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# ION BEAM DUMP FOR JT-60 NBI

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The design of the active cooling type ion beam dump for JT-60 NBI which receives the total beam power of 5.6 MW for 10 sec continuously is described. It is composed of array of many finned tubes which is made of oxygen free copper with 0.2 % silver content. The safety margin against thermal and mechanical troubles is estimated by the heat transfer and the thermal stress calculation.

Keywords: Neutral Beam Injector, Beam Dump, Active Cooling Type, Thermal Stress, Beam, JT-60.

* On leave from Mitsubishi Heavy Industries, Ltd.

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# ＪＴ－６０用ＮＢＩのビームダンプ

日本原子力研究所東海研究所核融合研究部

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（１９８１年９月２１日受理）

この報告は，ＪＴ－６０用ＮＢＩのビームダンプの設計について述べたものである。ビームダンプは最大5.6 MWの熱負荷を１０秒間連続で受けるため，熱的及び応力的問題を解決して設計する必要がある。これらの問題を解決するためのビームダンプ構造として，フィン付管を多数配列することにより，受熱面を構成するフィン付管構造とした。フィン付管の熱解析，及び応力解析を行ない，本ビームダンプは熱及び応力的に安全であることを確かめた。

＊外来研究員：三菱重工業（株）

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## 1. Introduction

The heat removal components such as ion beam dump and calorimeter in the beam line of neutral beam injector (NBI) for JT-60 are required to handle intense ion/neutral beam in a limited space of main vacuum chamber as shown in Fig. 1.1. There are quite difficult thermal and mechanical problems to be conquered in the design of these components.

Neutralization efficiency of ion beam extracted from ion source in the gas cell decreases with an increase of beam energy. For instance, the efficiency for an equilibrium neutralizer gas target decreases from 50 % at 50 keV to 27 % at 100 keV. The residual ion beams are bent by deflecting magnetic field to the ion dump. In the JT-60 NBI, the heat loading to the ion beam dump becomes about 5.6 MW for the extracted ion beam of 80A at 100 keV.

The present report describes the design of ion beam dump, which is one of the most severe components in the beam line because of large power loading of 5.6 MW and long-pulse of 10 sec.

## 2. Design of ion beam dump

The residual ion beam after passing through the neutralizer cell is bent by the deflecting magnet and is dumped on the ion beam dump. Since we have adoped the magnet of reflecting type with a large incident angle(1), the reflected ion beam becomes very divergent as shown in Fig. 2.1.

The specifications for the ion beam dump of JT-60 NBI are tabulated in Table 2.1.

Table 2.1

| | |
|---|---|
| Maximum power loading | 5.6 MW |
| Beam duration time | 10 sec |
| Duty cycle | 1/60 |

### 2.1 Shape of dump surface

As the ion beam dump have to handle the heat loading of 5.6 MW for 10 sec in a limited space shown in Fig. 1.1, its structure was designed

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### 2.1 Shape of dump surface

As the ion beam dump have to handle the heat loading of 5.6 MW for 10 sec in a limited space shown in Fig. 1.1, its structure was designed through the consideration of the heat removal capability and the thermal stress problems. The dump surface forms a "bowl" shape as shown in Fig. 2.2, so as to receive energetic ions uniformly. The maximum power density on the surface was chosen to be 500 $w/cm^2$ by considering the allowable heat flux against burn-out of cooling channels and the allowable space for the dump in the main vacuum chamber.

## 2.2 Heat removal

There are two kinds of cooling system to remove high heat flux. One is the inertia cooling type for the pulsed heat flux which relys on the heat capacity of the dump surface like calorimeter of JT-60 NBI[2]. The other is the forced convective cooling type for the continuous heat loading which relys on a large heat transfer coefficient in the nucleate boiling region.

The ion beam dump of JT-60 NBI is illuminated by the intense ion beam of 5.6 MW for 10 sec continuously, therefore the forced convective cooling type was adopted. Several types of structures like those shown in Fig. 2.3, were considered and evaluated. Among them, the No.10 type, that is, an array of the finned tubes was adopted because of small thermal stress, small temperature rise and the easiness of fabrication. The diameter of cooling channel and the width of fin shown in Fig. 2.4 were determined in terms of the water velocity, temperature rise of cooling water and thermal stress in the tube material. The cross-sectional view of the array is also shown in Fig. 2.4. The fin plays a role of reducing temperature gradient across the tube by absorbing beam on its furface and prevent beams from leaking through the gaps between the tubes. The tube is made of oxygen free copper with 0.2 % silver content, which has high qualities of thermal and mechanical properties up to 300 °C.

## 2.3 Release of axial thermal expansion of finned tube

In order to release thermal elongation of the finned tube when it is shot by ion beam, bend sections are provided at both ends of the tube. At the bend sections the fins are cut and the cooling tubes are shaped into a circular form. The curvature of the tubes at the bend sections is determined from thermal stress analysis. The result is shown in Fig. 2.2.

## 2.4 Burn out heat flux

The maximum heat flux of dump surface reaches 500 $w/cm^2$ for 10 sec when the beam dump receives the heat load of 5.6 MW. This heat flux is almost uniform over axial direction of the finned tube of about 1.6 m long. This value has been chosen based on a burn out experiment performed by the ITS-2 test stand[3]. The samples of the finned tube were irradiated by the intense ion beam. Within our experimental parameter range of cooling water velocity of $3\sim7$ m/s and pressure of $4\sim10$ $kg/cm^2G$, burn-outs take place when the finned tubes are exposed to the heat flux exceeding a level of $0.8\sim1.3$ $kw/cm^2$. From these results, we chose a permissible design heat flux of 500 $w/cm^2$, which has a safety margin of a factor of 2.

## 2.5 Control of the amount of flow

The beam dump is composed of an array of many finned tubes which are arranged parallel to reflected ion trajectories. Integrated heat flux along to the finned tubes are different with each other due to a gloval heat flux distribution. Therefore the finned tubes around the beam center are exposed to the heat flux of 500 $w/cm^2$, but the others are exposed to a lower heat flux. If the cooling water is circulated with a velocity in proportion to the heat load of the each tube, the total flow rate can be economized considerably. However, it is very difficult to adjust the flow velocities precisely in proportion to the beam intensity distribution, since the distribution moves in the cause of the beam axis displacement and/or leakage field from tokamak. Thus, the tubes are provided with oriffices of two different diameters to produce a stepwise flow distribution. This simple flow control reduces the total flow rate by 30 %.

# 3. Temperature distribution of finned tube

The calculation of temperature distribution of finned tube has been performed by using the heat conduction code "HEATING-3"[4]. The conditions used in the calculation are tabulated in Table 3.1.

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Table 3.1

| | |
|---|---|
| Heat flux : | 500 $w/cm^2$ (uniformly in the beam received region) |
| Cooling water velocity : | 7 m/s |
| Cooling water pressure : | 10 $kg/cm^2G$ |
| Thermal properties of oxygen free copper with 0.2 % silver content | |
| Thermal conductivity : | 0.377 w/cm·k |
| Specific heat : | 0.398 J/g·k |
| Density : | 8.96 $g/cm^3$ |

The two-dimensional temperature distributions in the cross section of the finned tube were calculated at four positions along the tube axis as shown in Fig. 3.1. The overall temperature distribution has been obtained by the interpolating of these results. It was assumed that the cooling water temperature is increased monotonically from the entrance temperatute of 40 °C to the exit of 115 °C. Two different heat transfer coefficients were used. Namely the heat transfer coefficient was changed from the coefficient of the pure convective heat transfer to that of the subcooled nucleate boiling when the wall temperature reaches the critical temperature described blow. At first, the convective heat transfer coefficient, h, of turbulent flow is given by,

$$Nu = 0.023\ Re^{0.8}\ Pr^{0.4}$$
$$h = Nu \cdot \lambda / d$$

where Nu is the Nusselt number, Re is the Reynolds number, Pr is the Prandtle number, $\lambda$ is the thermal conductivity of water and d is the pipe diameter.

The critical temperature point where the subcooled nucleate boiling starts can be estimated by,

$$T_W = T_S + \Delta T_{sat}$$

where $T_W$ : Wall temperatures at the nucleate boiling starts

$T_S$ : Saturation temperatures

$\Delta T_{sat}$ : Liquid film superheat, which is given by Thom(5) as

$$\Delta T_{sat} = \frac{5}{9}\{0.072(0.3687 \cdot q)^{\frac{1}{2}}\ \exp(14.22/1260 \cdot P)\}$$

In the parameters of our beam dump,

$$\Delta T_{sat} = 57\ ^{\circ}C \text{ and } T_s = 183.2\ ^{\circ}C,$$

thus $\quad T_w = 240.2\ ^{\circ}C.$

The subcooled nucleate boiling heat transfer coefficient is given by,

$$h_s = q/(T_w - T_b)$$

where $\quad T_b$ : bulk water temperature.

The temperature distributions at the four positions after 10 sec are shown in Figs. 3.2 and 3.3 for the type A tube, Figs. 3.4 and 3.5 for the type B. The type A and B differ in the width of fin. The temperature rise of type A and B tubes are almost equal. The maximum temperatures become 264 °C at the down stream of tube. The temperature is sufficiently lower than the softening point of about 350 °C for the oxygen free copper with 0.2 % silver content. It is clear that the tube is safe against thermal problem.

## 4. Thermal stress analysis

To estimate thermal stress intensity of a finned tube, a three dimensional thermal stress analysis has been made by using stress analysis code "SAP-5"[6].

The stress calculation has been performed under the following conditions:

a) Overall temperature distribution of finned tube was interporated from the calculation results of temperature distribution described in the previous section.
b) The three dimensional solid element was used as a model.
c) The calculation model was divided into 144 nodes along the tube axis and divided into mesh as shown in Fig. 4.1 in the cross-section perpendicular to the tube axis.
d) The base of monifolds were fixed and the others were free as the stiffiness conditions of the tube.

The mechanical properties of oxygen free copper with 0.2 % silver content is tabulated in Table 4.1.

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The mechanical properties of oxygen free copper with 0.2 % silver content is tabulated in Table 4.1.

Table 4.1 The mechanical properties of 0.2% silver content oxygen free copper.

| | |
|---|---|
| Young's modulus; | 12500 $Kg/mm^2$ |
| Poisson ratio; | 0.33 |
| Thermal expansion coefficient; | $1.68 \times 10^{-5}$ 1/°C |

The deformation figures of finned tube after 10 sec beam irradiation are shown in Fig. 4.2 for type A and Fig. 4.3 for type B. The maximum deformation quantities for types A and B are ∿9 mm and ∿8 mm, respectively. The distributions of stress intensities of overall finned tube are shown in Fig. 4.4 for type A and Fig. 4.5 for type B, respectively. The stress intensities become larger toward downstream of cooling water. The stress of the circular region where the tube is not shot by beams are smaller than the finned region. This is because, the tube can be deformed easily in the circular region due to a lack of fin. The stress intensity has maximum values in the root of fin, of 19.3 $kg/mm^2$ for type A and of 20.5 $kg/mm^2$ for type B.

The safety margin of thermal stress value against the mechanical strength of the finned tube material is evaluated based on ASME code-sec Ⅲ[7]. According to the ASME-code, the safety criterion is given by,

$$(\text{Primary stress}) + (\text{Secondary stress}) < 3\ \text{Sm} \quad \text{——} \quad ①$$

where Sm is a allowable stress of material. The primary stress is 0.3 $kg/mm^2$ by cooling water pressure of 10 $kg/cm^2$G. Thus the maximum value of the left hand side of eq.① is 20.8 $kg/mm^2$. Sine the value, 3 Sm at 270 °C which is the maximum temperature in the beam dump, is 28 $kg/mm^2$, refering to the Fig. 4.6[8] which shows the allowable stress, together with the values measured of yield and ulimate tensile strength of 0.2 % silver content oxygen free copper (25 % cold working ratio), the relation of eq.① is satisfied and safety margin is about a factor of 1.3. Though the cold working ratio is relaxed in the high temperature region, the relaxiation time at the temperature of 270 °C is above 1000 hrs according to the material test, and it is equivalent to the using time of 20 years of JT-60 NBI. Therefore, we have not considered the relaxiation time of cold working ratio in the estimation of thermal stress.

The fatigue life of the beam dump was estimated by the same way as that of the calorimeter which has been reported previously[(2)]. It Becomes clear that our beam dump can withstand the repetition of $\sim 5\times 10^4$ cycles for the 10 sec beam pulse.

## 5. Conclusion

The active cooling type ion beam dump for JT-60 NBI which recieves the total beam power of 5.6 MW for 10 sec has been designed. It is composed of arrays of many finned tubes which is made of oxygen free copper with 0.2 % silver content. The safety margin against thermal and mechanical troubles was estimated by the heat transfer and the thermal stress calculations, and its fatigue life is estimated to be $\sim 5\times 10^4$ cycles for the 10 sec beam pulse.

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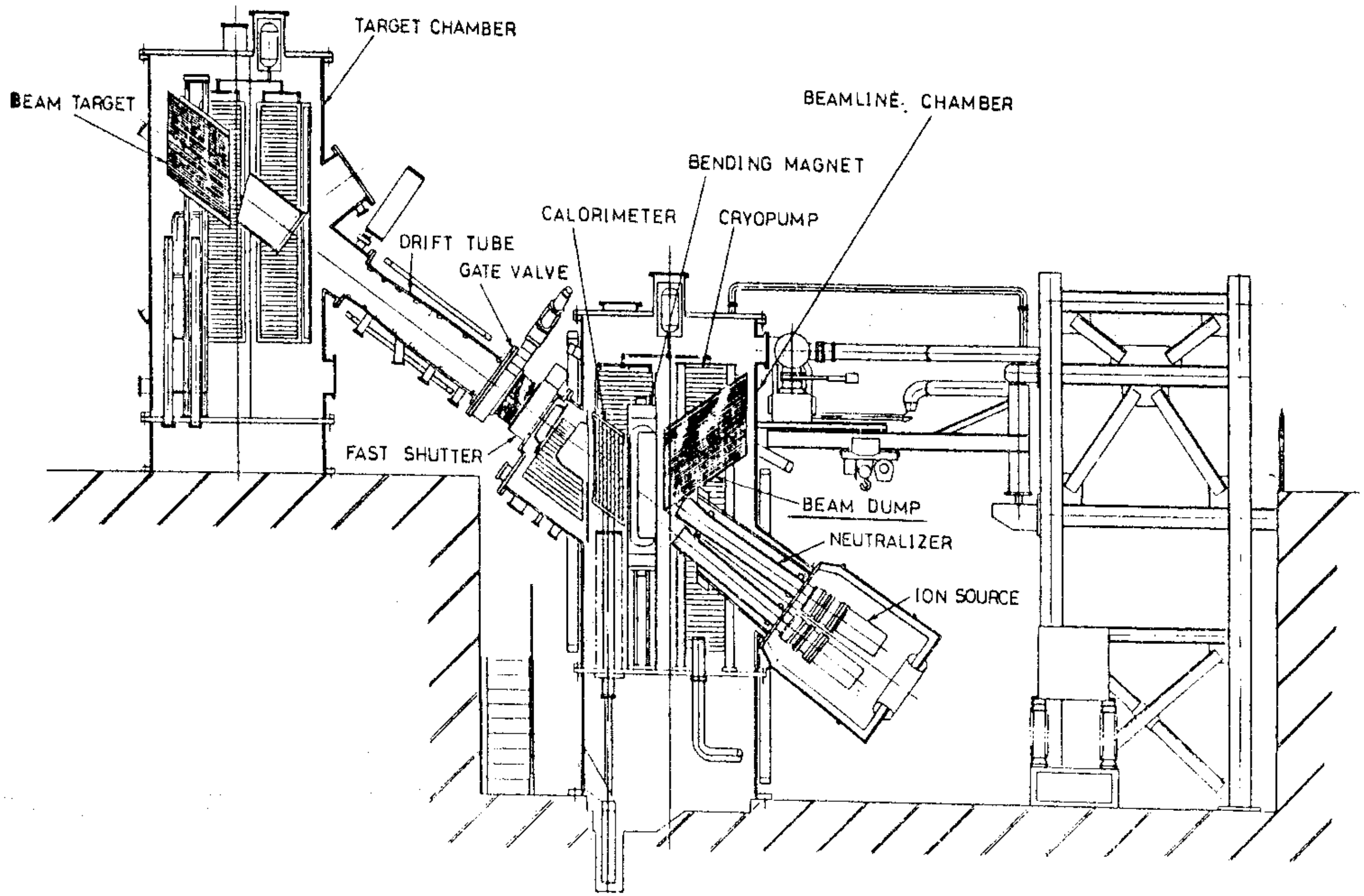



Fig.1.1 A view of the complete construction of the beam line of the JT-60 neutral beem injector (proto typl unit)

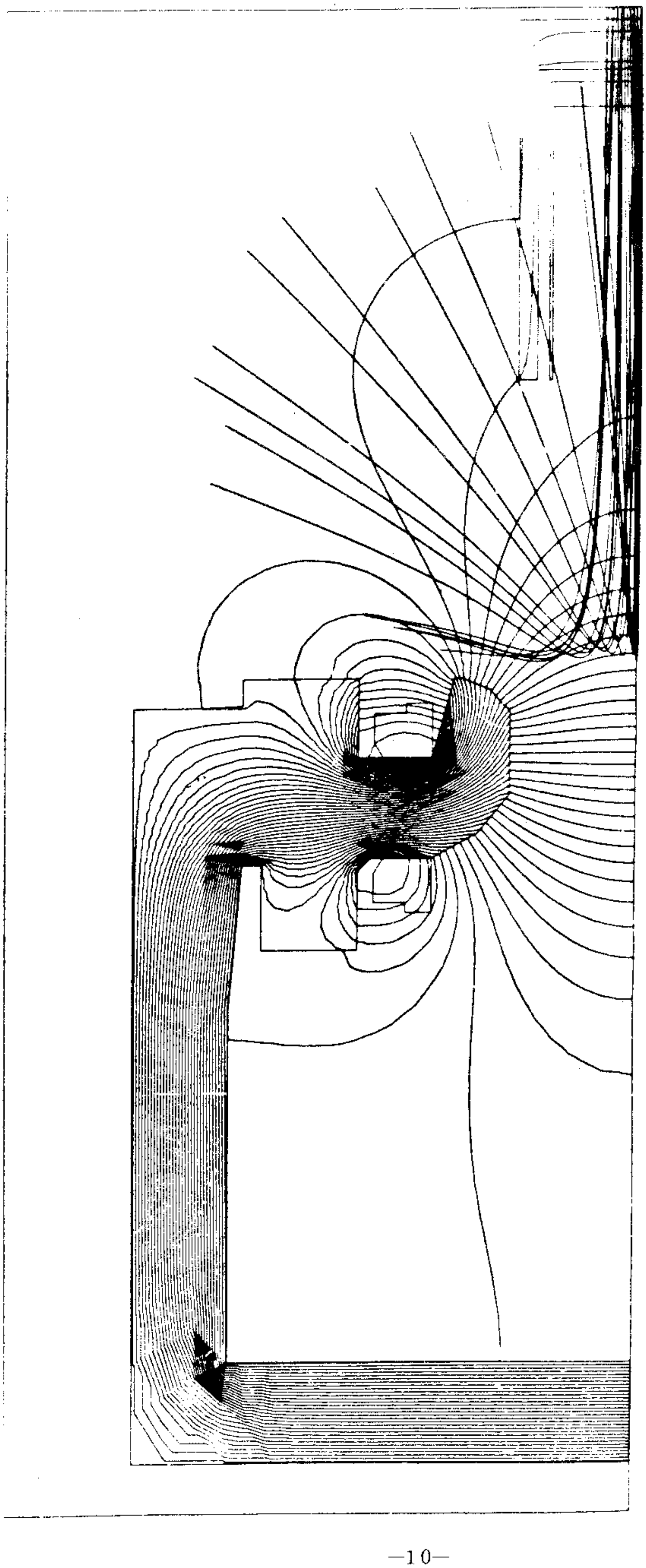


Fig.2.1 Ion beam trajectory in the deflector magnetic field

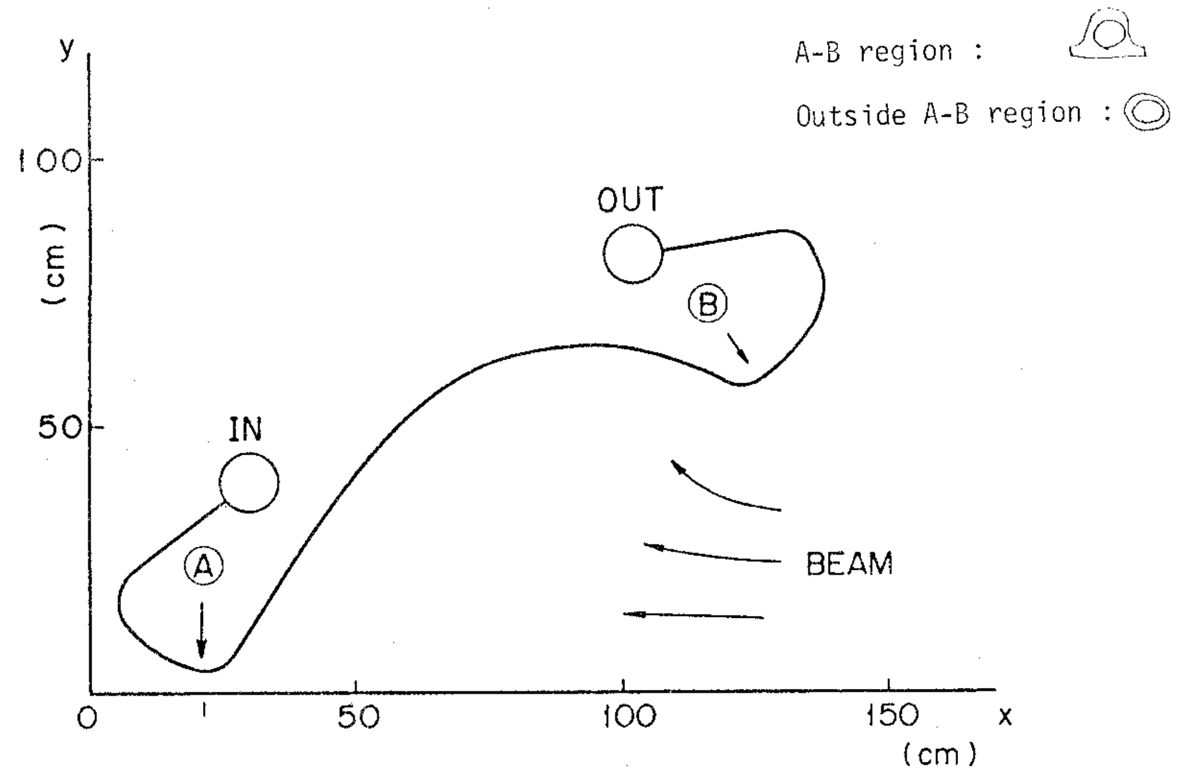



Fig.2.2 (A) Shape of ion beam dump (X-Y plane)
A-B ; beam receiving region (finned tube)
Outside of A-B ; released region of axial direction thermal expansion (circular tube)

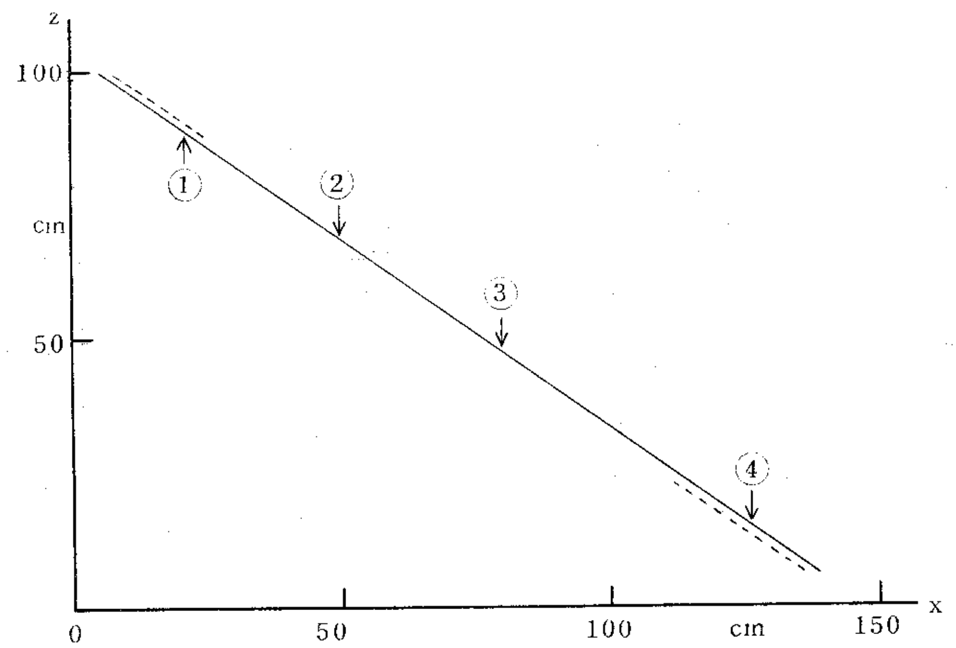



Fig.2.2 (B) Shape of ion beam dump (X-Z plane)

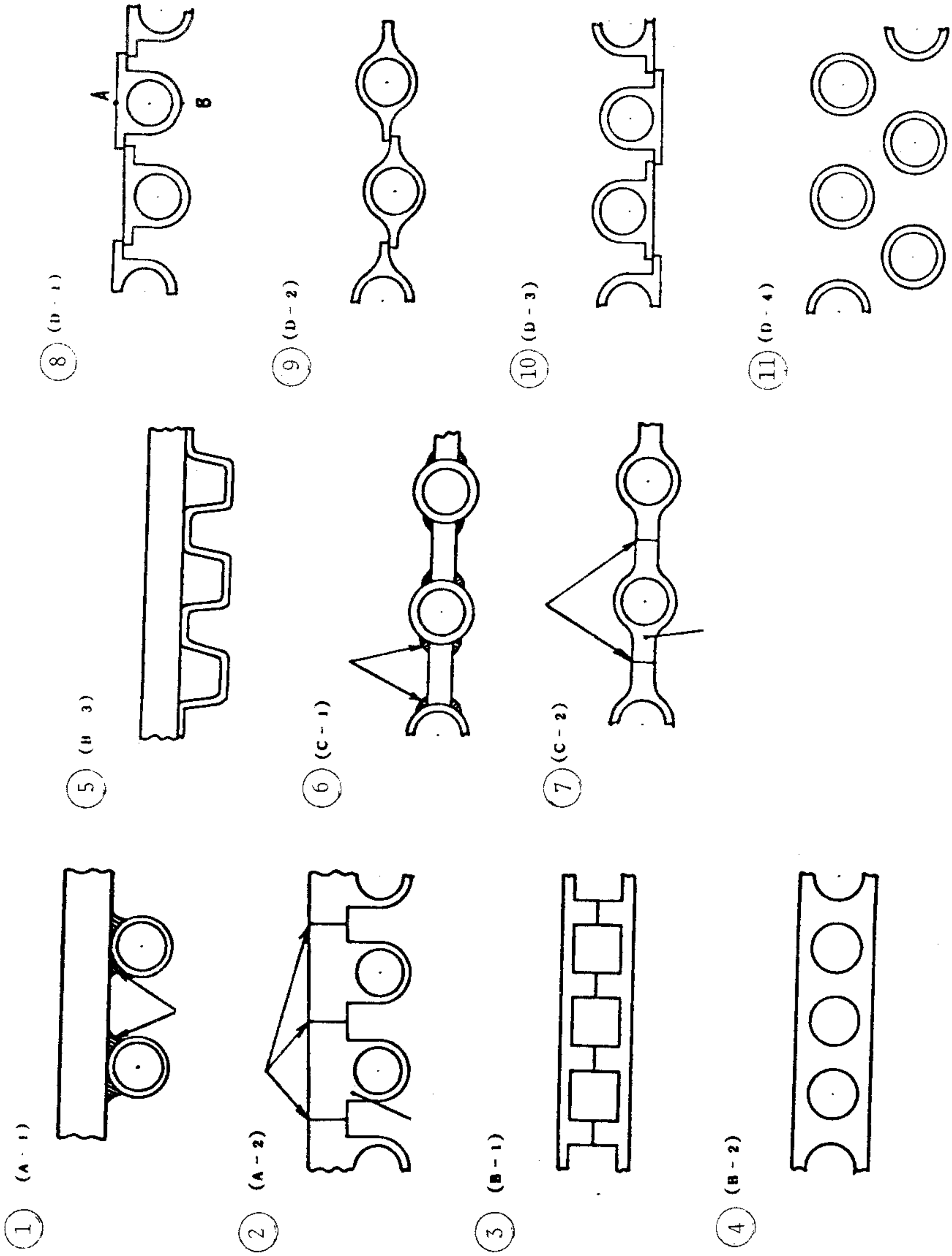



Fig.2.3 Cooling methods of active cooling type dump

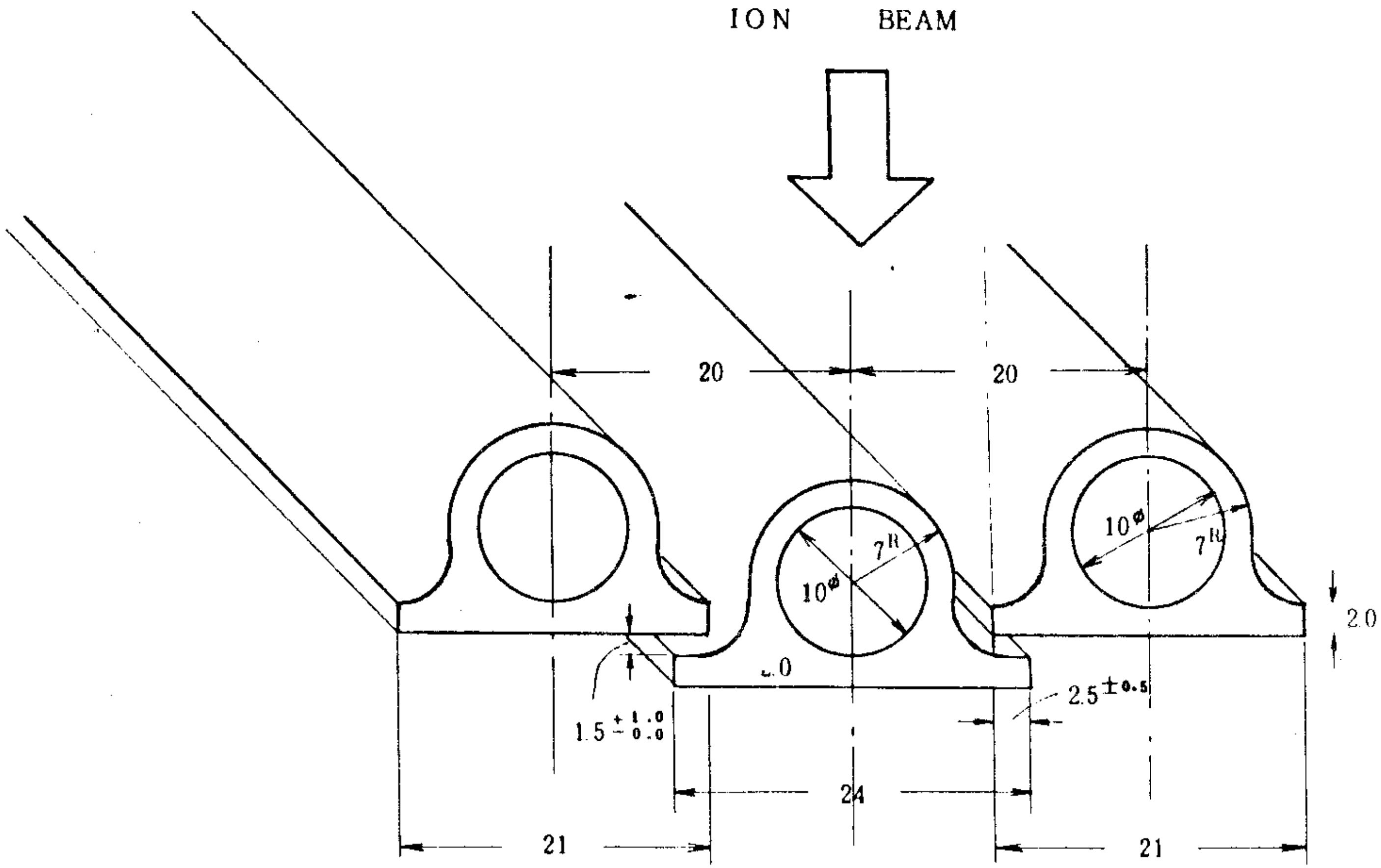



Fig.2.4 Beam dump structure. The plane view of the dump. The numbers show

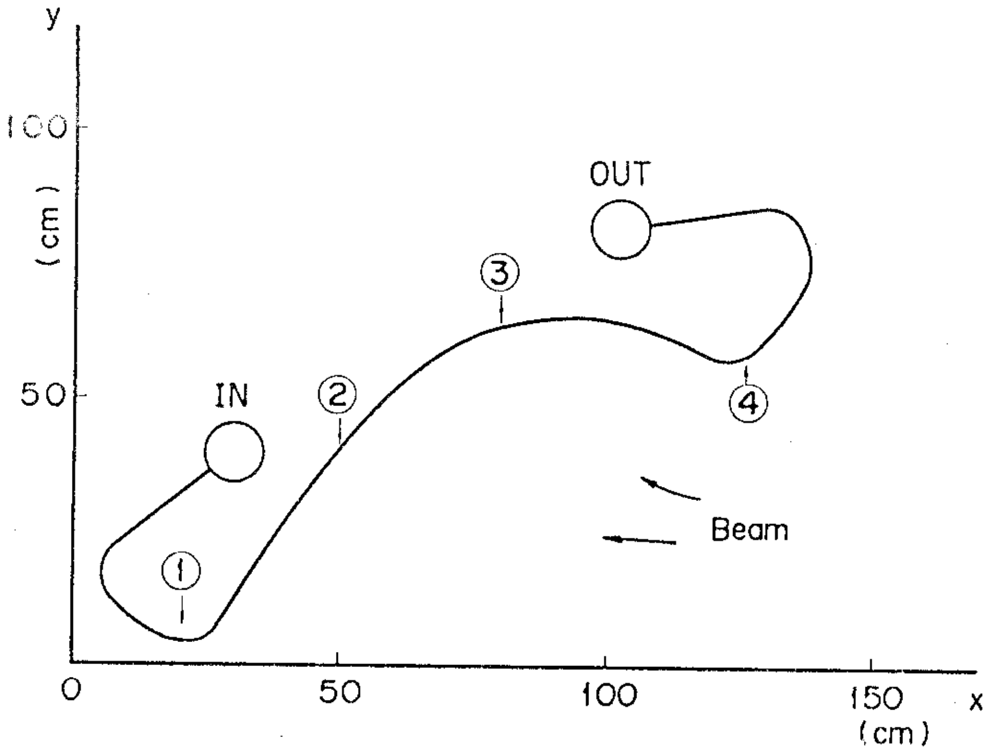



Fig.3.1 Heat transfer calculated points

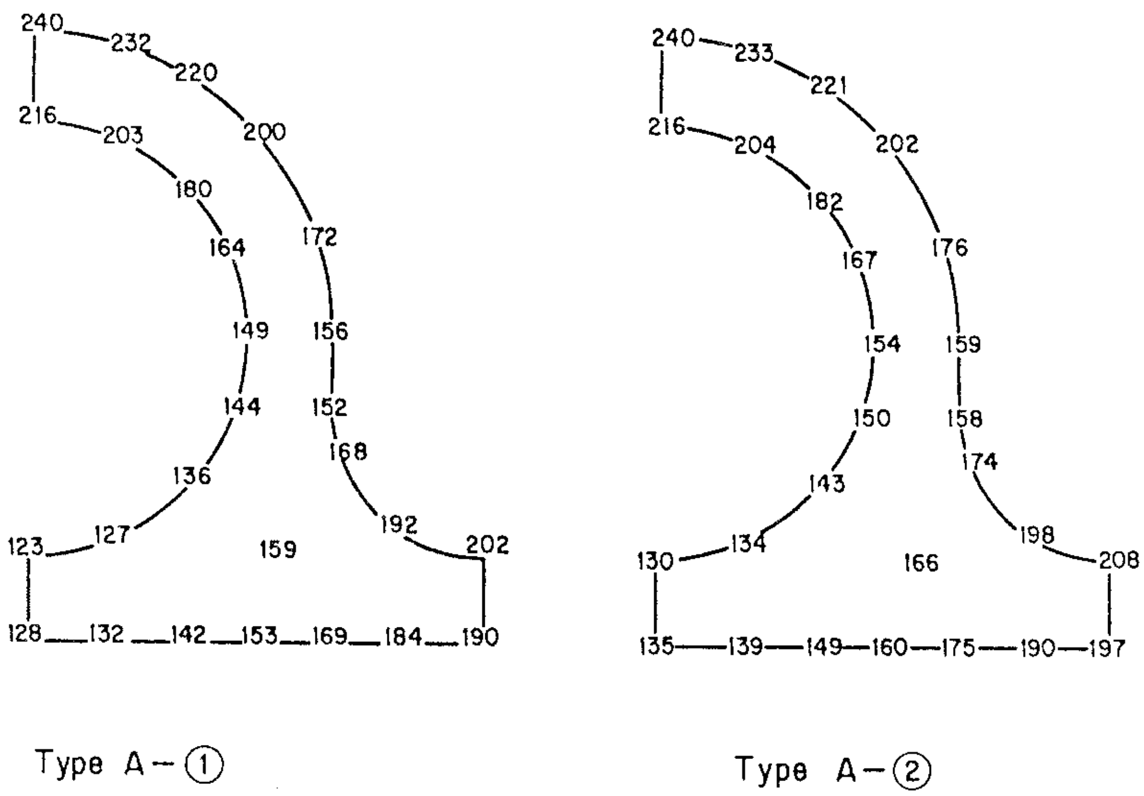
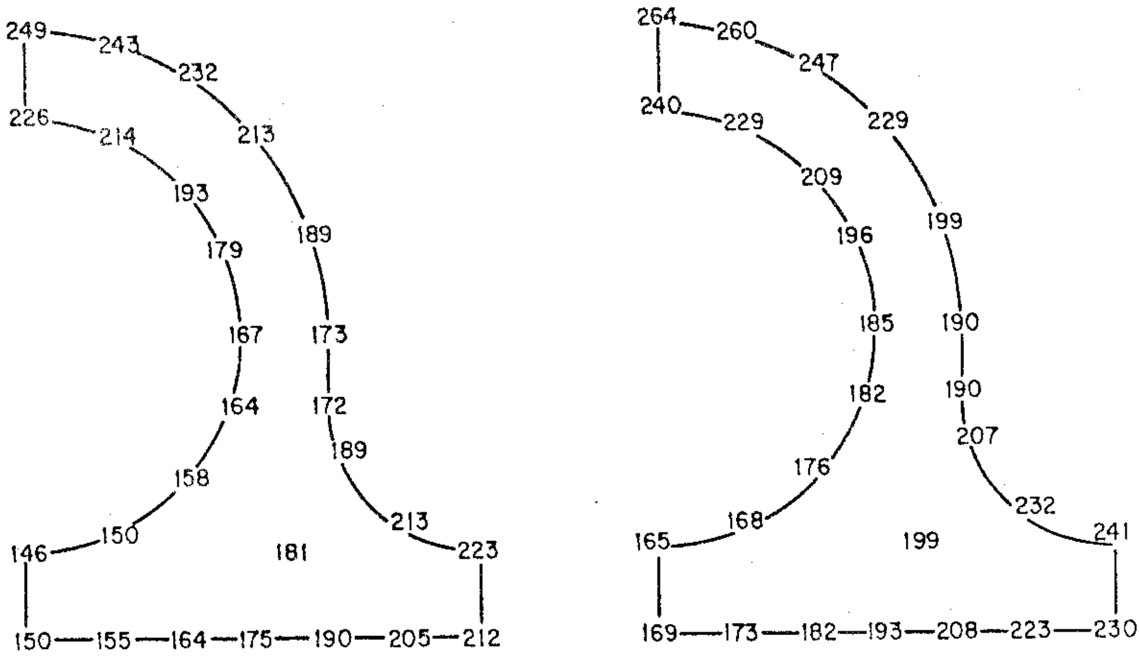
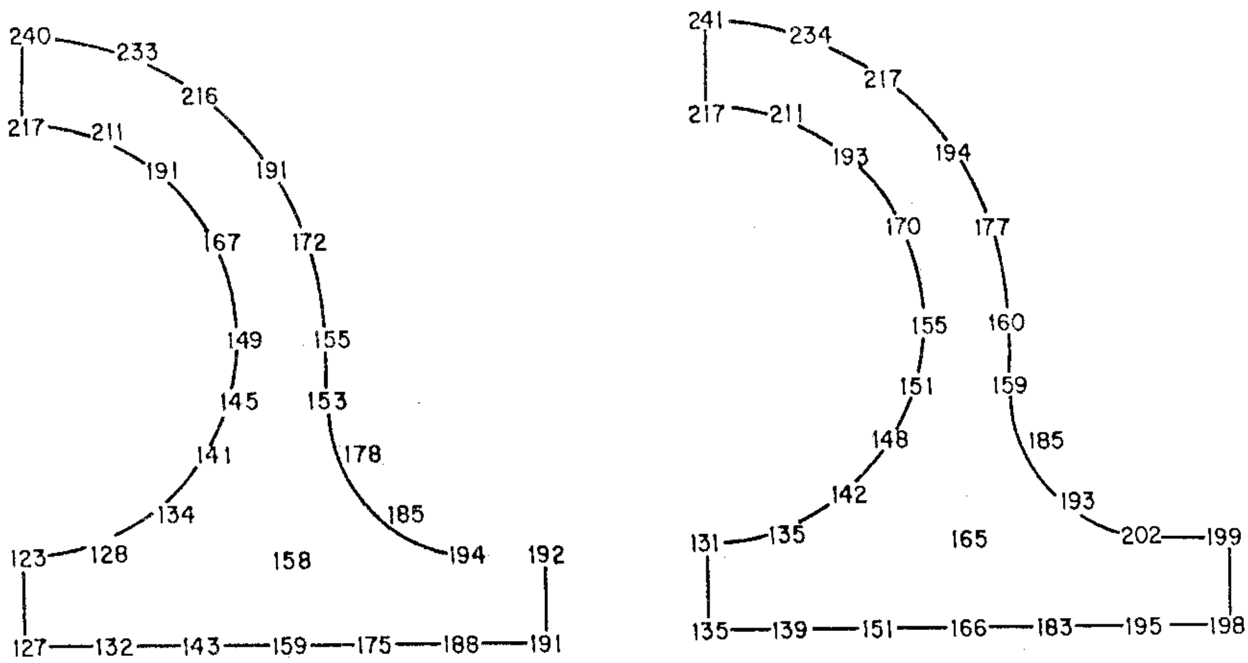



Fig.3.2 Temperature distribution of finned tube section for type A (I)



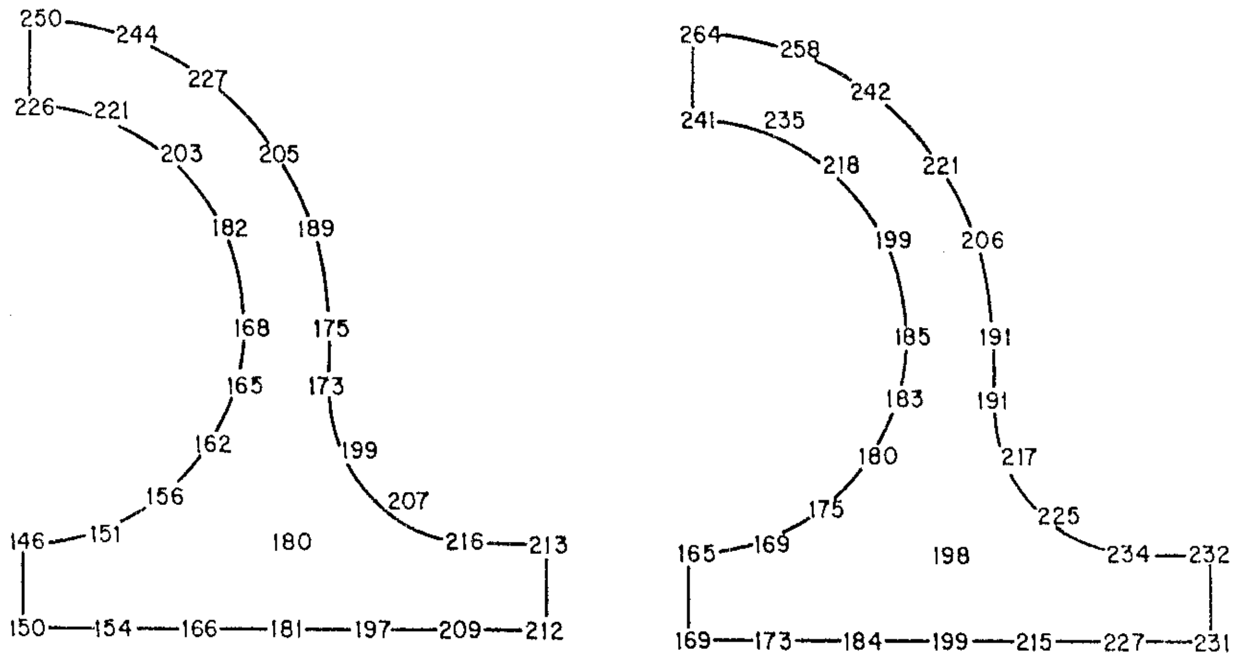

Type A－③ Type A－④

Fig.3.3 Temperature distribution of finned tube for type A (II)




Type B－① Type B－②

Fig.3.4 Temperature distribution of finned tube section for type B (I)




Type B — ③ Type B — ④

Fig.3.5 Temperature distribution of finned tube for type B (II)

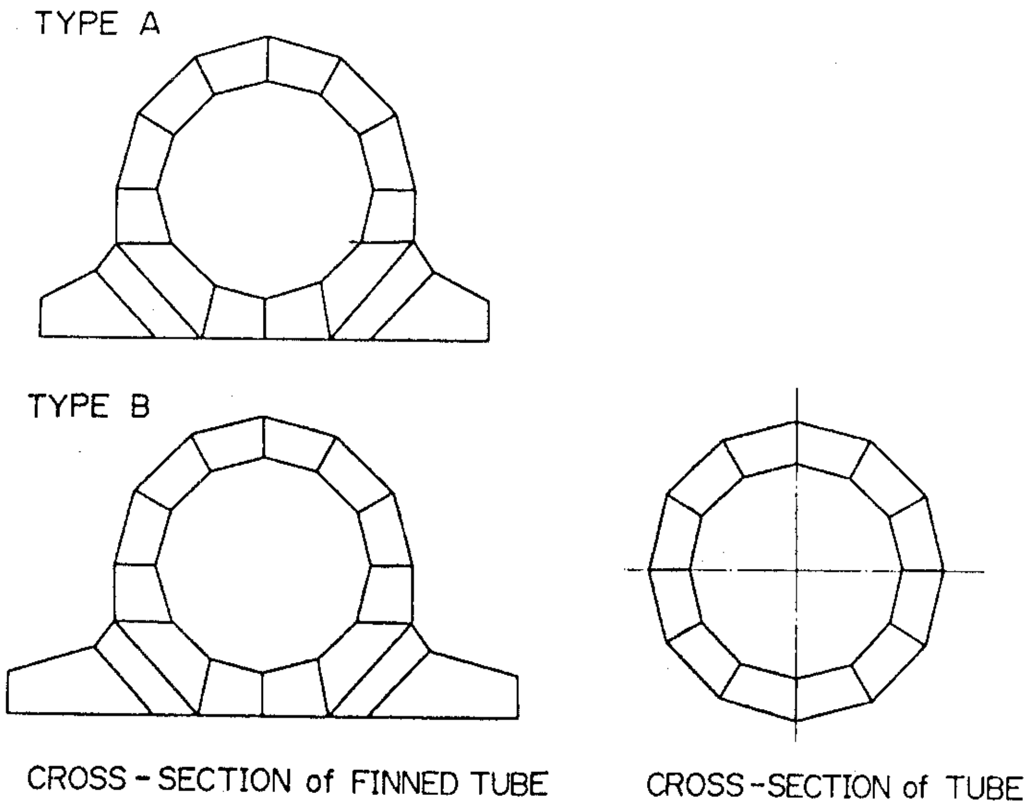



Fig.4.1 Calculation model for the cross-section perpendicular to the tube axis

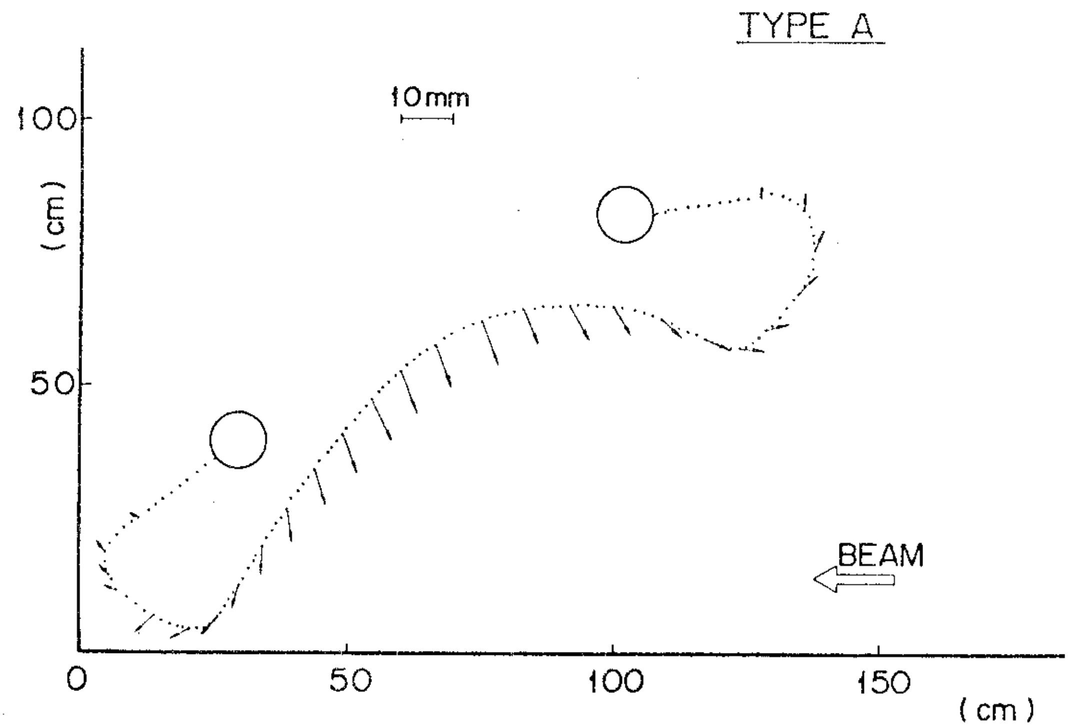



Fig.4.2 Deformation figure for type A

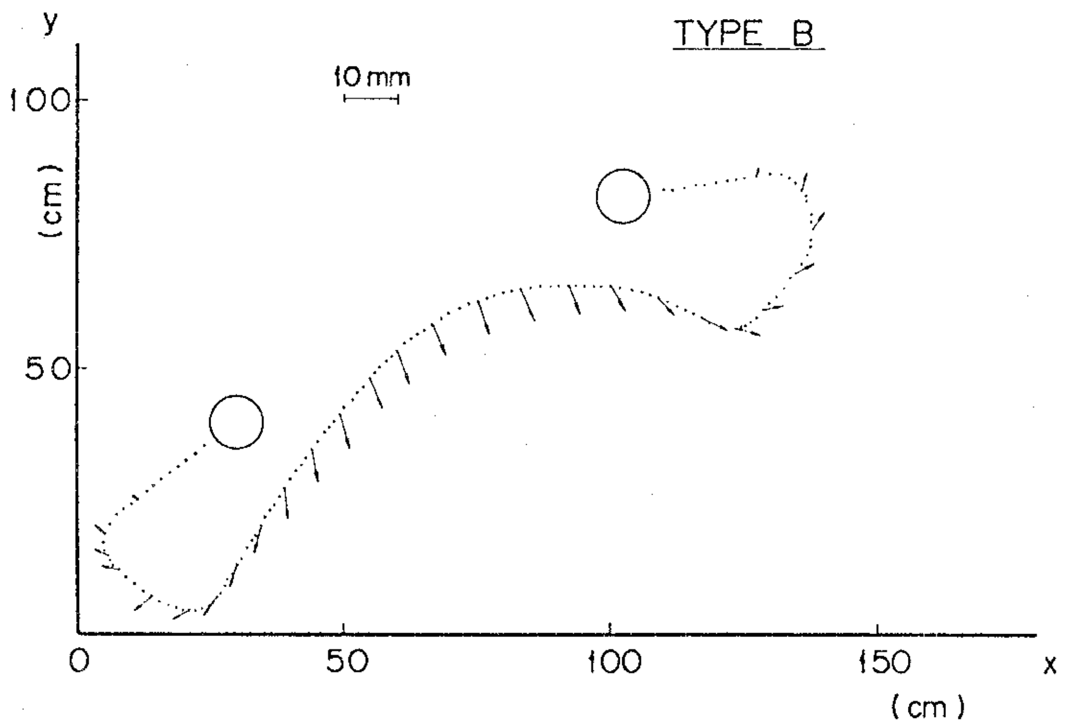



Fig.4.3 Deformation figure for type B

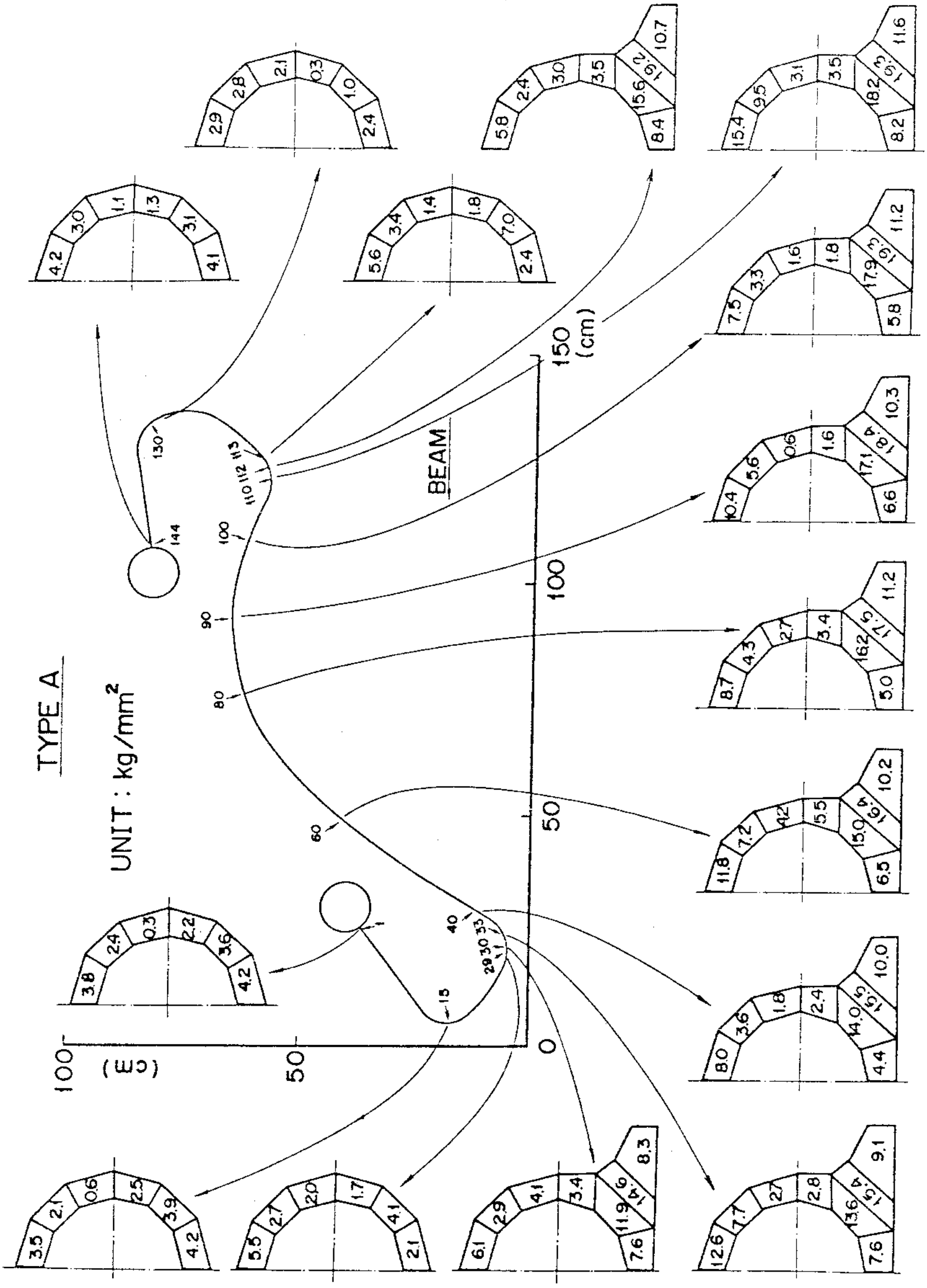



Fig.4.4 Stress intensity distribution for type A

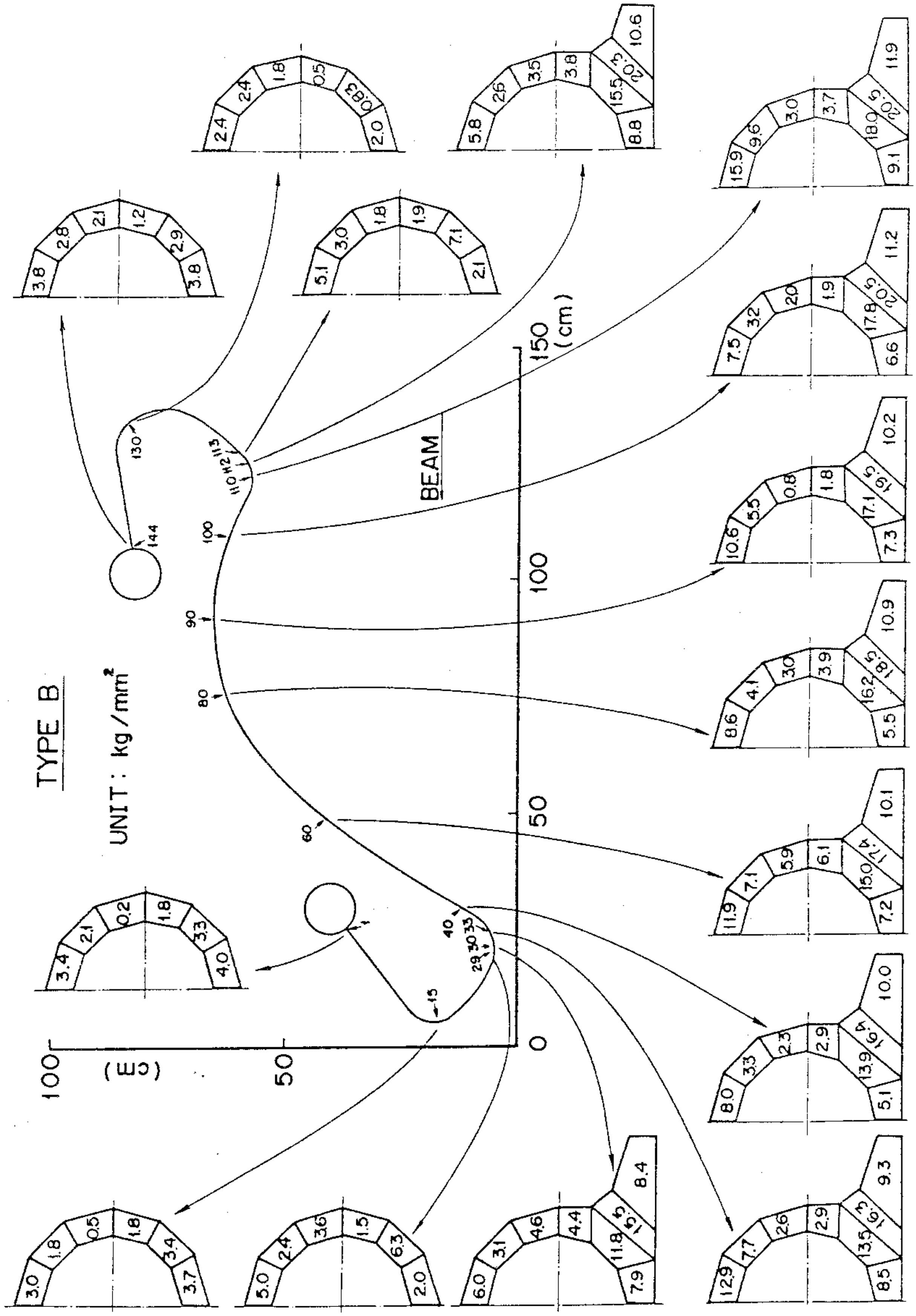



Fig.4.5 Stress intensity distribution for type B

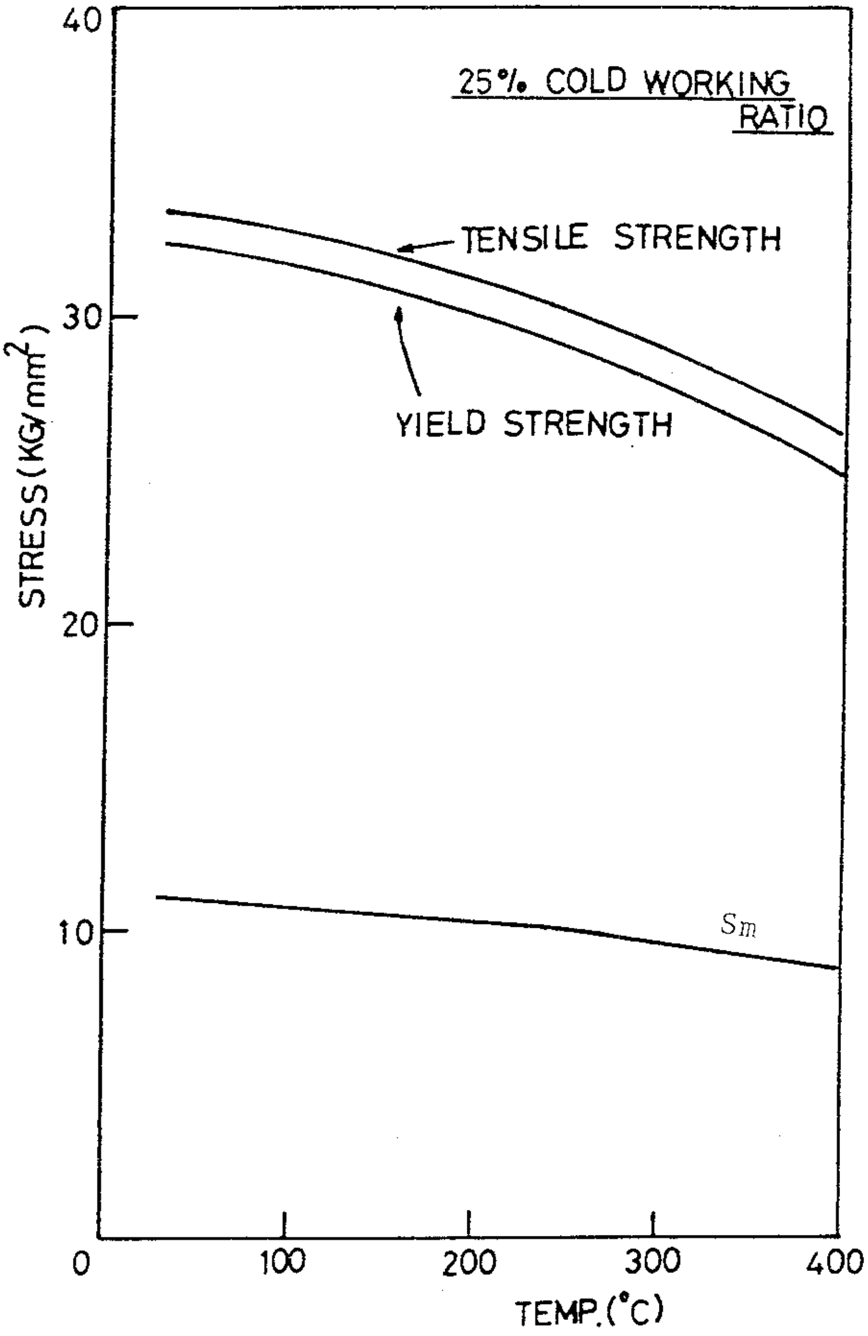



Fig.4.6 The mechanical strength of oxygen free copper with 0.2 % silver content. (25 % cold working ratio)