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A thermal design study of a tritium breeding blanket of a fusion reactor is conducted. A cooling structure with a helium gas gap between the cooling tube and the breeding material (Li_2O) is employed in order to keep the temperature of Li_2O within the range of 400°C to 1200°C. We determined, in detail, an optimum helium gap width and optimum cooling tube pitches in the Li_2O region taking into account the estimation error of nuclear heat deposition and the manufacturing error of the cooling tube.

The optimum helium gap width is selected to be 0.75 mm and the optimum cooling tube pitch of each row to be from 30 mm for the innermost row to 70 mm for the outermost row.

Keywords: Tokamak Reactor, Experimental Reactor, Tritium Breeding Blanket, Tube-in-Shell Type Blanket, Breeding Material of Li_2O, Thermal Analysis

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* On leave from Toshiba Corporation, Yokohama, Japan

核融合増殖ブランケットの熱設計

日本原子力研究所 東海研究所 核融合研究部

喜多村和憲*・飯田浩正・迫　淳

（1982年2月19日受理）

国内次期装置の一候補であるスイミングプール型トカマク炉の増殖ブランケットについて熱設計を行なった。ブランケットはチューブインシエルタイプとし，トリチウム増殖領域内 Li_2O 温度を400℃以上，1200℃以下に保つため，冷却管 Li_2O 間にヘリウムガス層を設ける構造とした。又，Li_2O 領域内の発熱密度誤差および冷却管の製作精度を考慮して最適ヘリウムギャップおよび最適冷却ピッチを決定した。

その結果，ヘリウムギャップは 0.75 mm となり，冷却管ピッチは最内列で 30 mm，最外列で 70 mm となった。

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* 外来研究員（東芝）

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1. Introduction

A thermal design study of a tritium breeding blanket with a lead layer is performed. The breeding blankets of a fusion reactor are placed closely around the plasma to produce the tritium by ^{6}Li(n, α)T and ^{7}Li(n, n' α)T reactions. The blankets are operated under severe conditions from the stand points of both thermal and mechanical design.

The following features are required for the thermal design of blanket.

① Radiation heat flux from the plasma and nuclear heat deposition due to neutron and gamma-ray should be sufficiently removed.

② The temperature of structural material, Type 316 stainless steel, is restricted so as not to exceed 350 °C in order to avoid the material damage due to neutron irradiation and to prevent high temperature and pressure of the coolant.

③ Tritium produced in the breeding material, lithium oxide, must be easily extracted from the blanket. Then, the temperature of lithium oxide must be in a suitable range [1]. In this report, the upper limit of the lithium oxide temperature is selected to be 1200°C and lower limit to be 400°C. The upper limit is generously determined for the following reasons.

- (i) The wide temperature range is required to increase the tritium breeding ratio by reducing the volume fraction of structural material.
- (ii) The equivalent thermal conductivity of lithium oxide in this analysis is slightly under-estimated because no account has been taken of the self-convection by helium gas among the lithium oxide pebbles. The maximum temperature of the lithium oxide in this study is estimated to be slightly higher than the actual temperature.

Some different consideration for the allowable temperature range of lithium oxide have been proposed in recent years. Thus, further study of the allowable temperature range is required.

In this report, we have conducted the thermal design study of the balnket in the fusion reactor. Special considerations are given to the design study of the temperature distribution around the cooling tube and the determination of the optimum cooling pitches in the lithium oxide layer.

This design study is applied to the balnket structure of a Swimming Pool Type Tokamak Reactor (SPTR) which is one of the candidates for the Next Tokamak Reactor of JAERI.

The vertical view of the SPTR is shown in Fig.1[2].

2. Configuration of breeding balnket structure

The vertical cross sectional view of the reactor module is shown in Fig.2[2]. Figure 3 illustrates the plane view of the outboard reactor module. The reactor structure consists of 24 reactor modules, each of which is composed of two inboard blanket segments, two outboard blanket segments, two divertor collector plates and a single vacuum vessel sector. The blanket segments are supported by the vacuum vessel.

A "Tube in Shell Type" structure is employed for the blanket segments. In order to obtain enough loop resistance in the toroidal direction, the adjacent balnket segments are electrically insulated from each other and bellows are installed on the center line of the vacuum vessel sector. Both the inboard and outboard blankets contain a lead layer as neutron multiplier, a lithium oxide (Li_2O) as tritium breeding material and light water as neutron moderator and reflector. The lead layer is installed most closely to plasma side and then the Li_2O region placed at the rear of the lead layer. The light water layer is arranged on the rear of the Li_2O region. These are separated from each other by a partition plate made of Type 316 stainless steel with alumina coating for thermal insulation.

Cooling tubes made of stainless steel are arranged in both the lead and Li_2O layers which are cooled by water. In order to minimize the volume fractions of the cooling tube and coolant in the lead and Li_2O layers, the diameter of the cooling tube must be as small as possible. The selection of 10 mm for the inner diameter and of 13 mm for the outer one of the tube may be realistic considering its fabrication.

The arrangement of cooling tubes in the lead layer is determined so that the maximum temperature of the lead is kept below 250°C. In order to keep the temperature of Li_2O within the allowable range of oxide layer.

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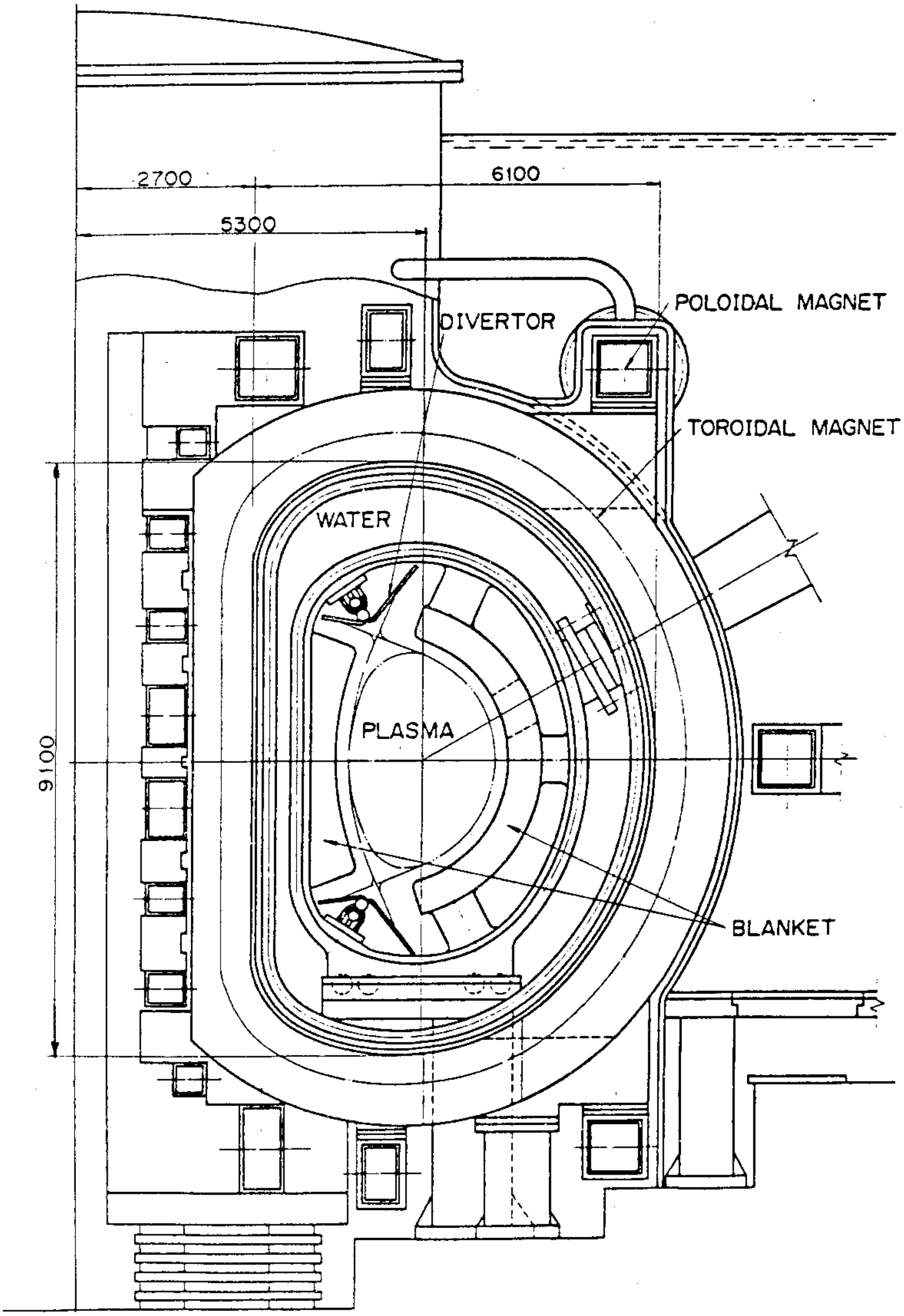

Fig.1 Vertical View of Swimming Pool Type Tokamak Reactor

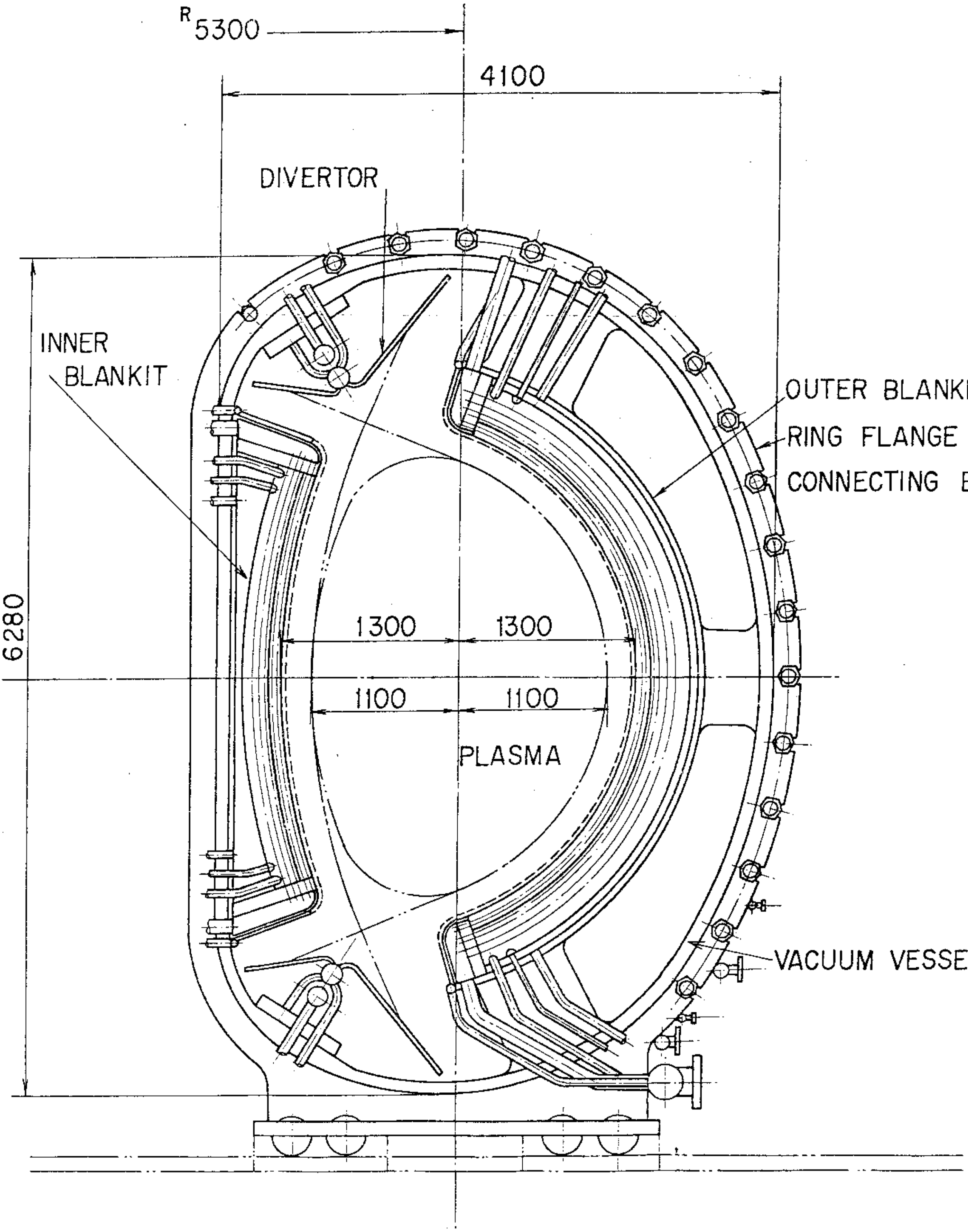

Fig.2 Vertical View of Reactor Module

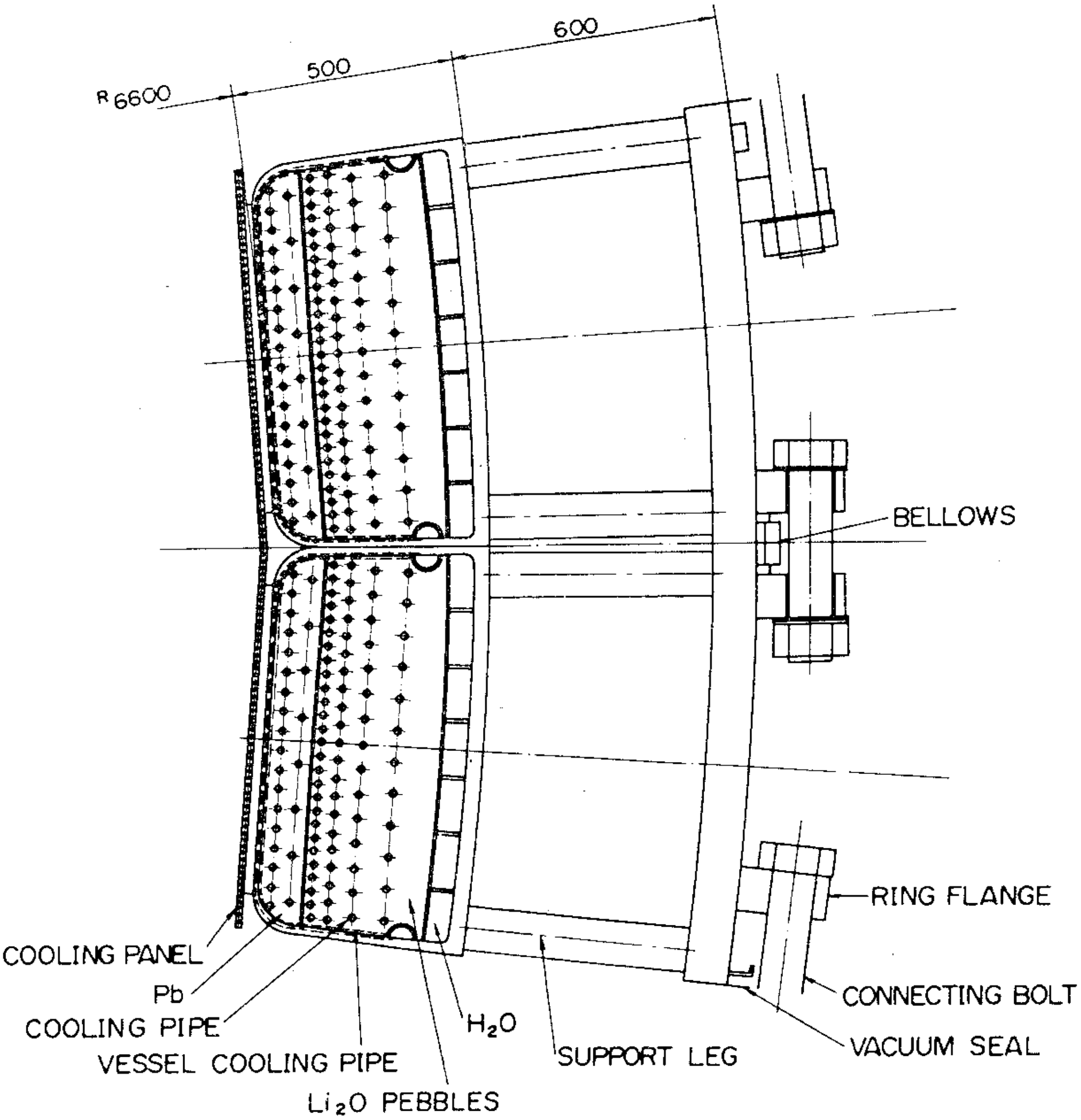

Fig.3 Horizontal View of Outboard Blanket Structure

400°C to 1200°C, a stainless steel sleeve with the thickness of 1 mm is installed between the cooling tube and Li_2O and a helium gas gap is kept between the sleeve and the tube. The pitches of the cooling tubes in the Li_2O region are selected so as to satisfy these temperature conditions for purging easily the tritium produced in the region with the use of helium gas.

A water layer is placed at the rear of the Li_2O region. It reflects neutrons and slows down their speed for easy absorption of neutrons by ^6Li.

3. Thermal design

The arrangement of cooling tubes in the lead layer is determined only by the restriction that the temperature of lead must be below 250°C. The pitches of the cooling tubes in the Li_2O region must be selected so that the temperature of Li_2O is within the range of 400°C to 1200°C. The procedure and results of the thermal analysis for the Li_2O region are described here since the selection of the cooling pitches in the Li_2O region is more complicated than that in the lead layer.

3.1 Effect of helium gas gap between cooling tube and breeding material

The one-dimensional thermal calculational models shown in Figs.4 and 5 are considered in order to obtain the rough temperature distribution around the coolant in the Li_2O region. The maximum temperature of Li_2O, T_p is set to be 1200°C and the coolant temperature to be 50°C in both cases shown in Figs.4 and 5. In the case of the model shown in Fig.4, the temperature of the outer surface of the cooling tube, T_2 is predicted to be below 400°C. As for the model shown in Fig.5, the temperature, T_2 can be above 400°C because of the existence of the helium gas gap. A thermal insulation sleeve such as an alumina sheet instead of the helium gas gap would be sensitive to neutron and gamma-ray irradiation and would have an unstable thermal conductivity in comparison with the helium gas gap.

Assuming the uniform distribution of the heat deposition rate in the calculational model, the temperature around the coolant in the

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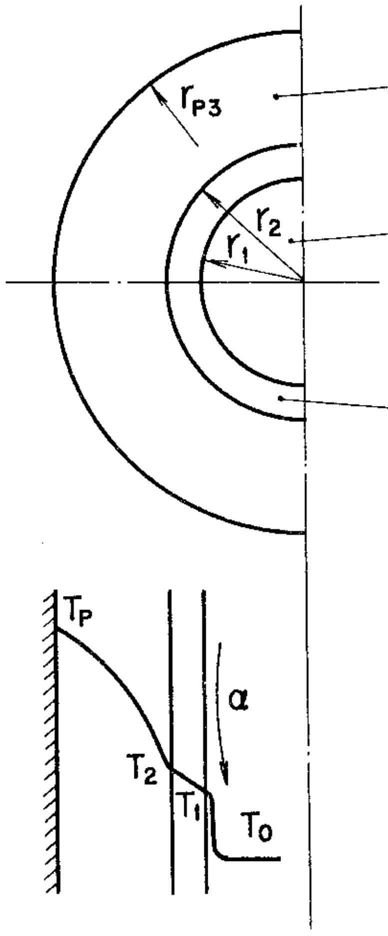


Fig. 4 Thermal calculational model without helium gas gap.

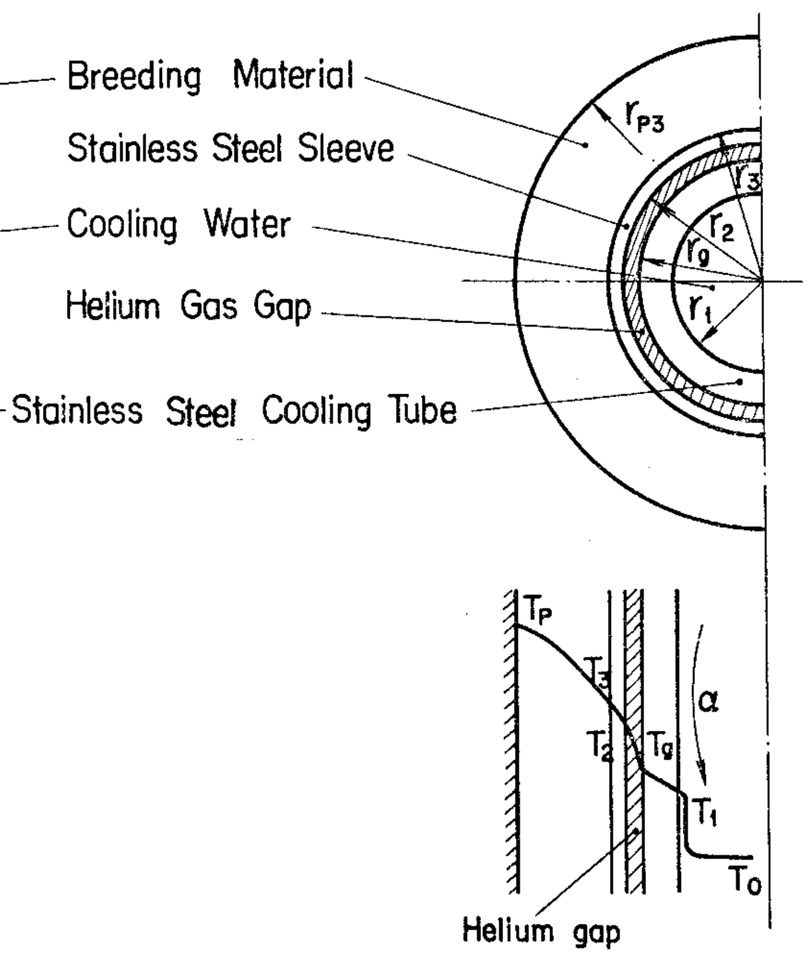


Fig. 5 Thermal calculational model with helium gas gap.

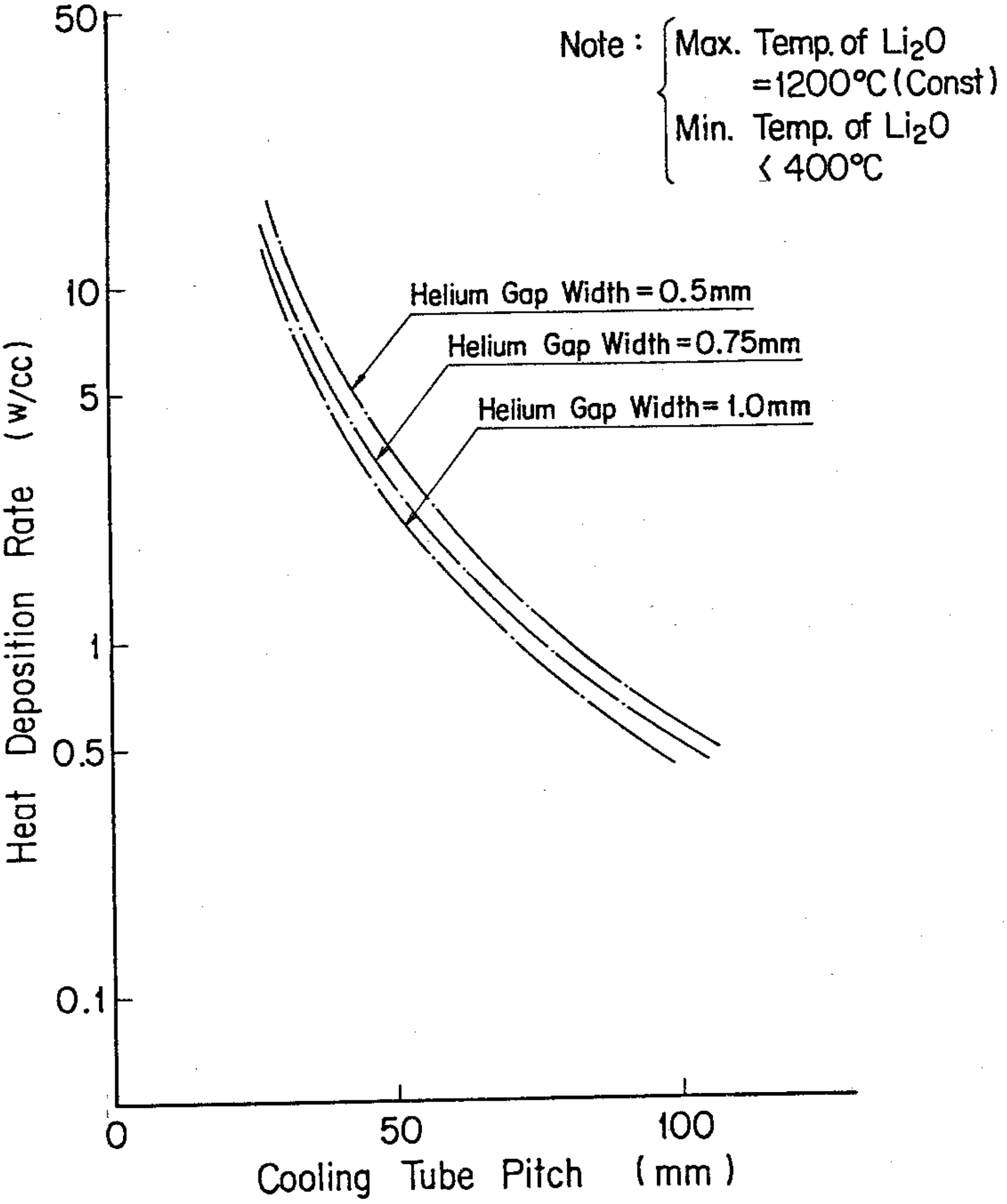


Fig. 6 Rough Estimation of the Relation between Nuclear Heating Rate and Cooling Tube Pitch

case of the model with the helium gas gap are given as follows.

$$T_p - T_3 = -\frac{q_2}{4\lambda_2}(r_p^2 - r_3^2) + \frac{q_2 r_p^2}{2\lambda_2} \cdot \ln\frac{r_p}{r_3} \qquad (1)$$

$$T_3 - T_2 = -\frac{q_1}{4\lambda_1}(r_3^2 - r_2^2) + \frac{q_2(r_p^2 - r_3^2) + q_1 \cdot r_3^2}{2\lambda_1} \ln\frac{r_3}{r_2} \qquad (2)$$

$$T_2 - T_g = \frac{q_2(r_p^2 - r_3^2) + q_1(r_3^2 - r_2^2)}{2\lambda g} \ln\frac{r_2}{r_g} \qquad (3)$$

$$T_g - T_1 = -\frac{q_1}{4\lambda_1}(r_g^2 - r_1^2) + \frac{q_2(r_p^2 - r_3^2) + q_1(r_3^2 - r_2^2 + r_g^2)}{2\lambda_1} \ln\frac{r_g}{r_1} \qquad (4)$$

$$T_1 - T_0 = \frac{1}{2\alpha r_1}\{q_2(r_p^2 - r_3^2) + q_1(r_3^2 - r_2^2 + r_g^2 - r_1^2)\} \qquad (5)$$

where,

T_0 : coolant temperature (°C)
T_1 : temperature at inner surface of cooling tube (°C)
T_g : temperature at outer surface of cooling tube (°C)
T_2 : temperature at inner surface of stainless steel sleeve (°C)
T_3 : temperature at inner surface of lithium oxide (°C)
T_p : temperature at r_p (°C)
q_1 : heat deposition rate in stainless steel (kcal/m^{3}h)
q_2 : heat deposition rate in lithium oxide (kcal/m^{3}h)
λ_1 : thermal conductivity of stainless steel (kcal/mh °C)
λ_2 : equivalent thermal conductivity of lithium oxide (kcal/mh°C)
λ_3 : thermal conductivity of helium gas (kcal/mh°C)
r_1 : inner radius of cooling tube (m)
r_g : outer radius of cooling tube (m)
r_2 : inner radius of stainless steel sleeve (m)
r_3 : outer radius of stainless steel sleeve (m)
r_p : equivalent radius of the cell cooled by cooling water ($= p/\sqrt{\pi}$) (m)
α : heat transfer coefficient of coolant (kcal/m^{2}h °C)
p : cooling tube pitch (m)

The cooling tube pitches in the Li_2O region, p can be obtained from the equations (1) ∿ (5), if the nuclear heat deposition rates q_1 and q_2 are known.

Figure 6 indicates the relation between nuclear heating rate and cooling tube pitch in the Li_2O region. In this figure, it is assumed that nuclear heat deposition rate in stainless steel, q_1 is equal to that in lithium oxide, q_2. These are obtained under the condition that maximum temperature of Li_2O is constant at 1200°C and minimum one is above 400°C. These equations include the assumption that the nuclear heat deposition rate is constant everywhere in the cell. However, it exponentially decreases from the plasma side to the outer side in the cell around the cooling tube. So the real maximum and minimum temperatures of Li_2O will be slightly different from the predicted temperatures.

3.2 Two-dimensional thermal analysis

In order to obtain the detailed temperature distribution around the cooling tube taking into account the exponential distribution of nuclear heat deposition in the Li_2O region, two-dimensional steady state thermal analysis of the cell around the cooling tube is carried out using the finite element method.

Figure 7 shows the nuclear heating rate distribution used in this analysis, which was obtained by a neutronics calculation [3]. Figure 8 illustrates the calculational model. The model includes only a half of the cell because of its symmetrical distribution of nuclear heat deposition. The surroundings of the cell are assumed to be in an adiabatic condition.

The temperature distribution in the cell by one-dimensional calculation is compared with that by two-dimensional analysis. From Figs.6 and 7 the cooling pitch of the first row's cooling tubes placed near the plasma side is shown to be 34 mm in the case of 0.75 mm helium gap width. The maximum and minimum temperatures of Li_2O are estimated to be 1200°C and 855°C, respectively, in the case of 34 mm cooling pitch and 0.75 mm helium gap width. The nuclear heat deposition rate is assumed to be uniform in the cell and the value for the center point of the cell is used. On the other hand, the temperature distribution

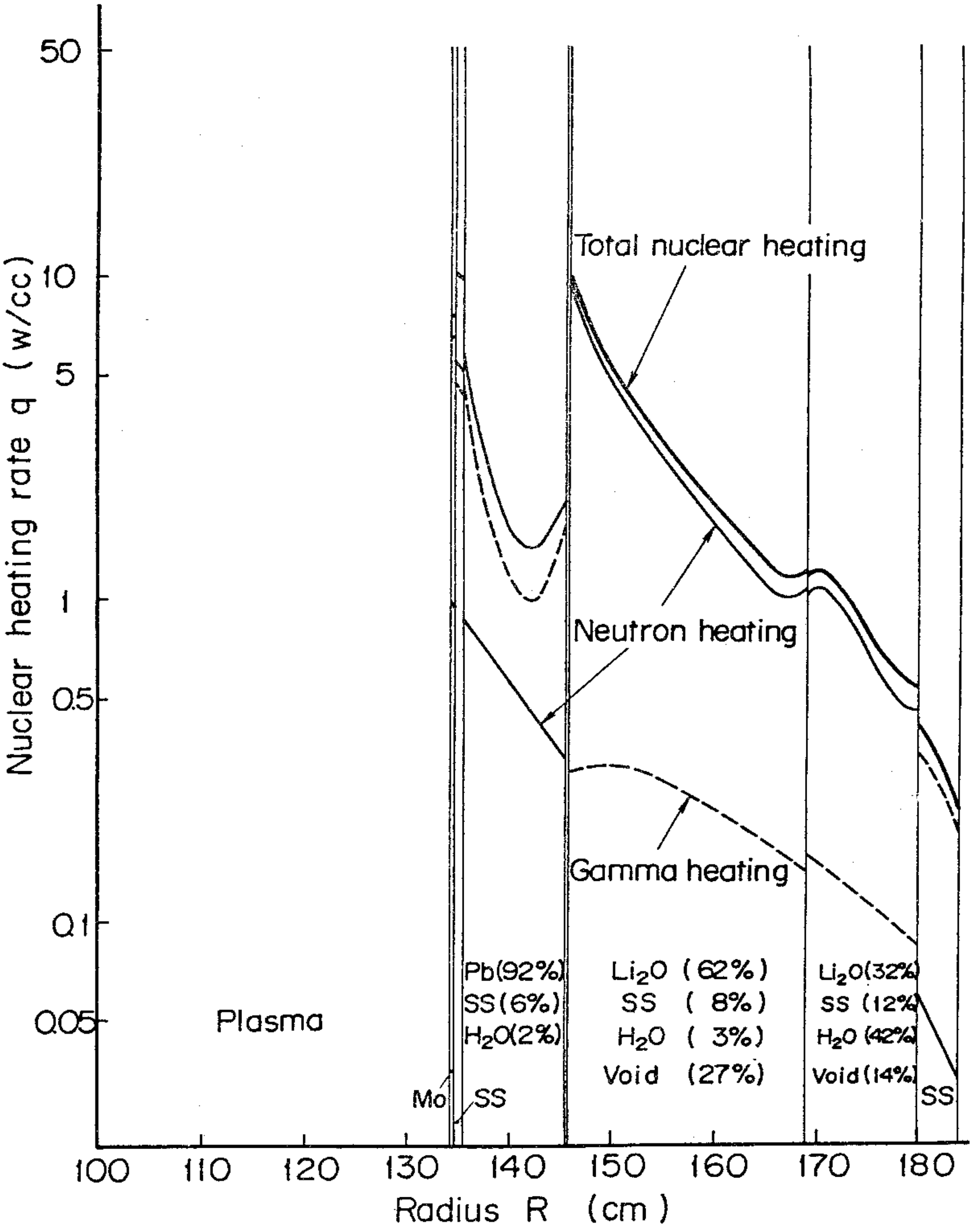


Fig. 7 Nuclear heating rate in the blanket

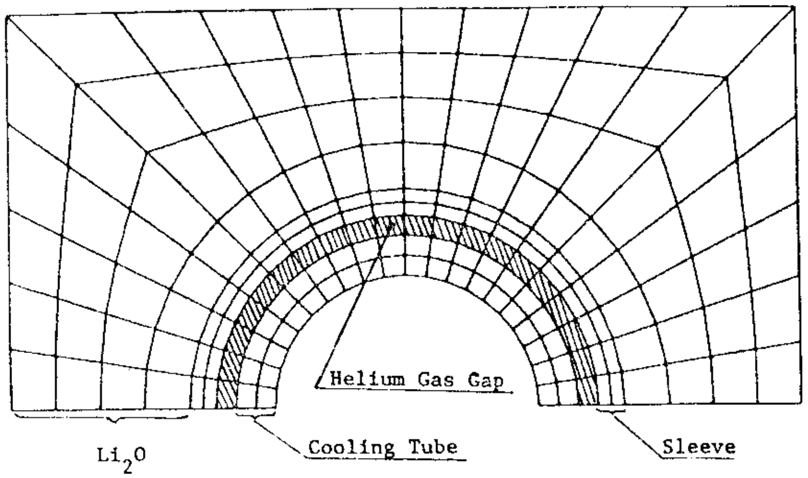


Fig.8 Thermal Calculational Model of Cell around Cooling Tube

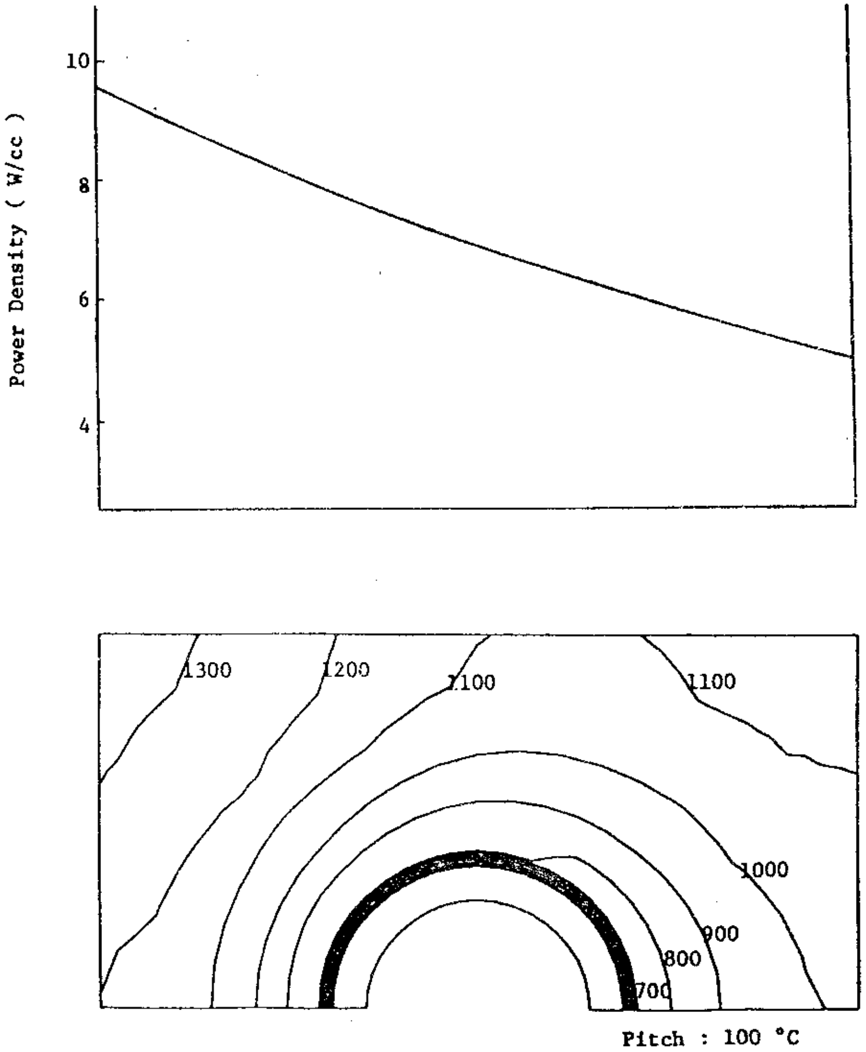


Fig.9 Power Density Distribution and Steady State Temperature Distribution in Cell of 1st Row Cooling Tube (Cooling Pitch = 34 mm, Helium Gap Width = 0.75 mm)

in the cell by two-dimensional analysis is shown in Fig.9. The distribution of the nuclear heating rate in the cell is also shown in Fig.9. The maximum and minimum temperatures of Li_2O are respectively estimated to be 1357°C and 777°C in two-dimensional analysis. The major difference between the results by one-dimensional and two-dimensional analyses is due to the distributions of the nuclear heating rate in the cell. In the case of the exponential distribution of nuclear heat deposition in the Li_2O region, the determination of the cooling tube pitches and helium gap widths requires two-dimensional analysis.

3.3 Determination of optimum cooling pitch and helium gap width

Figure 6 shows that the cooling tube pitch for the first row of cooling tubes will be about 30 mm to 36 mm considering a neuclear heat deposition rate of about 10 W/cc in the front part of the Li_2O region. Then, more detailed thermal analyses are parametrically conducted by varying the cooling pitches (36 mm, 30 mm and 25 mm). The helium gap widths are also varied parametrically in each case.

Figure 10 illustrates the maximum and minimum temperatures of Li_2O as a function of the helium gap width in the case of 36 mm cooling tube pitch. The temperature in the Li_2O region is restricted to the range of 400°C to 1200°C. Therefore, the upper and lower limits of the helium gap width in the ease of a 36 mm cooling tube pitch are estimated to be 0.39 mm and 0.3 mm, respectively. Similarily, Figs.11 and 12 indicate the maximum and minimum temperatures of Li_2O as a function of the helium gap width in the cases of the cooling tube pitch of 30 mm and 25 mm, respectively. The upper and lower limits of the helium gap width are estimated to be 1.12 mm and 0.46 mm in the case of 30 mm cooling pitch and to be 4.08 mm and 0.78 mm in the case of 25 mm cooling pitch. These values of helium gap widths, however, are results of the thermal calculation only.

The determination of allowable helium gap range must also take into account an estimation error for power density and a manufacturing error; i.e. the estimation error for the nuclear heating rate in the Li_2O region which is predicted by the neutronics calculation, and the manufacturing error of the cooling tube and the stainless steel sleeve.

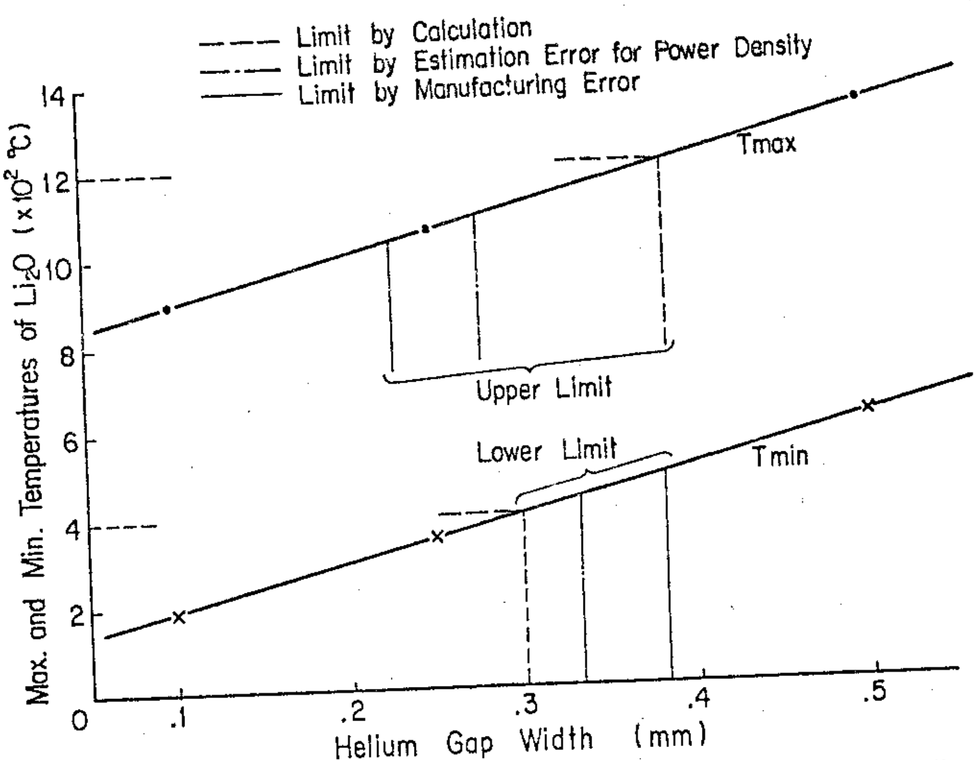


Fig.10 Maximum and Minimum Temperatures of Li_2O Region as a Function of Helium Gap Width in the Case of Cooling Tube Pitch of 36mm

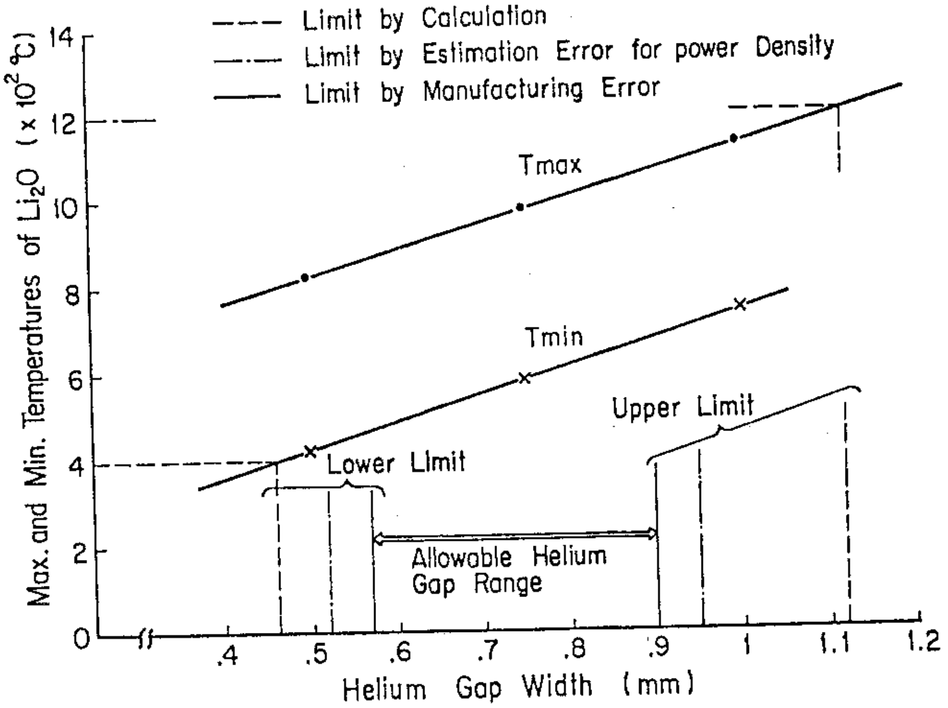


Fig.11 Max. and Min. Temperatures of Li_2O Region as a Function of Helium Gap Width in the Case of Cooling Tube Pitch of 30mm

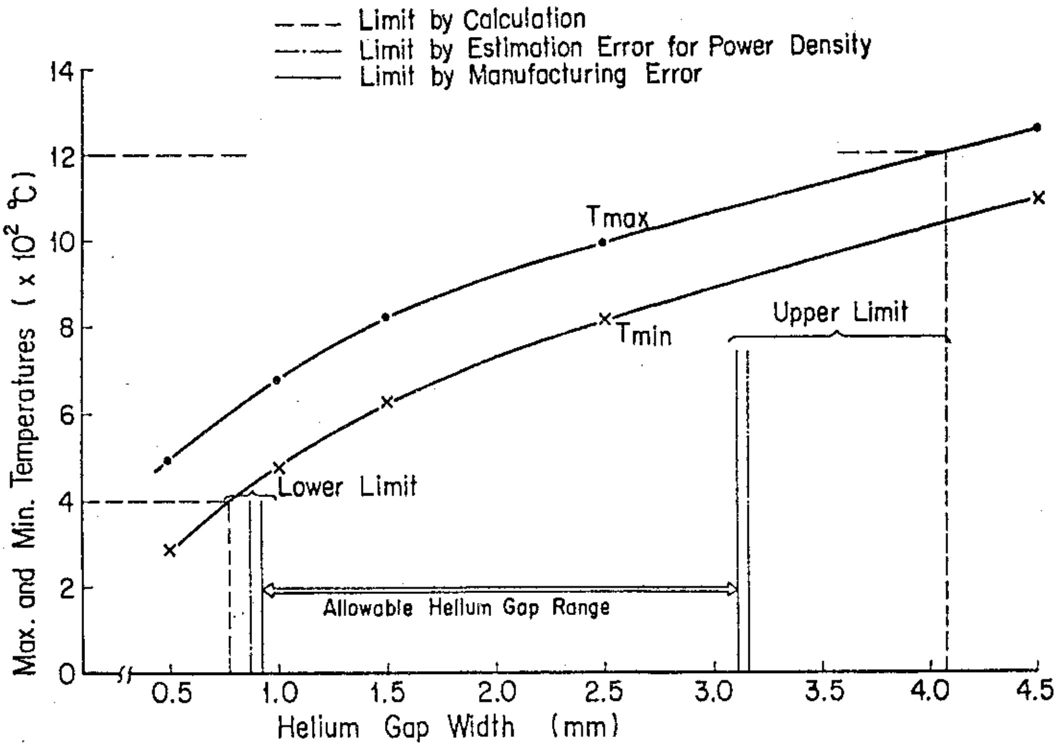


Fig. 12 Max. and Min. Temperatures of Li_2O Region as a Function of Helium Gap Width in the Case of Cooling Tube Pitch of 25 mm

The estimation error for the nuclear heating rate (power density) is assumed to be ±10 % and the manufacturing error to be ±0.05 mm. Taking into account these errors, the upper and lower limits of the helium gap widths become 0.23 mm and 0.38 mm in the case of 36 mm cooling pitch, 0.90 mm and 0.57 mm in the case of 30 mm cooling pitch and 3.11 mm and 0.92 mm in the case of 25 mm cooling pitch.

From the above results, there is no solution when the cooing pitch is 36 mm. the relation of the cooling pitch and helium gap width for the first row of the cooling tubes is indicated in Fig.13. From this figure, the optimum cooling pitch of the innermost row tube is estimated to be 34 mm and the optimum helium gap width is 0.43 mm. Both the optimum cooling pitch and helium gap width of other rows can be obtained by the same procedure. In the case of the outermost row, for instance, they are respectively estimated to be 73 mm and 0.6 mm, as shown in Fig.14.

The optimum cooling pitches and helium gap widths obtained by means of this method are accurate but this procedure is complicated. These optimum helium gap widths are different from each other. Providing a sleeve with different diameters makes the design of the cooling tubes complicated from the stand point of manufacturing. If the cooling pitch of 30 mm is used in the innermost and 70 mm is used in the outermost row, the helium gap width of both the rows become 0.75 mm.

Then, the helium gap widths of each other row are determined to be constant with a width of 0.75 mm everywhere because of the simple design of the cooling tubes. The cooling pitches of the respective rows are approximately obtained by making the heat flux on the outer surfaces of their stainless steel sleeves equal to that of the innermost row.

It is given by the following.

$$p_i = \sqrt{\pi \left(\frac{2Q_1 \, r_3}{q_i} + r_3^2 \right)} \qquad (6)$$

where,

p_i : cooling pitch of each row (m)

q_i : heat deposition rate at each row (kcal/m^{3}h)

Q_1 : heat flux on outer surface of stainless steel sleeve in innermost row tube (kcal/m^{2}h)

r_3 : outer radius of the sleeve (m)

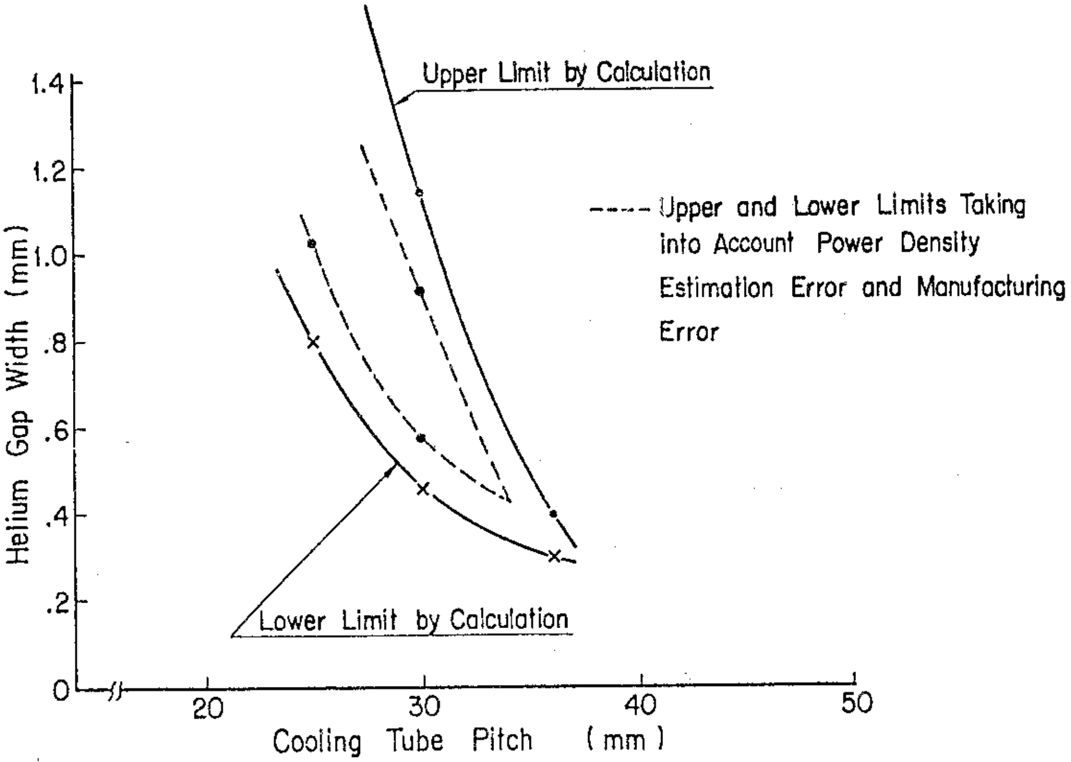


Fig.13 Relation of Allowable Cooling Pitch and Helium Gap Width
(Innermost Row of Cooling Tubes)

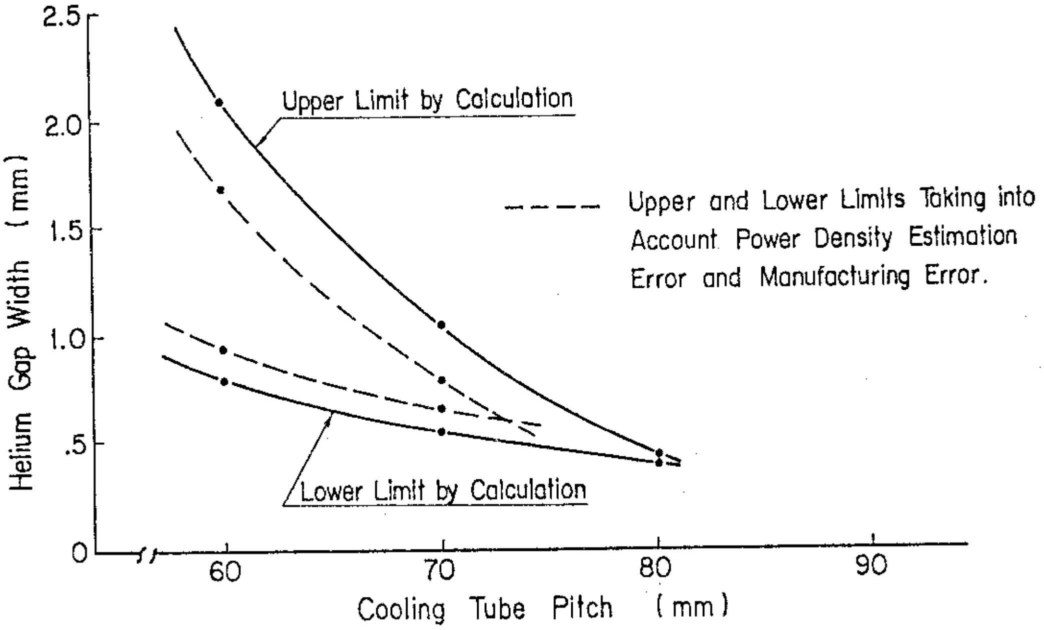


Fig.14 Relation of Allowable Cooling Pitch and Helium Gap Width
(Outermost Row of Cooling Tubes)

From the equation (6), the cooling pitches of the respective rows are estimated as follows.

$p_1 = 30$ mm
$p_2 = 38$ mm
$p_3 = 45$ mm
$p_4 = 55$ mm
$p_5 = 69$ mm
$p_6 = 70$ mm

3.4 Thermal analysis of a whole breeding region

The two-dimensional thermal analyses conducted previously are only with regard to the cell around the cooling tube in the Li_2O region. They are also performed assuming that the thermal boundary conditions of the cell is adiabatic. Since the temperature distributions of the cell in each row are a little different from each other, there would be some heat flux on the boundary between each row, However, the surroundings of the cell in these calculations are assumed to be in an adiabatic condition.

Then, a two-dimensional thermal analysis of a whole breeding region is carried out with the obtained arrangement of the cooing tubes in order to be compared with the analysis of the cell. Figure 15 shows the calculational model of the whole breeding region. A quarter of the breeding region, divided in a toroidal direction is used for the model because of the symmetrical arrangement of the cooling tubes. The model, however, includes all the breeding region in a radial direction. The surroundrings of the model are assumed to be in an adiabatic condition. The cross section of the cooling tube is represented as a rectangle to reduce the number of meshes in the calculational model. For simplicity of calculation, the cooling tube, helium gas gap and stainless steel sleeves are represented by a material of one layer with an equivalent heat conductance to the sum values of these materials.

Figure 16 illustrates the steady state temperature distribution in the whole breeding region. As the result, the temperature of the breeding material (Li_2O) is within the range of 400°C to 1200°C everywhere. Both the cooling tube pitches obtained and the procedure of obtaining them can be said to be reasonable.

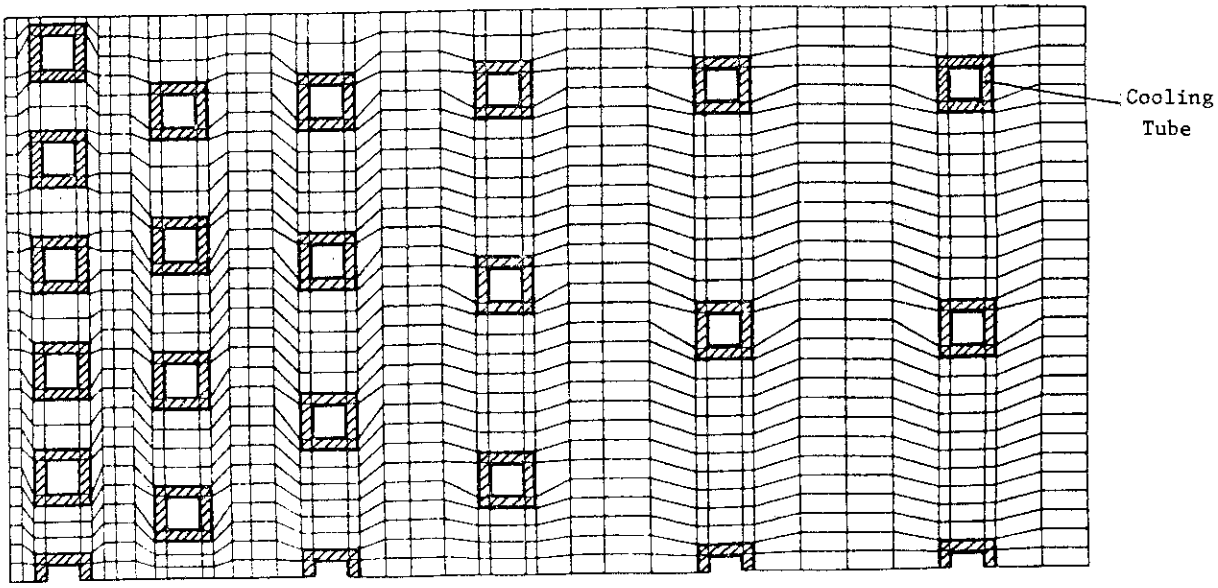
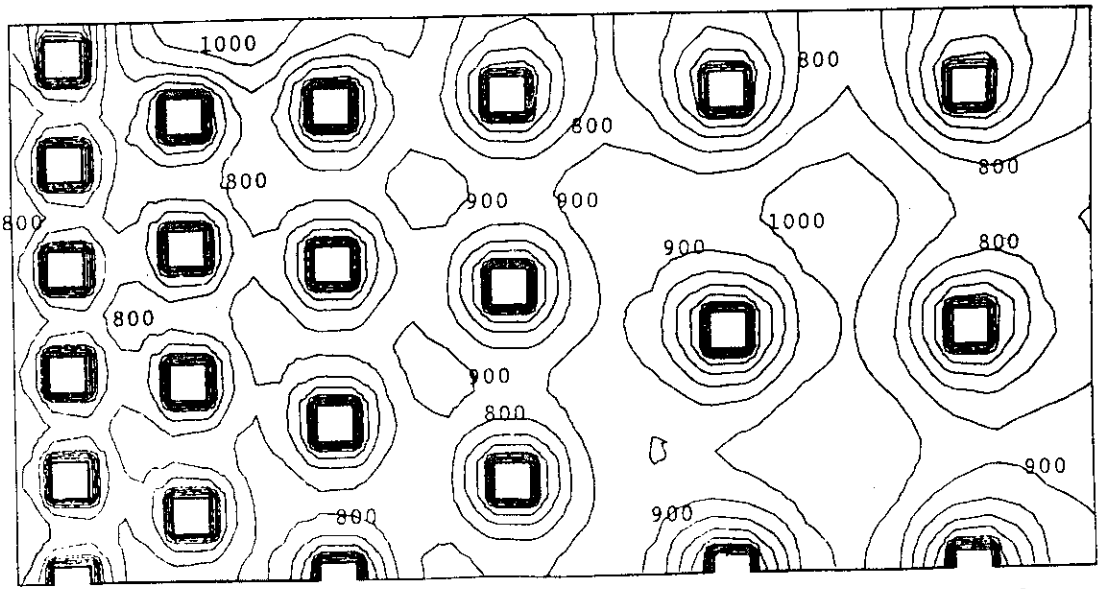


Fig.15 Thermal Calculational Model of a whole Breeding Region



Pitch : 100 °C

Fig.16 Temperature Distribution of a whole Breeding Region

4. Concluding remarks

The thermal design study of the tritium breeding blanket is conducted. The cooling structure with a helium gas gap between the cooling tube and the breeding material is employed in order to keep the temperature of Li_2O within the range of 400°C to 1200°C. We study in detail the temperature distribution around the cooling tube and determine an optimum helium gap width and cooling pitches in the Li_2O region.

From the relations of the helium gap width and the cooling pitch which are obtained by the thermal analysis, the optimum helium gap width is selected to be 0.75 mm and the optimum cooling pitch of each row is determined to be from 30 mm in the innermost row to 70 mm in the outermost row.

Thermal analysis of a whole breeding region is performed with the obtained arrangement of the cooling tubes and helium gap width. The temperature of Li_2O is found to be within the range of 400°C to 1200°C everywhere.

This design study is preliminary and the following features should be further studied.

(i) More detailed thermal design of blanket taking into account the temperature distribution in a poloidal direction.

(ii) Structural design of the blanket vessel considering atomospheric pressure, thermal stress and electro-magnetic force.

(iii) Detailed study on the allowable temperature range of lithium oxide

(iv) Detailed evaluation of equivalent thermal conductivity of lithium oxide taking into account self-convection between the Li_2O pebbles.

References

[1] H. Iida et al., "Structural Design Study of Tritium Breeding Blanket with a Lead Layer as a Neutron Multiplier", JAERI-M 9250, 1980.

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[Appendix] Thermal effect of fins between cooling tube and sleeve

In order to keep the helium gap width uniform, the fins or support will actually be installed between the cooling tube and stainless steel sleeve. The thermal analyses conducted previously do not take into account the fins. Total heat conductance between Li_2O and the cooling water is under-estimated because of the absence of fins.

Then, the thermal analysis of the cell around the cooling tube with fins is performed in order to be compared with the case without fins. Figure A.1 shows the calculational model with fins. The following assumptions are made for the fins in the analysis.

(i) The fins are made of stainless steel.

(ii) Surface contact rates of the fins are 0.1 in a circumferential direction and 0.5 in a longitudial direction.

(iii) Equivalent thermal conductivity of the fin is assumed to be 1/10 of that of stainless steel taking into account the surface contact rates.

Figure A.2 depicts the temperature distribution of the cell around the cooling tube in the case of 30 mm cooling pitch and 0.75 mm helium gap width for the innermost row. From this figure, the maximum and minimum temperatures of Li_2O are estimated to be 729°C and 341°C, respectively. Those temperatures of Li_2O in the case without fins are 976°C and 591°C. It is found that the temperature of Li_2O in the case with fins is considerably below those in the case without fins.

In the future, detailed determination of optimum cooling pitches and helium gap width is required to take into account the thermal effect of the fins between the cooling tube and sleeve.

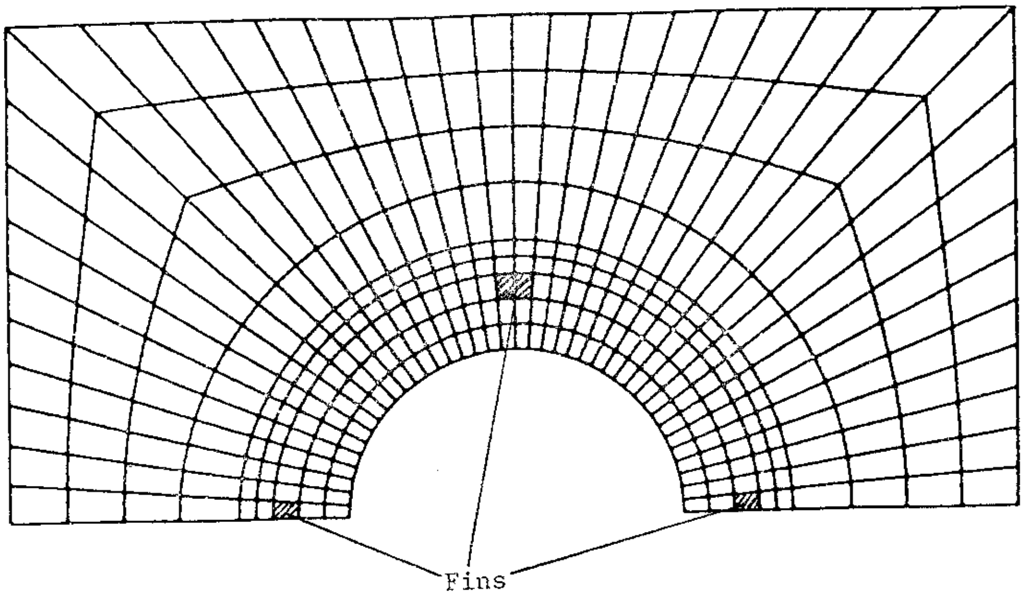

Fig.A.1 Thermal Calculational Model of Cell around Cooling Tube (with Fins between Cooling Tube and Sleeve)

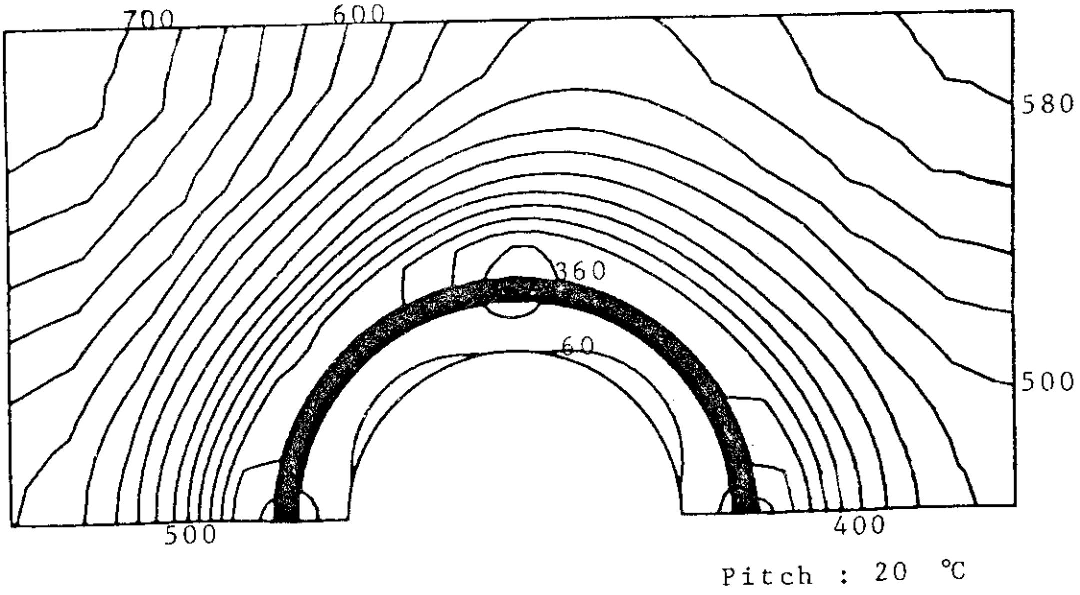

Fig.A.2 Temperature Distribution of Cell around Cooling Tube (with Fins between Cooling Tube and Sleeve)