig. 1), breeder pebble layer contained in SS can and Be pebble layer are alternately placed. Beryllium layers adjacent to a breeder layer also work as a thermal resistant layer for maintaining breeder temperature within an allowable range. Cooling panels are provided between Be layers to remove heat generated in the blanket. In the BIT concept (Fig. 2), double-tubes are embedded in Be pebble bed. Breeder pebbles are filled, via He gap for breeder temperature control, inside the inner tube. Coolant is provided in-between inner and outer tubes. The BOT concept (Fig. 3) consists of breeder pebble bed and Be pebble bed, which are separated by partition wall, and coolant tubes arranged according to attenuating heating rates in the blanket. For breeder temperature control, He gap is provided around the coolant tube. The configuration of the BOT/mixed concept (Fig. 4) is similar to that of the BOT concept , but no separation wall between breeder and Be. This concept employs binary pebble bed with primary pebble made of Be (2 mm in diameter) and secondary pebble which is the mixture of ceramic breeder and Be pebbles with volumetric ratio of 25/75 and 0.1-0.2 mm in diameter. (For the first three concepts, single diameter, < 1 mm, pebble is used. However, binary pebble bed could also be applied if it is required in terms of breeding and shielding performance.)

Design parameters above candidates are summarized in Table 1. All concepts use 316SS structure and H_2O coolant with inlet/outlet temperatures and pressure of 100/150 °C and 2 MPa, respectively, to meet the design requirements of ITER. Lithium oxide (Li_2O) is primary candidate for the ceramic breeder with ternary ceramic materials, such as Li_2ZrO_3, Li_4SiO_4 and $LiAlO_2$, as alternatives. In case of BOT/mixed concept, Li_4SiO_4 or other ternary ceramics might be in place of Li_2O for their wider allowable temperature range to be in contact with Be.

2. Conversion Method

These blankets are to be installed with only Be pebbles (the primary pebble in case of BOT/mixed) filled for the shielding purpose during the Basic Performance Phase of ITER. The region to be filled with ceramic breeder pebbles (the secondary pebble in case of BOT/mixed) is remained as voids during this phase. Then ceramic breeder pebbles (the secondary pebble) are additionally inserted into the voids in the blanket before the Enhanced Performance Phase. The He gas line for tritium purge will be also used as a supply line of ceramic breeder pebbles to the blanket. Concepts of the convertible blanket and the blanket in conversion process are illustrated in Figs. 5 and 6, respectively.

There are several methods for the conversion (breeder supply) such as wet method by liquid flow, dry method by gas flow, and mechanical method by gravity and/or mild gas flow with vibration. Table 2 summarizes advantages/disadvantages of these methods. Among these, the wet method seems expecting to obtain high and homogeneous packing of pebbles. However, selection of the liquid compatible with ceramic breeders and dry-out of the liquid after breeder packing are major issues for this method. Table 3 shows examples of candidate liquids for the wet method. Final selection of the conversion method will be done based on the results of R&D.

3. Neutronics Performance

Preliminary 1-D neutronics calculation have been performed for breeding and shielding performance of the candidate concepts. Calculation model is shown in Fig. 7. The results are indicated in Tables 4-6. Although the internal configuration of each blanket concept is not fully optimized yet, a comparison of each performance can be roughly summarized as follows:

1) The BOT/mixed concept has highest breeding and shielding performance due to its high packing fraction (80 %) of breeder and Be. (Pebble packing fraction of other three concepts are 65 % with single diameter pebble.)

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2) Local TBR's are 1.13 for the layered, 1.34 for the BIT, 1.38 for the BOT, and 1.48 for the BOT/mixed.
3) With breeder, relative shielding performance to the BOT/mixed is 77 % for the layered, 65 % for the BIT, and 64 % for the BOT.
4) Relative shielding performance without breeder (the secondary pebble in case of the BOT/mixed) to the BOT/mixed with the secondary pebble is 51 % for the layered, 61 % for the BIT, and 39 % for the BOT.
5) Though the shielding performance of the BOT without breeder is the lowest, it can satisfy the shielding criteria for ITER TF magnet.

Though the BOT/mixed has the highest neutronic performance as mentioned above, high and homogeneous packing of binary pebble would be more difficult than the packing of single diameter pebble. Therefore, more investigation and trade-off between performance and fabricability will be needed for the final selection of the convertible blanket concept.

4. Conclusions

From the preliminary neutronics calculations, it has been found that all candidate concepts are applicable to the ITER convertible blanket. Detail design of breeder pebble supply line for the conversion process should be developed taking into account of an interaction with the ITER basic machine. Further investigation to optimize each concept in terms of neutronic, thermo-mechanical and thermal-hydraulic performance will be needed for more precise comparison. Also for the selection of the concept to be used for ITER and verify the performance, R&D's of elementary tests, model developments including fabricability, out-of -pile and in-pile performance (and lifetime) tests, and conversion process should be performed. Table 7 summarizes required R&D's for the convertible blanket. Many of these are also required even for non-convertible blanket. However, R&D's for convertibility will be one of the most difficult parts and need significant efforts, and the installation of convertible blanket with required structures and lines for conversion will make the ITER basic machine more complicated.

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Acknowledgment

The authors would like to express their sincere appreciation to Drs.S.Shimamoto and S.Matsuda for their continuous guidance and encouragement. They also would like to acknowledge Kawasaki Heavy Industries Co. and all of other members who support this work.

Table 1 Design Parameters of Convertible Blanket Candidates

Concept	Layered	BIT	BOT	BOT/mixed
Structural material	316SS	316SS	316SS	316SS
Coolant	H_2O	H_2O	H_2O	H_2O
In/out temp. [°C]	100/150	100/150	100/150	100/150
Pressure [MPa]	2	2	2	2
Breeder material	Li_2O	Li_2O	Li_2O	Li_4SiO_4*
^6Li enrichment [%]	50	50	50	natural
Shape	sphere	sphere	sphere	sphere
Diameter [mm]	≤1	≤1	≤1	0.1-0.2**
Packing fraction [%]	65	65	65	5/80**
Neutron multiplier	Be	Be	Be	Be
Shape	sphere	sphere	sphere	sphere
Diameter [mm]	≤1	≤1	≤1	2**, 0.1-0.2**
Packing fraction	65	65	65	60/80**, 15/80**
Breeder temperature control	Be layer	He gap	He gap	He gap
Tritium recovery	He purge	He purge	He purge	He purge

* Li_2O is also a candidate breeder material.

** Binary pebble with total packing fraction of 80 %:
Primary pebble: Be (2 mm in diameter, packing fraction of 60 %)
Secondary pebble: ceramic breeder+Be (both 0.1-0.2 mm in diameter, volumetric fraction of breeder/Be = 25/75, packing fraction of 50 % in-between primary pebbles)

Table 2 Conversion Methods to Breeding Blanket

Method	*Advantage*	*Disadvantage*
Mechanical method by gravity or mild gas flow with vibration	- almost established for relatively small and independent equipment - compatible atmosphere (working fluid) with breeder	- vibration load on large component or development of local vibration technique required - possible to feed pebbles only downward
Wet method by liquid flow (liquid-solid two phase flow)	- less affected by gravity - low liquid pressure - low liquid velocity - low noise	- dry out of the liquid - selection of the liquid
Dry method by gas flow (gas-solid two phase flow)	- compatible working fluid with breeder - relatively low noise	- high gas pressure - high gas velocity - erosion of pipe and breeder can

Table 3 Examples of Candidate Liquids for Wet Conversion Method

◊ **Desirable characteristics for working liquids**

- No chemical reaction with breeder materials and Be
- Similar density to breeder materials
- Melting temperature at almost room temperature
- Low boiling temperature (100-200 °C)

Candidate liquid	Density (g/cm^3)	Boiling temperature at 0.1 MPa (°C)
H_2O	1.0	100
$C_2H_4(OH)_2$	1.1	198
$C_3H_5(OH)_3$	1.2	290
CCl_4	1.6	76
C_6H_{12}	1.1	132
C_2H_5OH	0.78	79
CH_3OH	0.78	65
$(CH_3)_2CO$	0.78	57
Freon	1.4-1.6	-41~48

◊ **The liquid to be used for the conversion will be selected through R&D including the investigation of other liquids.**

Table 4 Preliminary Comparison of Convertible Blanket Candidates

Concept	Layered	BIT	BOT	BOT/mixed
TBR (1-D local)	1.13	1.34	1.38	1.48
Relative shielding performance*				
With breeder	0.77	0.65	0.64	1
Without breeder	0.51	0.61	0.39	0.93
Critical fabricability issue	Precise Be layer thickness	Precise He gap width	Precise He gap width and tube arrangement	Precise He gap width and tube arrangement
Convertibility issue	Breeder supply line for each breeder layer	Breeder supply line for each tube	Homogeneous breeder packing in-between tubes	Homogeneous packing of secondary pebbles

* based on neutron fluxes behind blanket/shield

Table 5 Nuclear Responses in the Inboard TFC with BOT/mixed blanket

	Response	Limit
14-MeV neutron fluence to NbSn superconductor [$1/cm^2$]	5.6×10^{15}	-
Fast (E>0.1 MeV) neutron fluence to NbSn superconductor [$1/cm^2$]	3.6×10^{17}	1.0×10^{19}
Total neutron fluence to NbSn superconductor [$1/cm^2$]	8.9×10^{17}	-
Peak displacement damage in Cu stabilizer [dpa]	3.6×10^{-4}	6.0×10^{-3}
Peak dose to electrical insulator [rad]	1.3×10^{9}	5.0×10^{9}
Peak nuclear heating in winding pack [mW/cm^3]	0.29	5

Remarks)
- All results except for the peak nuclear heating are normalized on the 3 MWa/m^2 neutron fluence.
- No safety factors are included.
- Additional layers of B_4C/Pb at the back of the shield are not included.

Table 6 Neutron Fluxes behind the 100cm - thick Blanket/shield

Unit: $1/cm^2/s$

Blanket concept		14-MeV	Fast (E>0.1 MeV)	Total
Layered	with breeder	7.7×10^7	4.9×10^9	12.2×10^9
	without breeder	12.7×10^7	7.5×10^9	18.5×10^9
BIT	with breeder	9.1×10^7	5.8×10^9	14.5×10^9
	without breeder	9.8×10^7	6.2×10^9	15.4×10^9
BOT	with breeder	9.2×10^7	5.9×10^9	14.7×10^9
	without breeder	17.2×10^7	9.9×10^9	24.4×10^9
BOT/mixed	with breeder	5.9×10^7	3.8×10^9	9.4×10^9
	without breeder	6.4×10^7	4.1×10^9	10.1×10^9

Remarks) All results are normalized at the 1 MW/m^2 neutron wall load.

Table 7 R & D required for Convertible Blanket Development

◊ **Material data base without/with neutron Irradiation**
- Irradiation effects on tritium release and swelling behavior of ceramic breeders and Be
- Compatibility of ceramic breeders, Be, structural material, and coolant
- Thermal cycle durability of ceramic breeders and Be
- Other basic properties

◊ **Thermal-hydraulics characteristics**
- Effective thermal conductivity of pebble beds
- Temperature control of breeder materials (performance of thermal resistant layer such as He gaps)
- Coolant flow distribution
- He purge gas characteristics (flow distribution, pressure loss)

◊ **Mechanical strength**
- Coolant pressure
- Purge gas pressure
- Electromagnetic force (simulated)
- Thermal stress
- Interaction of ceramic breeder/Be pebbles and blanket vessel/liner walls

◊ **Chemical reaction and hydraulics**
- Mass transfer behavior of ceramic breeders (esp. Li_2O) in pebble bed

◊ **Fabricability**
- Ceramic breeder and Be small spherical pebbles
- Packing of ceramic breeder/Be pebbles
- He gap (or thermal resistant layer) for breeder temperature control
- Coolant tube/panel arrangement

Table 7 R & D required for Convertible Blanket Development (cont'd)

◊ **Safety features**
- Development of tritium permeation barrier
- Behaviors during LOCA and LOFA

◊ **Overall performance under neutron irradiation (in-pile functional and lifetime tests)**
- Breeder temperature control and in-situ tritium release for pebble beds with nuclear heating

◊ **Model development and out-of-pile functional (and lifetime) tests**
- Small-scale
- Mid-scale
- Prototype

◊ **Convertibility**
- Selection of conversion method (working fluid)
- Ceramic breeder pebbles transporting system (piping route, system outside blanket etc.)
- Inspection and assurance of packing fraction
- Vibration (including local vibration) mechanism if necessary
- Dry-out method of working liquid in case of wet method

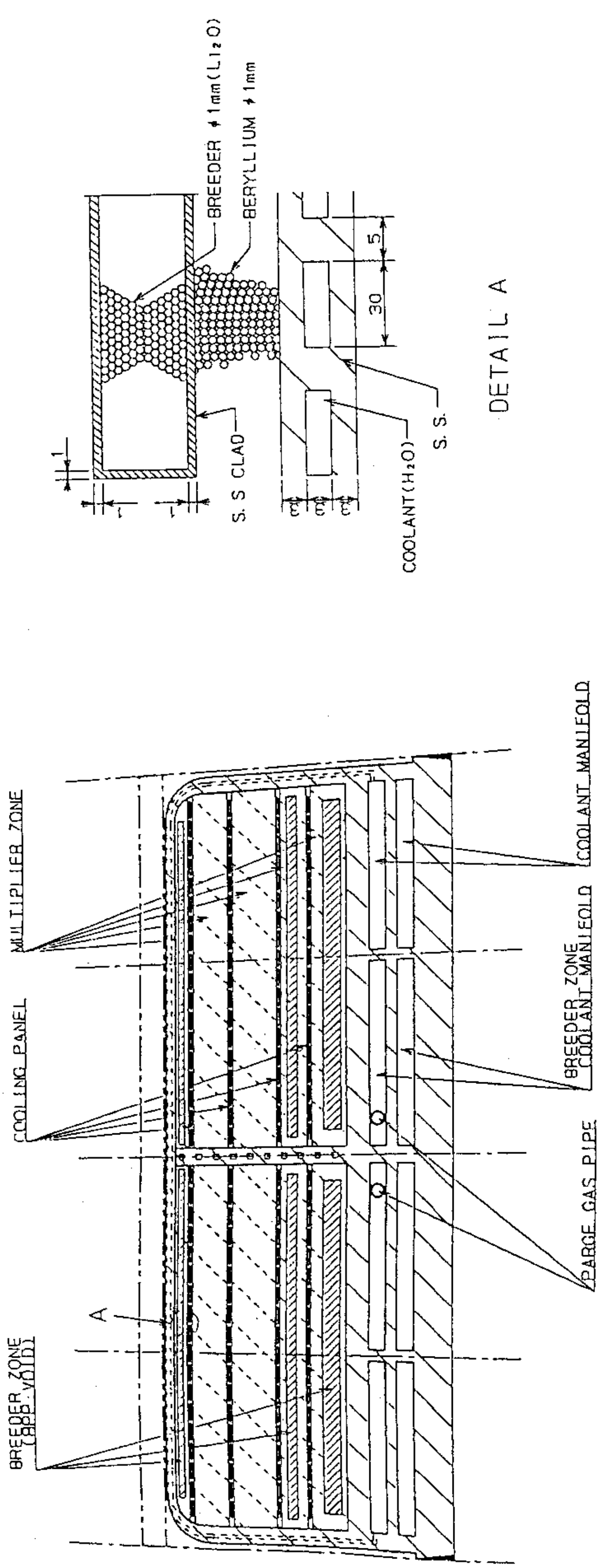

Fig.1 Layered Concept

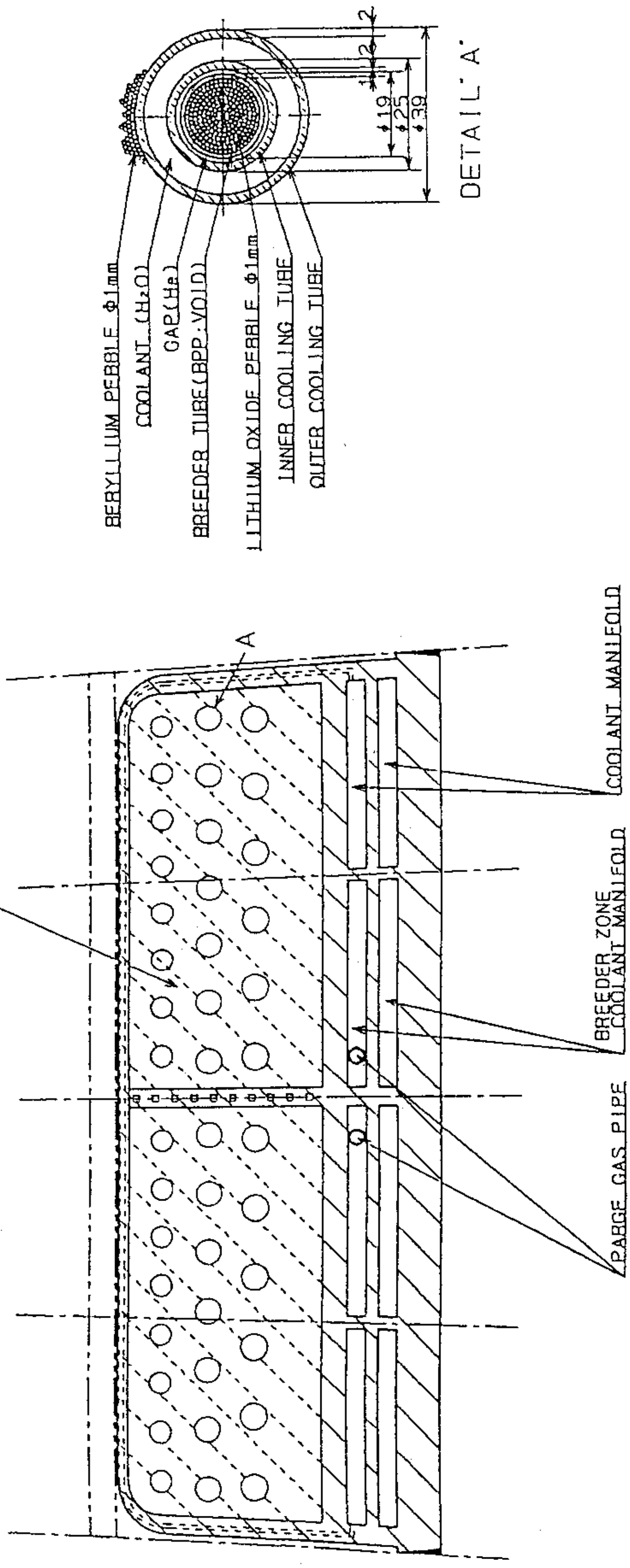

Fig.2 BIT Concept

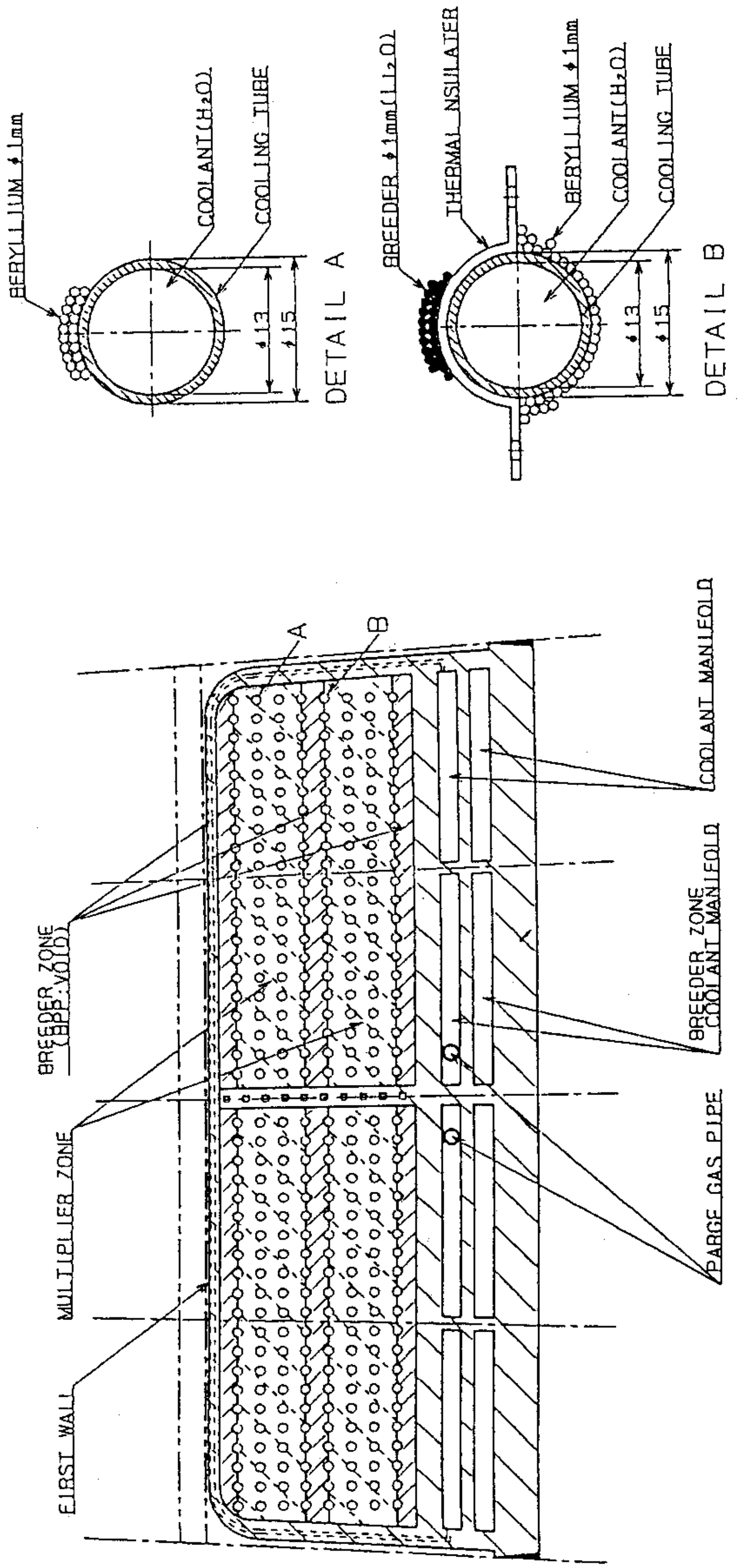

Fig.3 BOT Concept

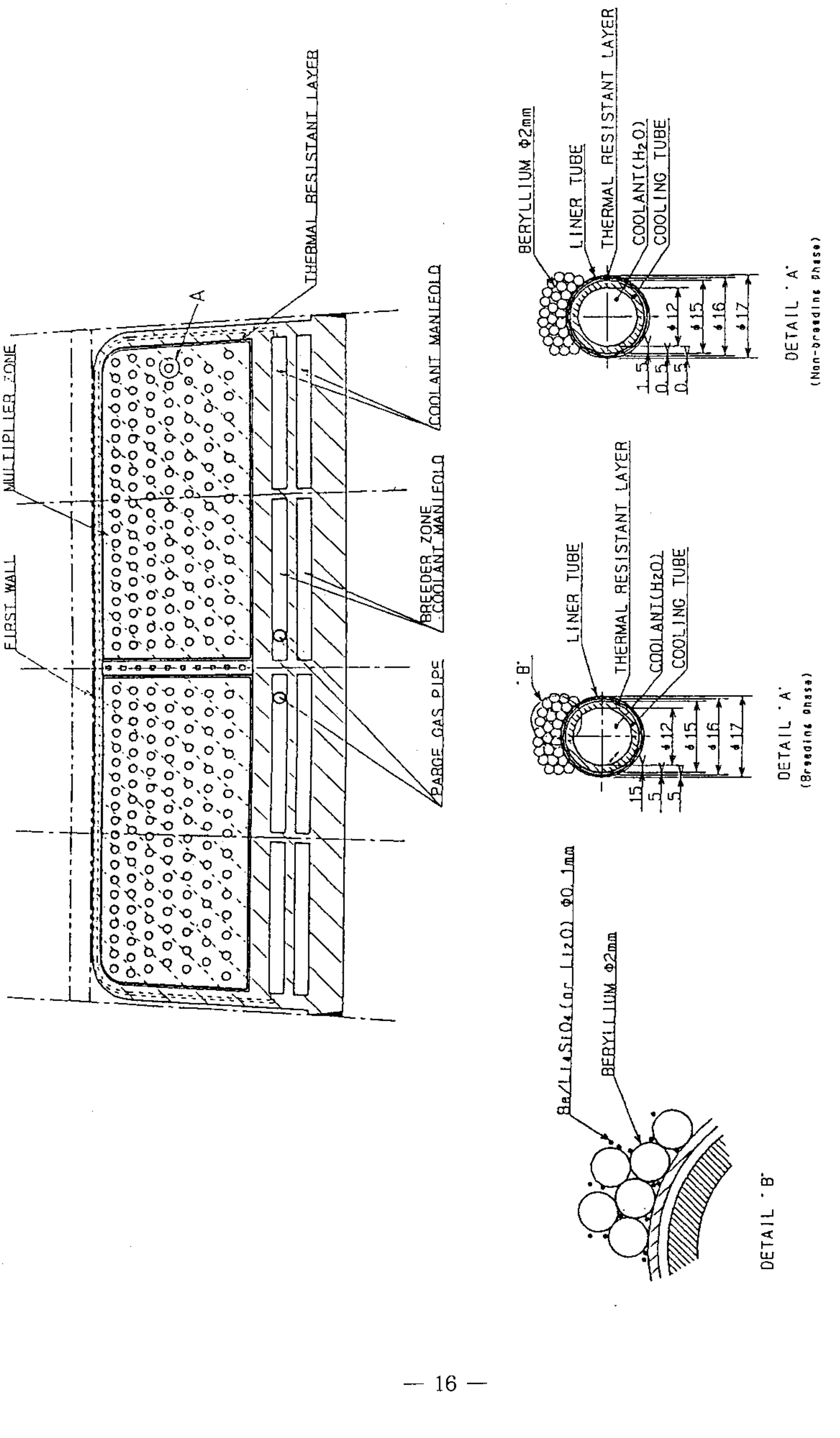

Fig.4 BOT/mixed Concept

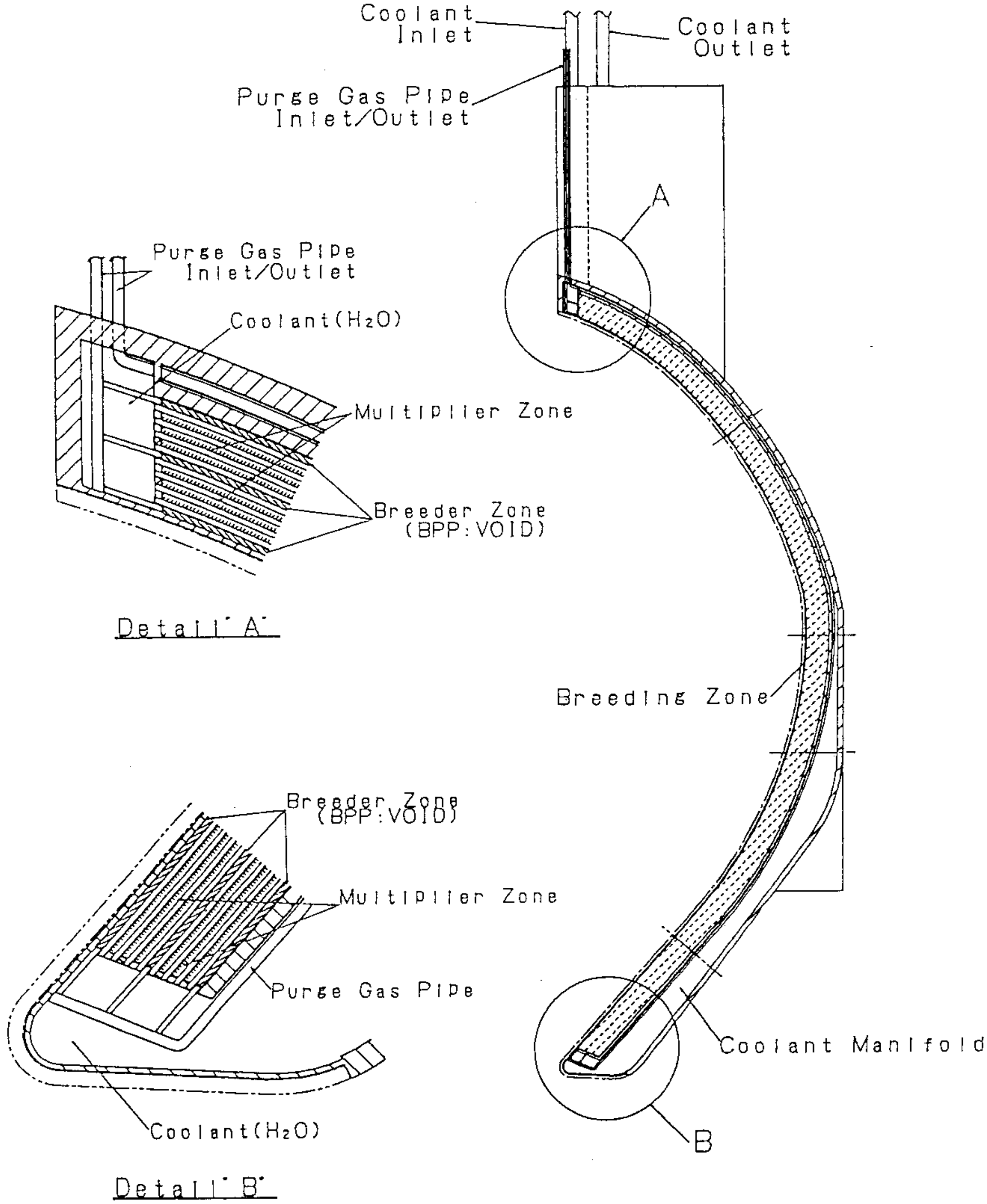

Fig.5 Convertible Blanket Concept

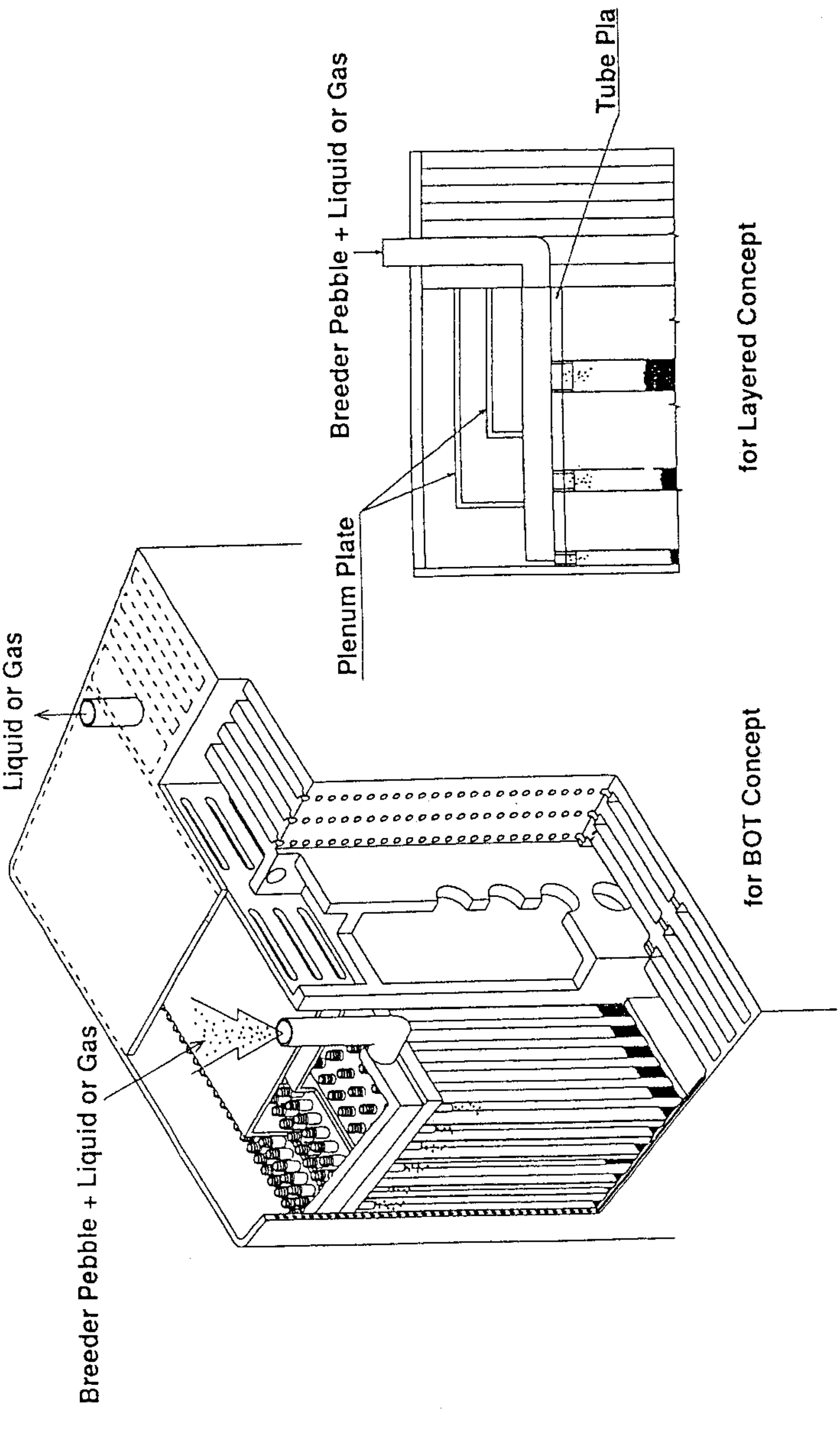

Fig.6 Conversion to Breeding Blanket

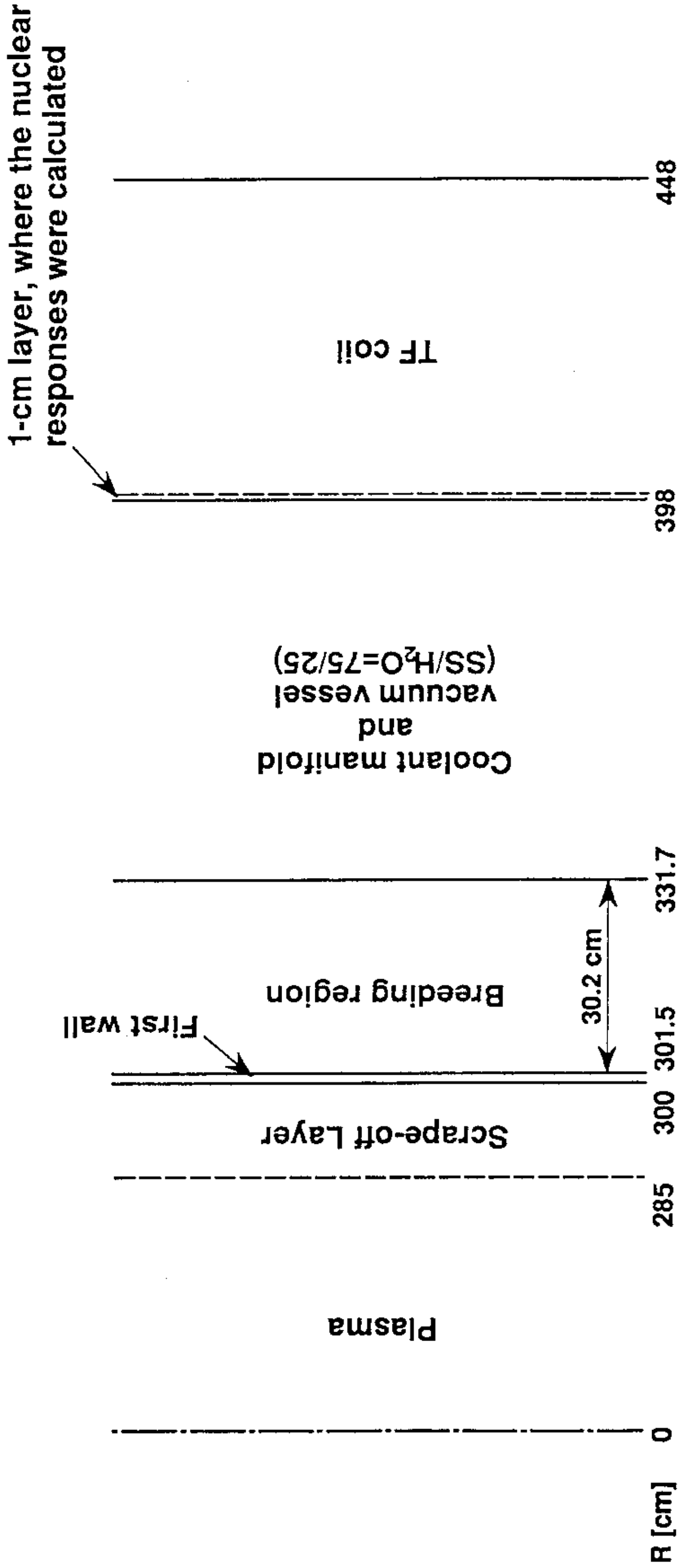

Fig.7 Neutronics Calculation Model