JAERI-M
9250

STRUCTURAL DESIGN STUDY OF TRITIUM BREEDING BLANKET WITH A LEAD LAYER AS A NEUTRON MULTIPLIER

December 1980

Hiromasa IIDA, Kazunori KITAMURA,[*1]
Akio MINATO,[*2] Hiroki SAKAMOTO,[*3]
Takashi YAMAMOTO,[*4] Yasushi SEKI
and Kiyoshi SAKO

日本原子力研究所
Japan Atomic Energy Research Institute

JAERI-M 9250

Structural Design Study of Tritium Breeding Blanket with a Lead Layer as a Neutron Multiplier

Hiromasa IIDA, Kazunori KITAMURA[*1], Akio MINATO[*2], Hiroki SAKAMOTO[*3]
Takashi YAMAMOTO[*4], Yasushi SEKI and Kiyoshi SAKO

Division of Thermonuclear Fusion Research,
Tokai Research Establishment, JAERI

(Received December 3, 1980)

Thermal and structural design study of a tritium breeding blanket with a lead layer for a International Tokamak Reactor (INTOR) is carried out. Tube in shell type blanket with a lead layer is found to be promising. The volume fraction of structural material in the lead layer can be small enough to keep the neutron multiplication effect of lead. Reasonable value of shell effect is attainable due to lead layer in the front part of the blanket.

Keywords: INTOR, Tritium Breeding Blanket, Lead, Neutron Multiplier, Shell Effect.

[*1] On leave from Tokyo Shibaura Electric Co. Ltd., Kawasaki, Japan.

[*2] On leave from Kawasaki Heavy Industries, Ltd., Tokyo, Japan.

[*3] On leave from Mitsubishi Heavy Industries, Ltd., Kobe, Japan.

[*4] On leave from Fuji Electric Co. Ltd., Kawasaki, Japan.

鉛を中性子増倍材として用いた核融合炉ブランケットの構造設計

日本原子力研究所東海研究所核融合研究部
飯田　浩正・喜多村　和憲[*1]・湊　章男[*2]
坂本　寛巳[*3]・山本　孝[*4]・関　泰
迫　淳

（1980年12月3日受理）

国際協力トカマク（INTOR）のトリチウム増殖ブランケットの一候補として，鉛を中性子増倍材として用いたブランケットの熱・構造設計を行った。その結果チューブインシェルタイプのブランケットは有力である事が分った。すなわち，鉛領域の構造材・冷却材の体積率は，鉛の中性子増倍効果を損わない程度に小さくできる。また鉛をブランケットの前方に置く事によって，プラズマ位置不安定性制御のために必要なシェル効果も期待できる。

[*1] 外来研究員（東芝）

[*2] 外来研究員（川崎重工）

[*3] 外来研究員（三菱重工）

[*4] 外来研究員（富士電機）

CONTENTS

目　次

1. Introduction

Thermal and structural design study of a tritium breeding blanket with a lead layer is profitable since it is shown by the neutronics calculation that a large value of tritium breeding ratio is attainable when lead is employed as a neutron multiplier. The followings are required for a blanket structure design from the stand point of neutronics.

① In order to multiply neutrons effectively by (n,2n) reactions in a lead layer the position of a lead layer should be as near to the plasma as possible so that attenuation of neutron flux and softening of neutron energy spectrum due to materials placed between plasma and lead layer are sufficiently small. The volume fraction of cooling tube and coolant in the lead layer should be minimized since they also soften the neutron spectrum in the lead layer.

② Neutron moderator in or at the rear of a breeding region is necessary to induce ^{6}Li(n,α)T reactions effectively with the multiplied neutrons by the lead layer.

The following general features are also necessary for a tritium breeding blanket of a Tokamak fusion reactor.

ⓐ Radiation heat flux from plasma and nuclear heat deposition due to neutron and gamma-ray should be removed sufficiently.

ⓑ Tritium produced in a blanket must be quickly extracted from the blanket.

ⓒ Blanket vessels and cooling tubes should be stiff enough to endure inner pressure, dead weight, thermal stress and electromagnetic force.

ⓓ Blanket must have enough shell effect for controlling positional instability of plasma.

Another restriction is imposed to the design of INTOR blanket. The temperature of structural material in INTOR must be below 150°C to moderate various structural problems such as material damages due to neutron irradiation. In this report, we try to propose a tritium breeding blanket with a lead layer which satisfies the above requirements.

2. Configuration of blanket structure

Blanket assembly consists of twelve modules which can be withdrawn to a radial direction from bays between toroidal field coils for repair and maintenance of a reactor. Each module is formed with six blanket rings joined with connecting bolts as shown in Fig.2.1. The cross section of the ring is shown in Fig.2.2 which is called "Tube in Shell Type". Both blanket vessel and cooling tubes are made of Type 316 stainless steel.

Helium gas is prefered rather than light water for cooling the vessel wall in order to prevent the moderation of neutron energy. The pressure and velocity of the gas are 50 ata and 55 m/sec, respectively. A lead layer is placed at the rear of the front wall of the vessel and cooled by light water.

The cooling tubes of the blanket shell are arranged horizontally(toroidal direction), while the coolant in Li_2O and lead flows in poloidal direction.

In order to minimize the volume fraction of cooling tube and coolant in the lead layer, the diameter of cooling tube must be as small as possible. The selection of 10 mm for the inner diameter of the tube may be realistic considering its fabrication. The arrangement of cooling tubes in lead layer is determined so that the maximum temperature of lead is below 250 °C.

Between the lead layer and Li_2O region a partition plate made of stainless steel with alumina coating on it is placed for thermal insulation.

The pitches of cooling tubes in Li_2O region are selected so that the temperature of Li_2O becomes sufficiently high and tritium will be easily purged by helium gas. A water layer is placed at the rear of Li_2O region. It reflects neutrons and slow down their speed for easy absorption of neutrons by ^6Li.

Volume fraction of element in the blanket is summerized in Table 2.1. Tritium breeding ratio of 1.44 is obtained by one dimensional neutronics calculation using these values(1). Molybdenum is assumed as a cooling panel material instead of aluminium in the neutronics calculation.

---

(1) Private comunication Y. Seki , et al.

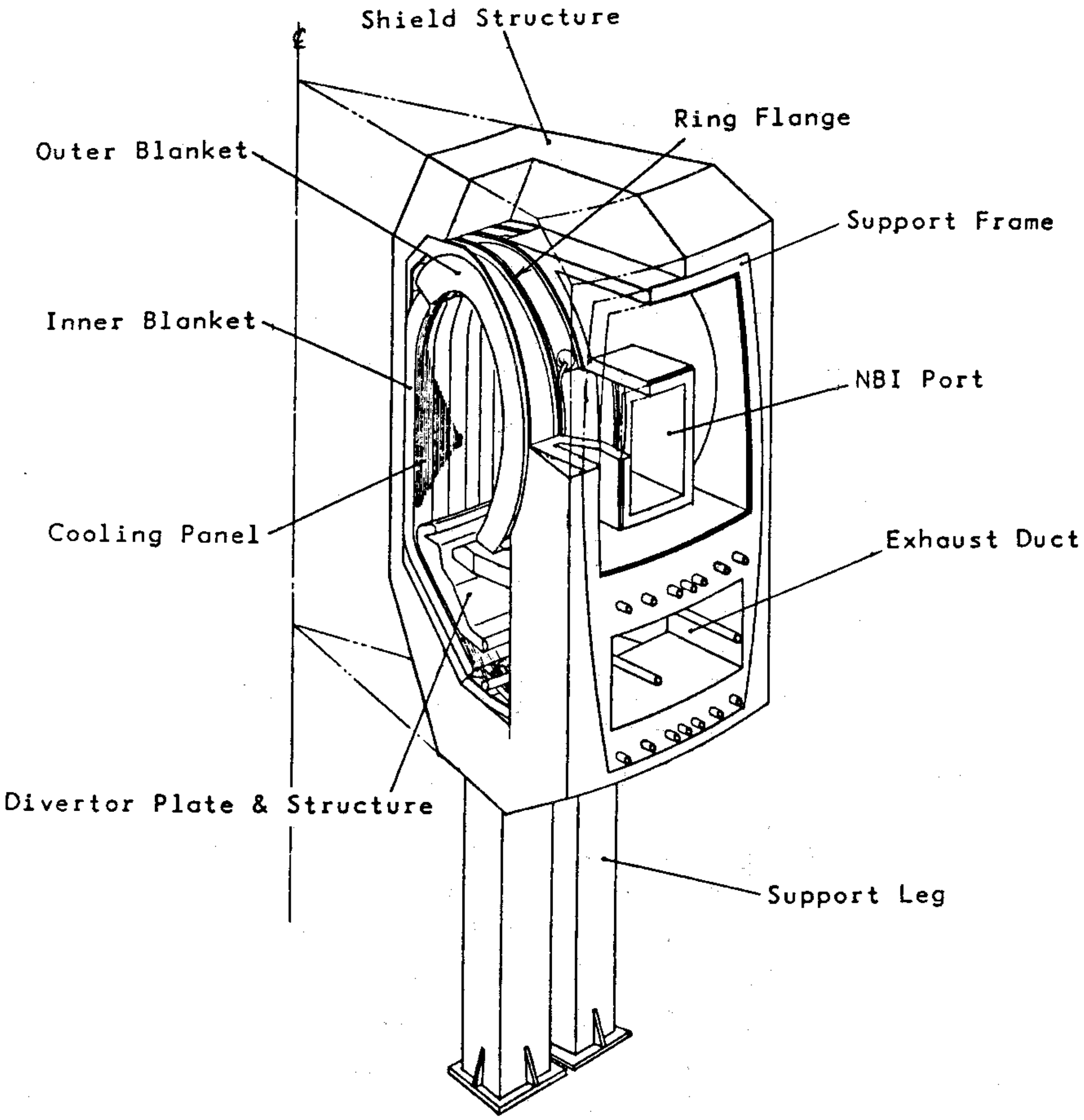


Fig.2.1 Overview of Blanket Segment

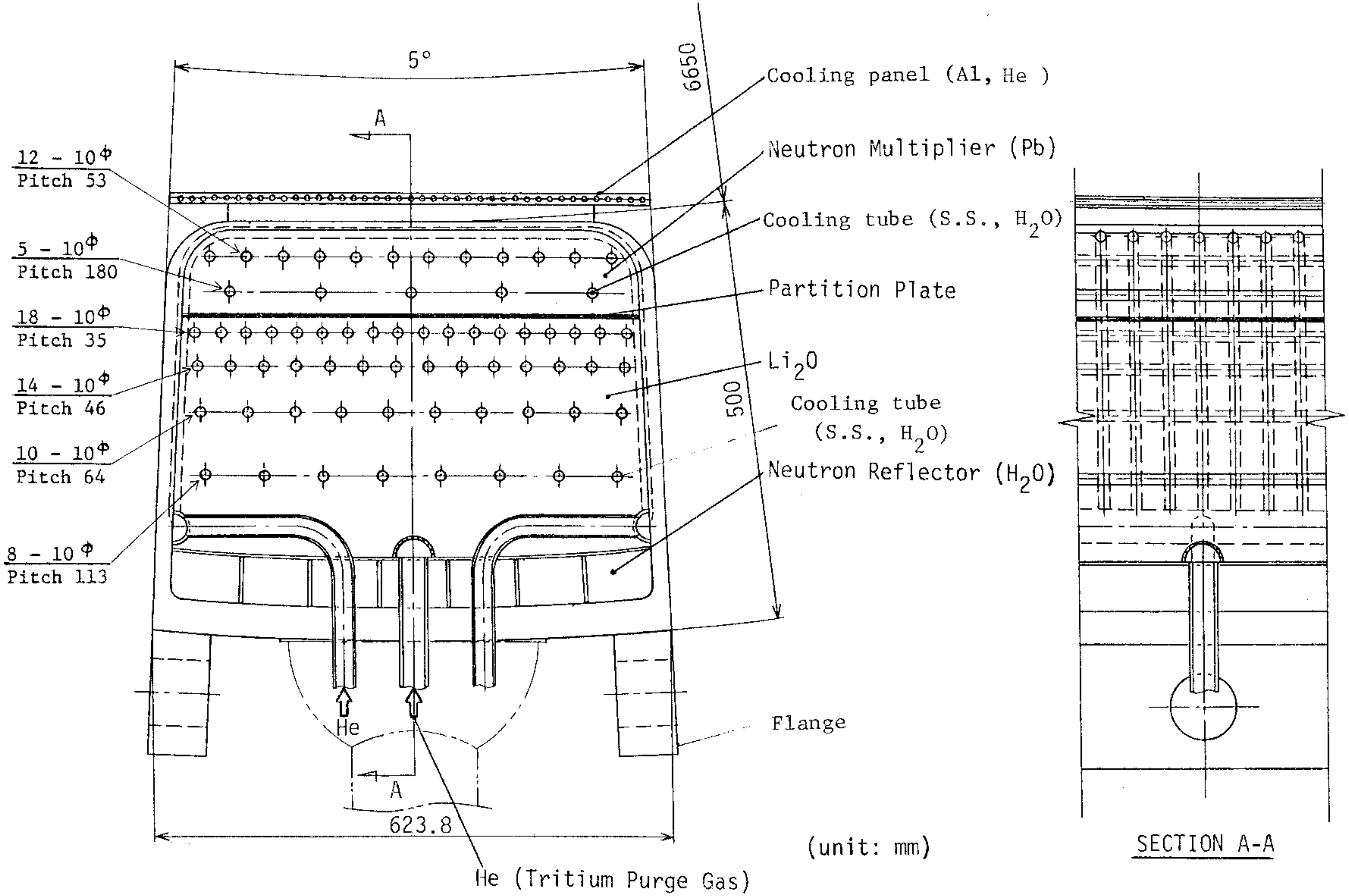
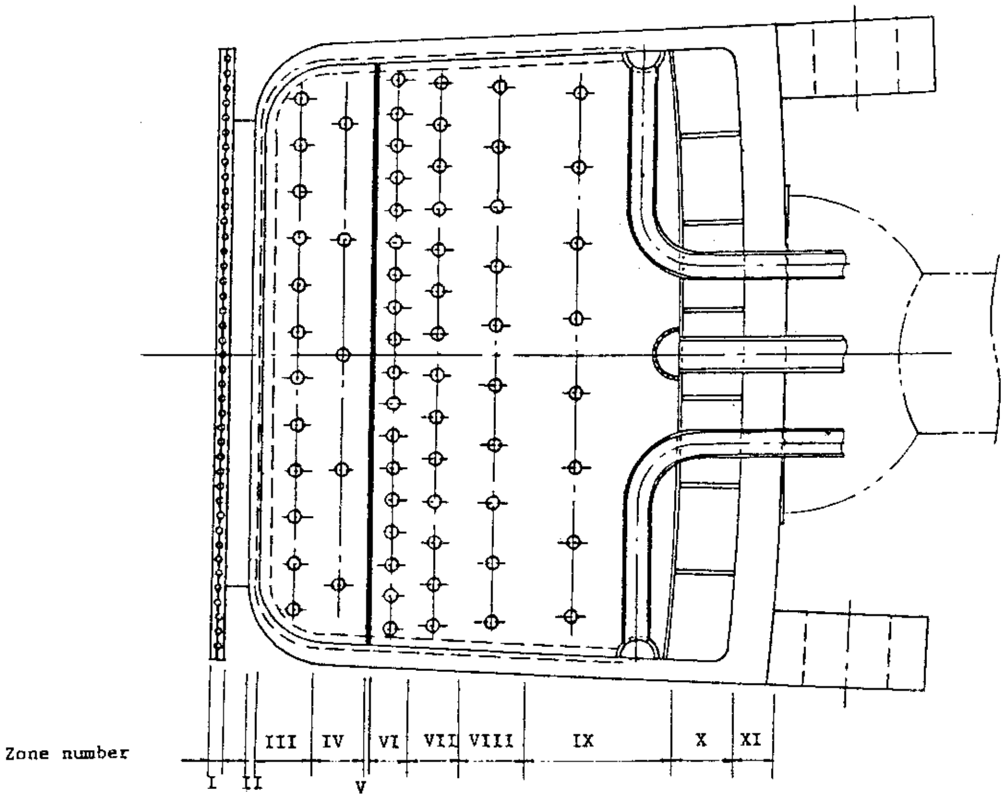


Fig.2.2 Cross sectional view of outboad blanket ring

Table 2.1 Volume ratio of each element

Structure Component	Zone number	Thickness (mm)	Volume ratio of each element
Cooling panel	I	13	Al(60%),Void(40%)
Front wall	II	10	SS(70%),Void(30%)
Lead region	III	58	Pb(91%),SS(7%),H_2O(3%)
	IV	42	Pb(92%),SS(6%),H_2O(2%)
Partition plate	V	4	SS(53%),Al_2O_3(47%)
Lithium oxide region	VI	36	Li_2O(58%),SS(11%),H_2O(6%),Void(25%)
	VII	46	Li_2O(61%),SS(9%),H_2O(4%),Void(26%)
	VIII	64	Li_2O(63%),SS(8%),H_2O(2%),Void(27%)
	IX	85	Li_2O(64%),SS(7%),H_2O(1%),Void(28%)
	X	115	Li_2O(32%),SS(12%),H_2O(42%),Void(14%)
Back plate	XI	40	SS(100%)



3. Thermal analysis

Thermal analysis has been carried out to decide arrangements of cooling tubes in blanket. In the case of the lead layer, thermal effect of gap produced between lead and stainless steel cooling tube is taken into account.

3.1 Optimum arrangement of cooling tubes in lithium oxide layer

Thermal calculational model is shown in Fig.3.1. Temperature distribution around the coolant brought about by heat generations due to neutron and gamma ray are given as follows.

$$T_3 - T_2 = -\frac{q_2}{4\lambda_2}(r_3{}^2 - r_2{}^2) + \frac{q_2\ r_3^2}{2\lambda_2} \cdot \ell n\,\frac{r_3}{r_2} \tag{3.1}$$

$$T_2 - T_1 = -\frac{q_1}{4\lambda_1}(r_2^2 - r_1^2) + \frac{q_2 r_3^2 - (q_2 - q_1) r_2^2}{2\lambda_1} \cdot \ell n\,\frac{r_2}{r_1} \tag{3.2}$$

$$T_1 - T_0 = \frac{1}{2\,\alpha\, r_1}\{q_2(r_3^2 - r_2^2) + q_1(r_2^2 - r_1^2)\} \tag{3.3}$$

where,

T_0 : coolant temperature ~70 °C
T_1 : temperature at the inner surface of cooling tube
T_2 : temperature at the outer surface of cooling tube
T_3 : temperature at the radius r_3 ~1200 °C
q_1 : heat generation rate in s.s cooling tube
q_2 : heat generation rate in lithium oxide
λ_1 : thermal conductivity of stainless steel
λ_2 : effective thermal conductivity of lithium oxide
r_1 : inner radius of cooling tube
r_2 : outer radius of cooling tube
r_3 : equivalent radius of the cell cooled by the cooling tube
α : heat transfer coefficient

Nuclear heating rates as shown in Fig.3.3 obtained by neutronics calculation is used in this analysis. If T_0 and T_3 are set to be constant we can obtain the relations between pitches of cooling tubes (r_3) and heat generation rate. Figure 3.4 shows the result with coolant temperature of 70°C and the maximum Li_2O temperature of 1200 °C.

Optimum arrangement of cooling tubes in lithium layer is decided as shown in Fig.2.2.

The lowest temperature of Li_2O may be required to be higher than 400°C from the stand point of tritium recovery. When temperature of outer surface of cooling tubes (T_2) is below 400°C sleeves around the tubes with helium gaps between them may work to make the lowest temperature of Li_2O above 400°C.

3.2 Optimum arrangement of cooling tubes in lead layer

Lead layer in blanket will be fabricated by pouring the liquid lead into the blanket vessel with the cooling tubes made of stainless steel. Thermal stress will be caused by the difference of thermal expansions between lead and cooling tube in a process of solidification of lead. Maximum stress in lead is 7.2 kg/mm^2 and -32 kg/mm^2 in stainless steel tube. Cracks will be produced in the lead around the stainless steel tube, since the ultimate strength of the lead is about 2 kg/mm^2. When temperatures of cooling tube and lead rise from room temperature to operating temperature, gaps might be caused between cooling tubes and lead.

Temperature rise of lead layer around the tubes is about 150 °C during normal operation and the width of the gap becomes about 20 μm. The gap is expected to be filled with helium purge gas. Thermal calculational model with helium gap between lead and cooling tube is illustrated in Fig.3.2. Temperatures around the coolant are given as follows.

$$T_3 - T_g = -\frac{q_2}{4\lambda_2}(r_3^2 - r_g^2) + \frac{q_2 r_3^2}{2\lambda_2} \cdot \ell n \frac{r_3}{r_g} \tag{3.4}$$

$$T_g - T_2 = \frac{q_2}{2\lambda_g}(r_3^2 - r_g^2) \cdot \ell n \frac{r_g}{r_2} \tag{3.5}$$

$$T_2 - T_1 = -\frac{q_1}{4\lambda_1}(r_2^2 - r_1^2) + \frac{q_2(r_3^2 - r_g^2) + q_2 r_2^2}{2\lambda_1} \cdot \ell n \frac{r_2}{r_1} \tag{3.6}$$

$$T_1 - T_0 = \frac{1}{2\alpha r_1}\{q_2(r_3^2 - r_g^2) + q_1(r_2^2 - r_1^2)\} \tag{3.7}$$

where,

T_0 : coolant temperature ~70 °C
T_1 : temperature at inner surface of cooling tube
T_2 : temperature at outer surface of cooling tube
T_g : temperature at inner surface of lead
T_3 : temperature at r_3 ~250 °C
q_1 : heat generation rate in stainless steel cooling tube
q_2 : heat generation rate in lead
λ_1 : thermal conductivity of stainless steel
λ_2 : thermal conductivity of lead
λ_g : thermal conductivity of helium gas
r_1 : inner radius of cooling tube
r_2 : outer radius of cooling tube
r_g : inner radius of lead
r_3 : equivatent radius of the cell cooled by the cooling tube
α : heat transfer coefficient

The relation between pitches of cooling tubes and heat generation rates in the lead layer is obtained as shown in Fig.3.5 by the same process as in Li_2O region. Arrangement of cooling tubes in lead layer is determined as shown in Fig.2.2.

It is found that a temperature drop of about 40 °C is caused in helium gas layer of 20 μm gap. The relation between pitch of cooling tubes ($2 \cdot r_3$) and heat generation rate in the front wall is also obtained as shown in Fig.3.6. Since nuclear heating rate of the front wall is 10 W/cc the pitch of cooling tube is selected to be 30 mm.

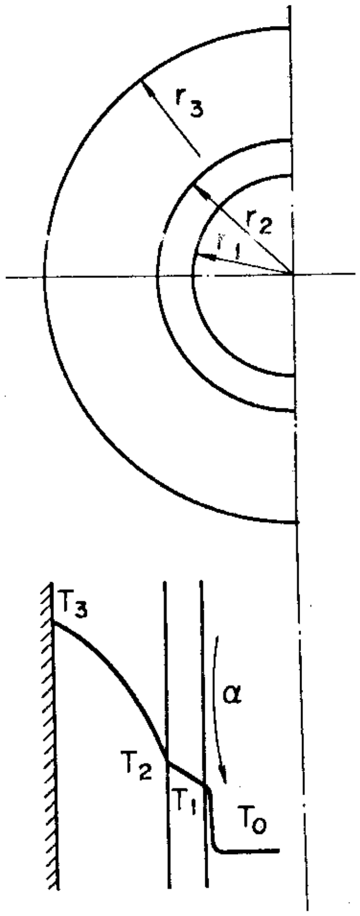


Fig.3.1 Thermal calculational model without helium gas gap.

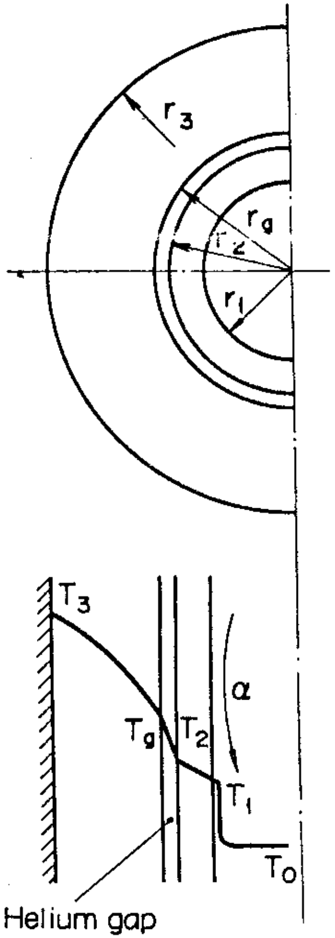


Fig.3.2 Thermal calculational model with helium gas gap

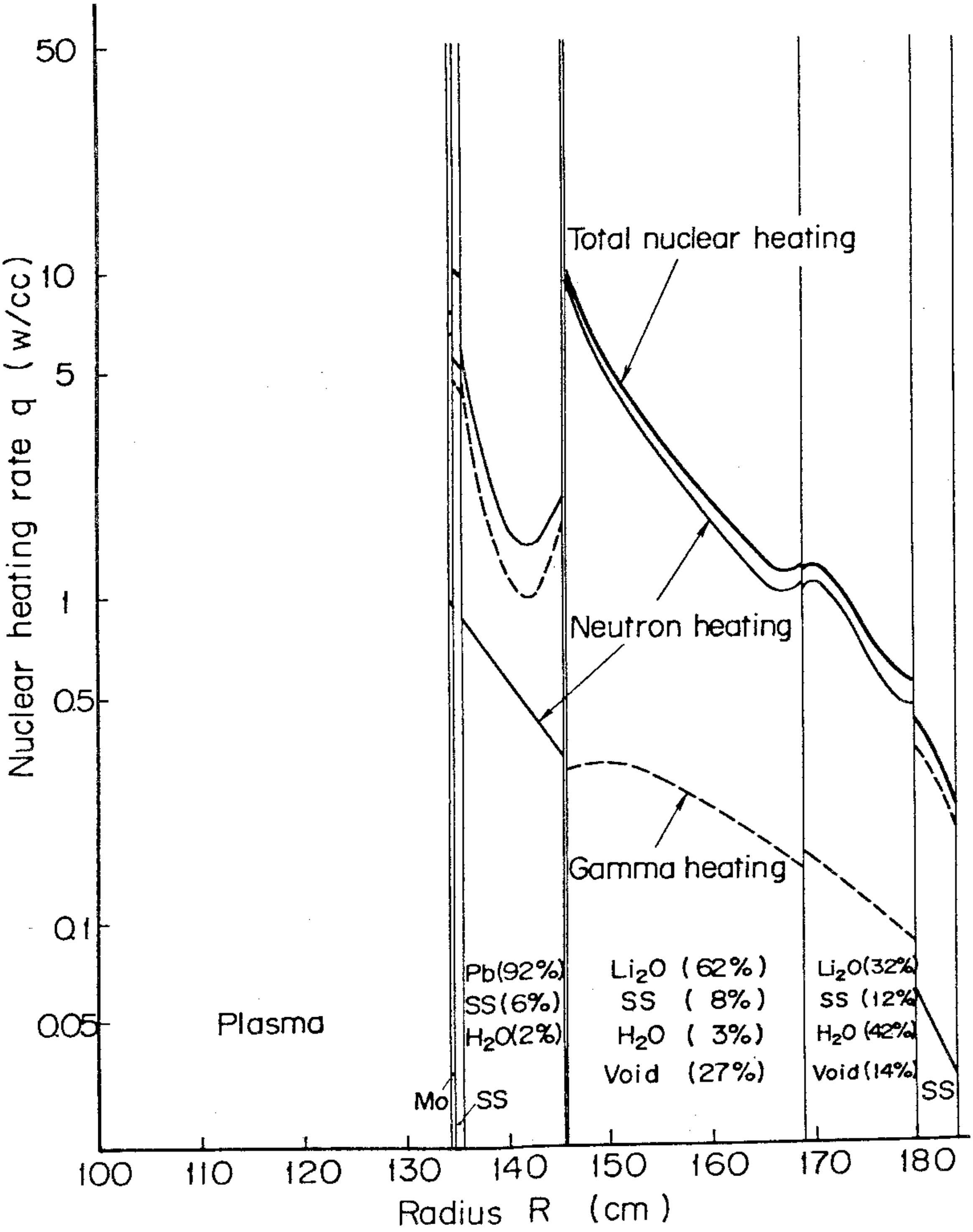


Fig. 3.3 Nuclear heating rate in the blanket

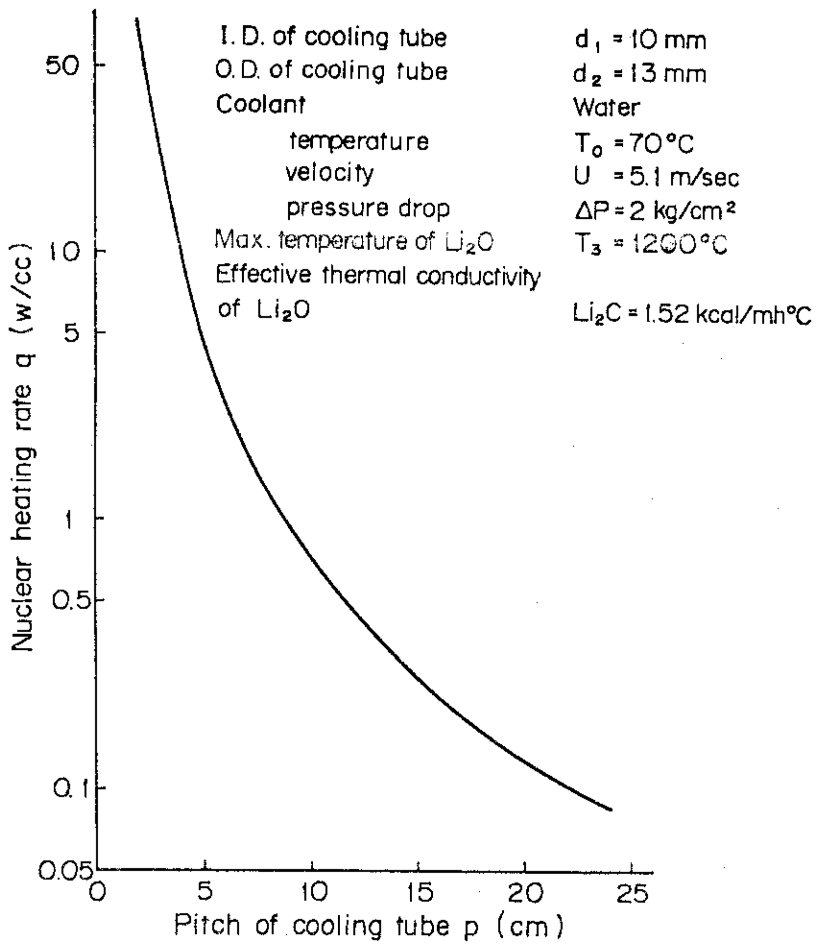


Fig. 3.4 Nuclear heating rate and pitch of cooling tube in lithium region

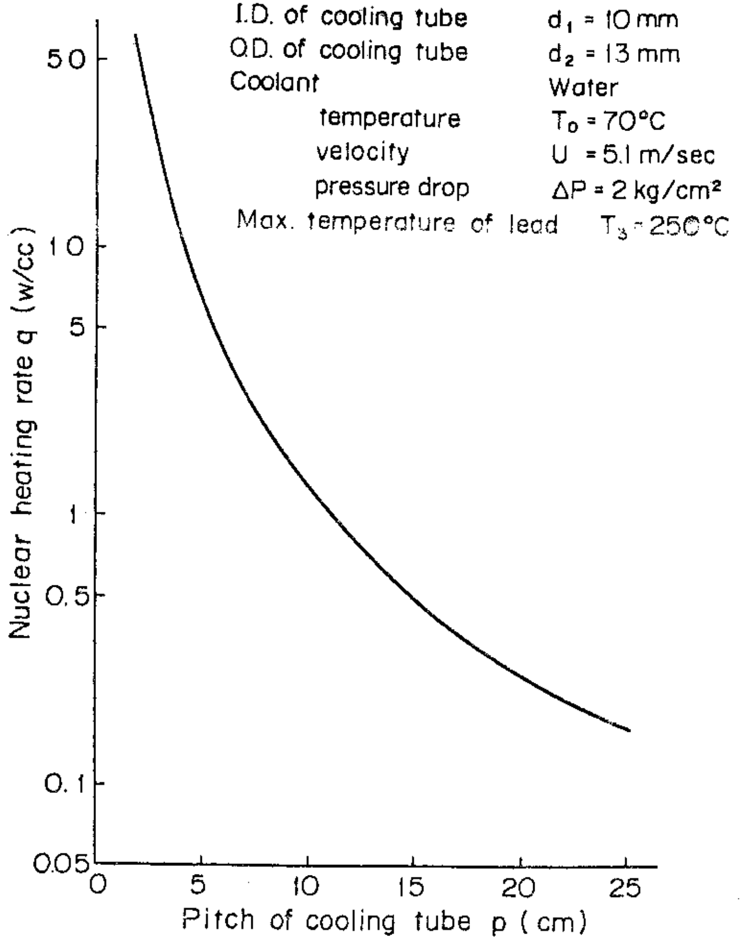


Fig. 3.5 Nuclear heating rate and pitch of cooling tube in lead region

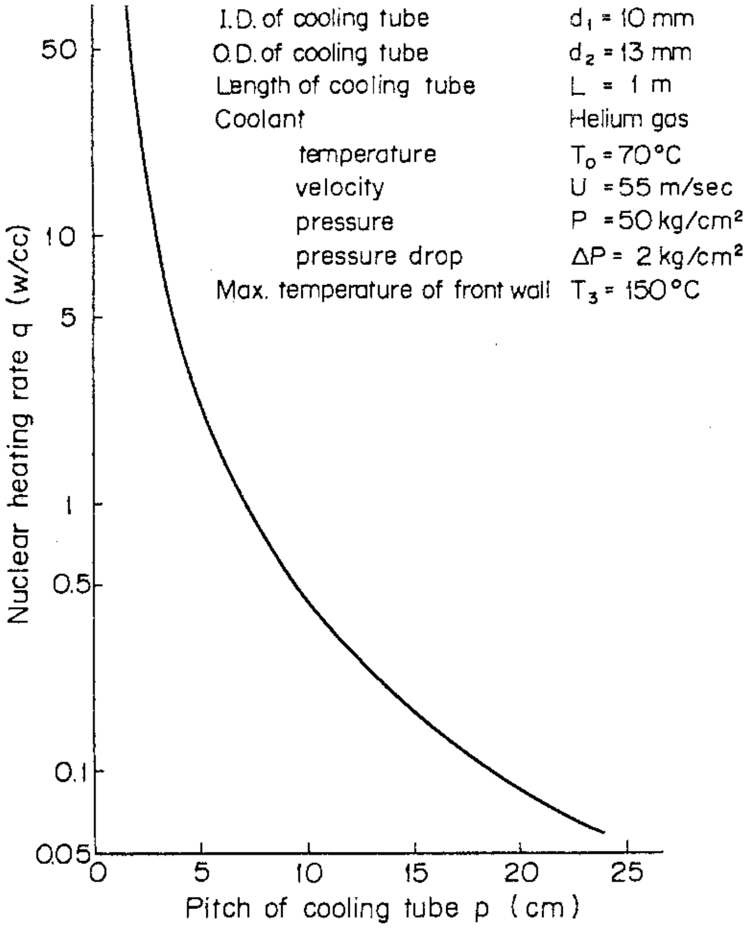


Fig. 3.6 Nuclear heating rate and pitch of cooling tube in front wall of blanket vessel

4. Stress analysis

Stress analysis of blanket vessel has been carried out taking into account of inner pressure of 1 kg/cm^2, and thermal stress.

4.1 Maximum stress in blanket vessel due to inner pressure

Since pressure of tritium purge gas is 1 kg/cm^2 and outside of the vessel is vacuum, vessel should endure the inner pressure of 1 kg/cm^2. Stress of blanket vessel is estimated by assuming that blanket vessel is approximately a straight tube with a square cross section and rounded corners as shown in Fig.4.1. Since longitudinal stress is small enough in comparison with stress in the cross section, it is neglected in this calculation. Stresses of each position in a blanket vessel are given by the followings.

(1) At the corner of vessel

$$\frac{M}{Pb^2} = \frac{M_B}{Pb^2} - \sqrt{2} \cdot n(1 - \cos\varphi)$$

$$\frac{N}{Pb} = 1 + \sqrt{2} \cdot \cos\varphi$$

$$\sigma = \frac{N}{h} \pm 6\,\frac{M}{h^2}$$

(2) At the straight part

$$\frac{M}{Pb^2} = \frac{M_A}{Pb^2} + \frac{n^2}{2} \cdot \frac{x^2}{a^2}$$

$$\frac{N}{Pb} = n + 1$$

where, $$\frac{M_B}{Pb^2} = \sqrt{2} \cdot n - \frac{4n}{\pi + 4n}\left(1 + n - \frac{n^2}{3}\right)$$

$$\frac{M_A}{Pb^2} = \frac{M_B}{Pb^2} - \frac{n^2}{2} + (1 - \sqrt{2})\,n$$

h : thickness of blanket vessel
front wall : 7.5 mm
corner : 10 mm
b : curvature of the corner
a : length of the straight part

φ : angle of the corner

p : inner pressure

n : a/b

N : membrane force

M_A, M_B : bending moments at point A and B, respectively

σ : stress in vessel

Maximum stresses of corner and straight part are 15.4 kg/mm^2 at the point B and 16.8 kg/mm^2 at the point A. These stresses corresponds to $P_L + P_b$ in ASME Boiler and Pressure Vessel Code Section III, and must be less than 1.5 Sm. Since allowable stress (Sm) of Type 316 stainless steel at 150 °C is 12 kg/mm^2, blanket vessel has an enough safety margin against inner pressure.

4.2 Maximum stress in blanket vessel due to thermal load

Heat deposition rate in the front wall of blanket vessel is 14 W/cc as shown in Fig.3.3. Temperature difference between inner and outer surface of the front wall becomes 43 °C according to following equation.

$$\Delta T = \frac{qh^2}{2\lambda}$$

where ΔT : temperature drop between inner and outer surface of front wall

λ : thermal conductivity of stainless steel

h : thickness of vessel

q : heat deposition rate in the front wall

Maximum thermal stress in the front wall is estimated to be 10.3 kg/mm^2 by using a equation of $\sigma = E\alpha\Delta T / 2(1-v)$.

Here, E : Young's modulus

v : Poisson's ratio

α : thermal expansion coefficient

Total stress in the front wall of blanket vessel becomes 27.1 kg/mm^2. This stress corresponds to $P_L + P_b + Q$ in ASME Boiler and Pressure Vessel Code Section III, and must be less than 3 Sm, 36 kg/mm^2. Therefore, blanket vessel has an enough safety margin against both inner pressure and thermal load.

The calculation of stress due to dead weights of lead and lithium oxide has been carried out using beam model in which the blanket vessel is assumed to be straight beam with end supports and uniform load.

Stress of vessel due to the dead weights becomes about 4.8 kg/mm^2. Detail stress analysis against seismic load should be carried out in future.

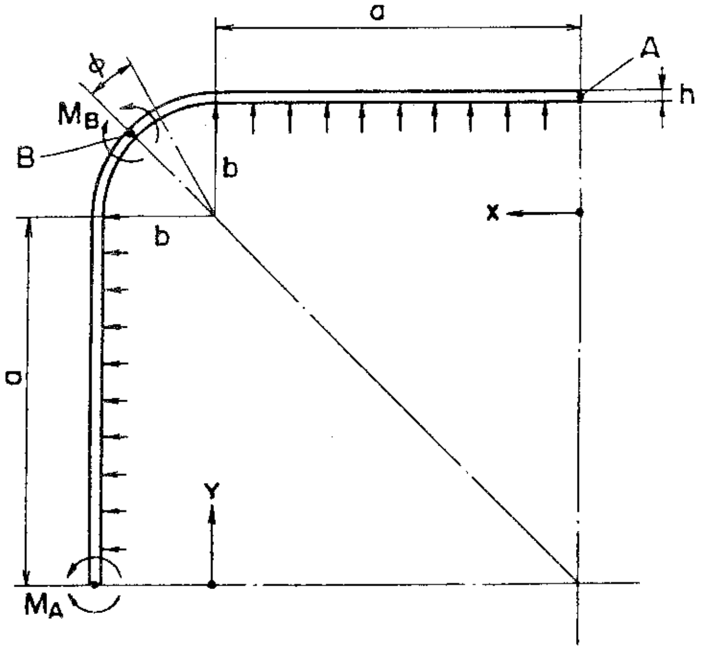


Fig.4.1 Stress calculational model of blanket vessel

5. Shell effect of the blanket

Shell effect of the blanket vessel in which a lead layer is contained at the plasma side has been evaluated in this section.

5.1 Analytical model

The blanket is assumed to be connected in the poloidal direction and to be formed with 72 blanket rings in the toroidal direction. The electrical resistance of the rip seal between the adjacent blanket rings is very high, therefore the analytical model devided into 72 blanket rings, which has an electorical insulation between adjacent blanket rings, is employed to calculate the shell effect.

The cooling panel of Al alloy is attached in front of the blanket vessel. An effective resistance in parallel circuit of a lead and Al alloy is employed to calculate the shell effect.

Material	Thickness (m)	Resistivity ($\times 10^{-8}$ Ωm)
Al alloy	0.013	4.0
Lead	0.10	20.0

Effective resistance : 1.21×10^{-6} Ω

The Finite Element Circuit Method Code "EDDYTORUS" is employed in this analysis.

5.2 Analytical results

In order to simulate the positional instability of a plasma, we swung up and down the plasma which is assumed to be a line plasma and calculated the time constant from the variations of the mutual inductance for each current mode.

The time constants from the first mode to the tenth were 60 - 38 msec. From the above results, it is estimated that the time constant in this model will be about 44 msec. This value is near the lowest of the time constant (50 - 150 msec) required as the shell effect. Figure 5.1 shows decay time constant and current distribution of the first mode. If the blanket is devided into 36 blanket sectors each of which

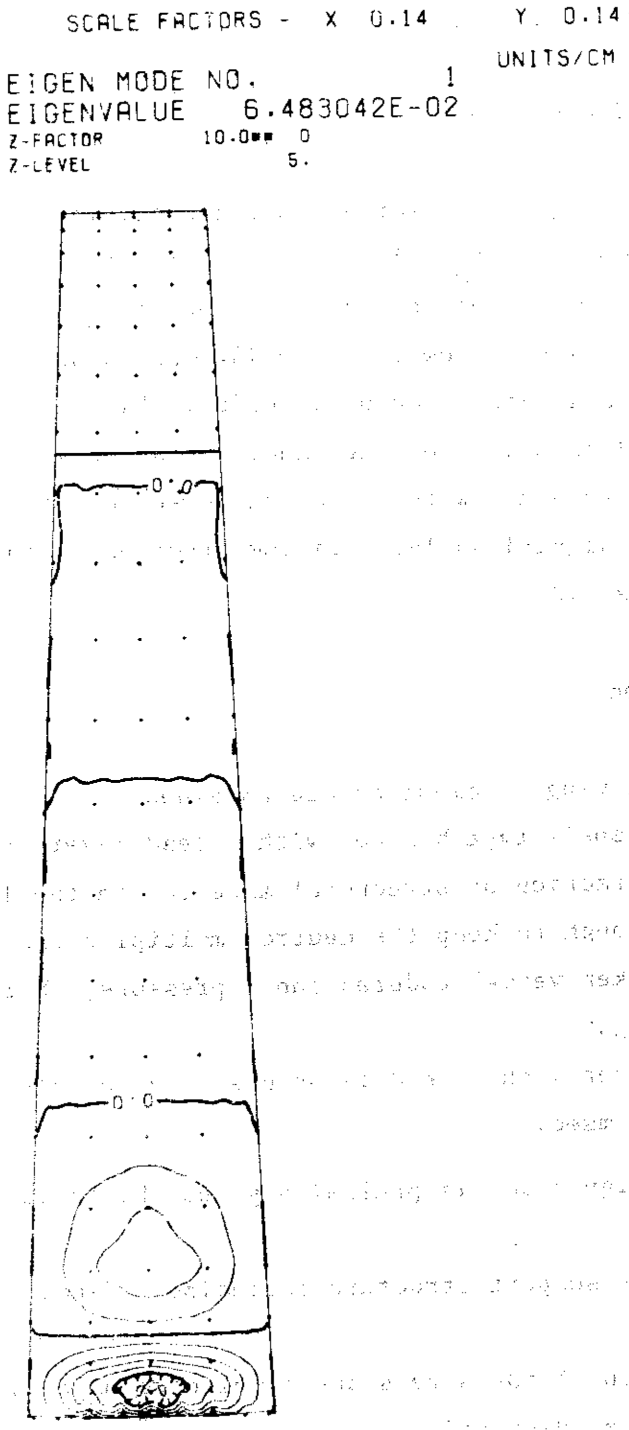


Fig.5.1 Decay time constant and current distribution of the first mode

is consists of two electrically connected blanket rings, the time constant will be 85 msec.

6. Alternative design

In front of the blanket a cooling panel is necessary for removing radiation power from the plasma. Since light water in cooling panel deteriorate neutron multiplication effect of lead layer helium gas is selected as coolant. However, cooling the pannel with helium gas causes severe problem in its structural design. Figure 6.1 shows our alternative proposal in which cooling panel, vessel wall, lead layer and Li_2O are cooled with heavy water. In this case the structural problems will be moderated significantly. Tritium breeding ratio of this blanket is calculated as 1.27.

7. Conclusion

The following conclusions are obtained

(1) Tube in shell type blanket with a lead layer is promising. The volume fraction of structural material in the lead layer can be small enough to keep the neutron multiplication effect of lead.

(2) The blanket vessel endures inner pressure, thermal stress and its dead weight.

(3) The blanket with a lead layer has a reasonable shell effect of about 50 msec.

This design study is preliminary and the followings should be studied futher.

(a) Design of support structure including seisemic analysis.

(b) Estimation of the stress due to electro magnetic force accompanied with plasma disruption.

(c) Estimation of tritium inventry in the blanket.

(d) Safety analysis including piping rupture.

(e) Detail cooling panel design including its support structure.

is consists of two electrically connected blanket rings, the time constant will be 85 msec.

6. Alternative design

In front of the blanket a cooling panel is necessary for removing radiation power from the plasma. Since light water in cooling panel deteriorate neutron multiplication effect of lead layer helium gas is selected as coolant. However, cooling the pannel with helium gas causes severe problem in its structural design. Figure 6.1 shows our alternative proposal in which cooling panel, vessel wall, lead layer and Li_2O are cooled with heavy water. In this case the structural problems will be moderated significantly. Tritium breeding ratio of this blanket is calculated as 1.27.

7. Conclusion

The following conclusions are obtained

(1) Tube in shell type blanket with a lead layer is promising. The volume fraction of structural material in the lead layer can be small enough to keep the neutron multiplication effect of lead.

(2) The blanket vessel endures inner pressure, thermal stress and its dead weight.

(3) The blanket with a lead layer has a reasonable shell effect of about 50 msec.

This design study is preliminary and the followings should be studied futher.

(a) Design of support structure including seisemic analysis.

(b) Estimation of the stress due to electro magnetic force accompanied with plasma disruption.

(c) Estimation of tritium inventry in the blanket.

(d) Safety analysis including piping rupture.

(e) Detail cooling panel design including its support structure.

is consists of two electrically connected blanket rings, the time constant will be 85 msec.

6. Alternative design

In front of the blanket a cooling panel is necessary for removing radiation power from the plasma. Since light water in cooling panel deteriorate neutron multiplication effect of lead layer helium gas is selected as coolant. However, cooling the pannel with helium gas causes severe problem in its structural design. Figure 6.1 shows our alternative proposal in which cooling panel, vessel wall, lead layer and Li_2O are cooled with heavy water. In this case the structural problems will be moderated significantly. Tritium breeding ratio of this blanket is calculated as 1.27.

7. Conclusion

The following conclusions are obtained

(1) Tube in shell type blanket with a lead layer is promising. The volume fraction of structural material in the lead layer can be small enough to keep the neutron multiplication effect of lead.

(2) The blanket vessel endures inner pressure, thermal stress and its dead weight.

(3) The blanket with a lead layer has a reasonable shell effect of about 50 msec.

This design study is preliminary and the followings should be studied futher.

(a) Design of support structure including seisemic analysis.

(b) Estimation of the stress due to electro magnetic force accompanied with plasma disruption.

(c) Estimation of tritium inventry in the blanket.

(d) Safety analysis including piping rupture.

(e) Detail cooling panel design including its support structure.

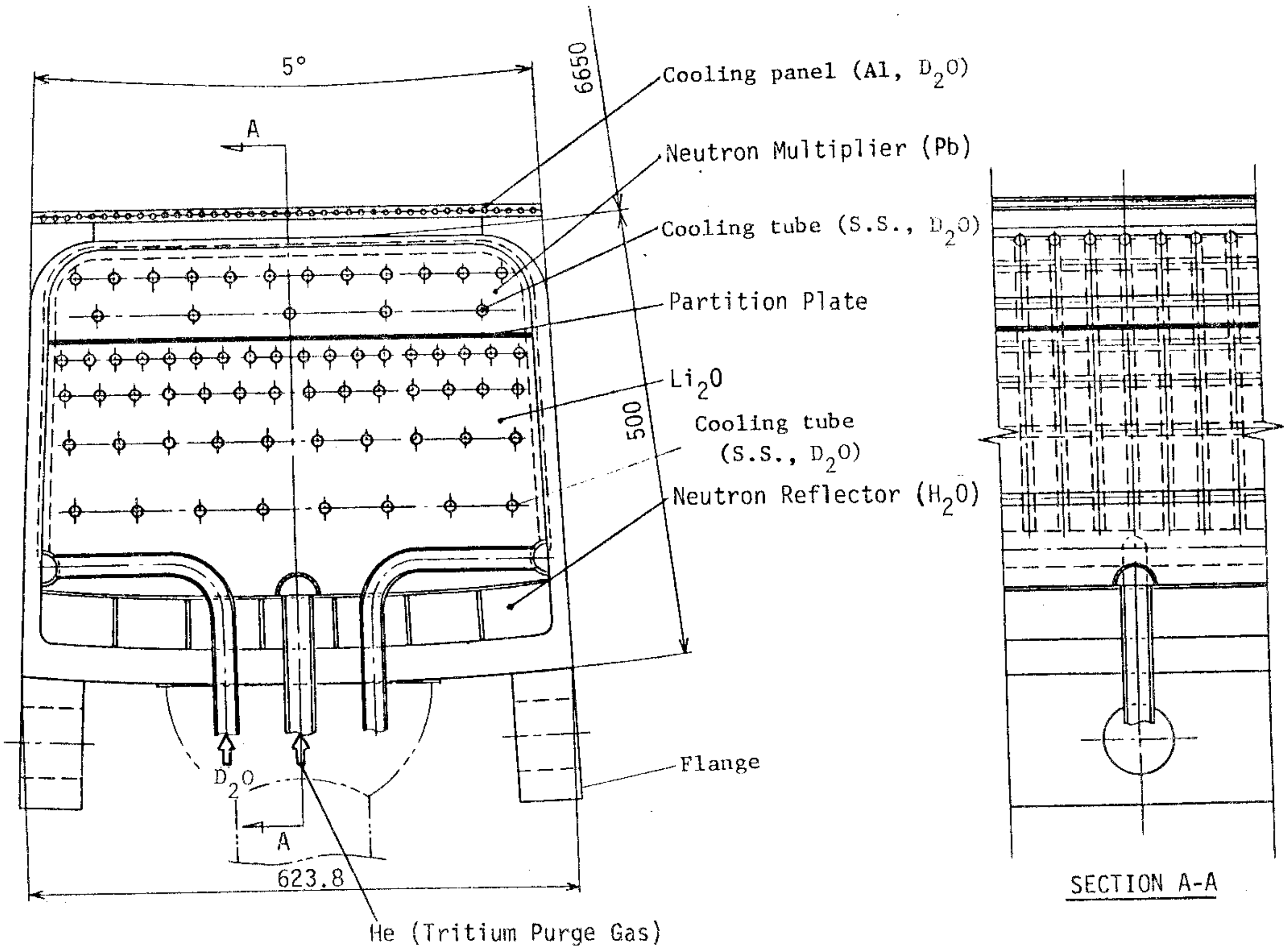


Fig.6.1 Cross sectional view of alternative blanket ring