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DESIGN OF CALORIMETER FOR JT-60 NBI

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The present report describes the design of calorimeter of the neutral beam injector for JT-60.
The calorimeter is an inertial cooling type, and is composed of many dumplinglike lumps on skewers.
It is safe from thermal and mechanical troubles and its fatigue life is estimated to be 10^6 cycles for 0.5 beam pulse.

Keywords; Neutral Beam Injector, Calorimeter, Beam, Inertial Cooling Type, Thermal Stress, Fatigue Life

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* On leave from Mitsubishi Heavy Industries,Ltd.

JT−60用NBIのカロリメータの設計

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（1980年7月12日受理）

この報告は，JT−60用中性粒子入射装置のカロリメータの設計について述べたものである。カロリメータの除熱方式は慣性冷却方式であり，この受熱面は熱応力による破壊を防ぐため，多数の串だんご状の受熱セグメントにより構成されている。この受熱面を構成しているセグメントについて熱及び応力計算を行い，カロリメータは熱及び応力的に安全であることを確かめた。また，疲労寿命は0.5 secビームパルスに対して10^6回であることを確かめた。

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1. Introduction

The beam line of the neutral beam injector for JT-60 contains a lot of hardwares necessary to treat intense ion beams and concomitant gasses in a limited space as shown in Fig.1. Therefore there are many complicated problems in the design work of the beam line.

The present report describes the design of calorimeter of the neutran beam injector(NBI) for JT-60. The calorimeter is located at a distance, about 3.5 m, from the accelerator grid of the ion sources, and is illuminated by two neutral beams simultaneously. It is used for the measurements of the total neutral beam power, the beam profile, and is also used as a beam target in the case of source conditioning or flashing. It can be retracted from the beam pathes by a movable mechanism, when the neutral beam is being injected into the JT-60 plasma.

2. Calorimeter Design

The calorimeter receives the total neutral beam power of 2.4 MW for 0.5 sec with a duty cycle of one pulse per every thirty seconds when the ion sources are being conditioned. Since the maximum power density perpendicular to the beam axis is as high as 6 KW/cm^2 as shown in Fig.2-1, it is necessary to reduce the heat flux by tilting the dump surface. There are two kinds of cooling systems to remove such a high heat flux. One is the forced convective cooling system for the continuos heat flux which relys on the large heat transfer coefficient in the nucleate boiling region, and the other is the inertia cooling system for the pulsed heat flux which relys on the large heat capacity of dump surface. In the calorimeter of JT-60 NBI, it is difficult to reduce the surface heat flux to less than 1 KW/cm^2 due to

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The shape of the dump surface along the beam axis is shown in Fig.2-3. This surface is exposed to the beam with an equal heat flux of 1 KW/cm^2 corresponding to the peak power density profile of Fig.2-1. It can afford to handle 2.4 MW beam with up to $\pm 0.3°$ displacement of beam axis from the center of the calorimeter. A view of the complete structure and a cross-sectional view of the horizontal plane are shown in Figs.2-4 and 2-5, respectively. The dump is composed of about 800 lumps like a dumpling, which are fixed by 27 arrays of skewers. Each skewer which is also made of 0.2% silver content oxygen free copper, is connected to the pipe bend section to relief thermal expansion. The curvature of the bending section was determined from the stress analysis of the cooling pipe.

3. Calculation of Temperature Distribution

The calculation of temperature distribution of the dump has been performed to confirm the limit of beam pulse length. On the three dimensional calculation about a dumplinglike lump of the dump, the heat conduction code HEATING-3 [2)] was used. The calculation model for this code is shown in Fig.3-1, and the boundary conditions of calculation are tabulated in Table 3-1. Since water velocity in cooling pipes is 2 m/s, the heat transfer coefficient, α, of the turbulent pipe flow is given by,

$$N_u = 0.023\, R_e^{0.8}\, P_r^{0.4}$$

and $\alpha = N_u\, \lambda / d$

, where N_u is the Nusselt's number, R_e is the Reynolds number, P_r is the Prandtle number, λ is the thermal conductivity of water, and d is the pipe diameter. The modified heat transfer coefficient was used in the calculation taking account of the different cooling area between calculation model and actual pipe geometry. The thermal properties of the oxygen free copper with 0.2% silver content are tabulated in Table 3-2.

The calculated temperature distributions are shown in Figs. 3-2 and 3-3 at t=0.5 sec. The transient temperature evolution at the surface center of the lump is shown in Fig. 3-4. The temperature rise of the lump reaches 218 °C after 0.5 sec and 314 °C after 1 sec from the beam initiation for every pulse, while the equilibrium temperature of the lump for a duty cycle of 1/60 is about 100 °C under the water temperature of 42 °C. Thus, the maximum temperature of the lump is 318 °C after 0.5 sec beam pulse, and is 414 °C after 1 sec pulse. Since the maximum temperature of lump must be less than 300-350°C which is a safty limit of the material, the beam pulse length is limited within 0.5 sec.

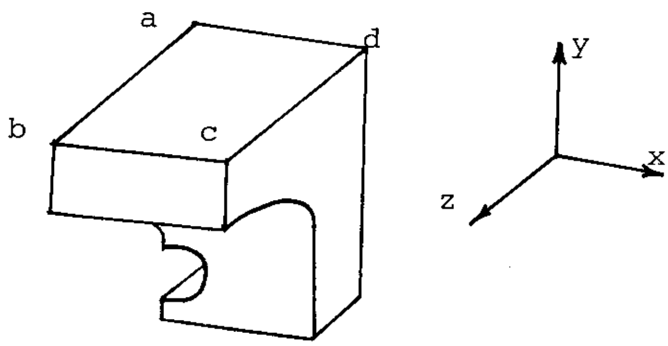
4. Thermal Stress Analysis

The thermal stress analysis of lumps of the dump was performed to evaluate the mechanical strength. The thermal stress was analyzed in three dimensional space using stress analysis code SAP-5 [3]. The calculation model is shown in Fig.4-1. The only load condition is the thermal loading which is origenated from the temperature difference across the lump cosequent on recieving 0.5 sec beam pulse with 1 KW/cm^2 heat flux. The boundary condition for stress analysis were given by,

fix for x-direction at x=0 plane,
fix for z-direction at z=0 plane,
and all other plane are free

as shown in Fig.4-1. The mechanical properties of 0.2% silver content oxygen free copper are tabulated in Table4-1.

The displacement figure of the lump due to the thermal load is shown in Fig.4-2, and the displacement of dump surface are following.



	Δx (mm)	Δy (mm)	Δz (mm)
a	0.0	$3.5x10^{-2}$	0.0
b	0.0	$1.2x10^{-2}$	$4.9x10^{-2}$
c	$4.7x10^{-2}$	$9.1x10^{-3}$	$4.8x10^{-2}$
d	$4.8x10^{-2}$	$1.4x10^{-2}$	0.0

The distribution of "stress intensities" are shown in Fig.4-3, where the stress intensity is defined by the difference between maximum principal stress and minimum one. It is equivalent with the two times of the maximum shear stress. Stress intensity has its maximum in the center of the lump surface, and its value is 11.6 Kg/mm^2.

In the next place, the safty factor for the stress is evaluated based on ASME code-sec 3 [4]. According to the ASME-sec 3, the safty criterion is given by $P_m + P_b + Q < 3S_m$, where P_m is the membrane stress, P_b is the bending stress, Q is the secondary stress, and S_m is the allowable stress. The value of P_m+P_b+Q, which is calculated in the Appendix, is 3.079 Kg/mm^2. Since the value, $3S_m$ at 300°C,is 9 Kg/mm^2, refering to the Fig.4-4 [5] which shows the allowable stress, together with the values measured of yield and ultimate tensile strength of 0.2% silver content oxygen free copper, the relation, $P_m+P_b+Q<3S_m$, is satisfied, and the safty factor is 3.

The fatigue life of the calorimeter is then discussed. The fatigue life curve as a measure of the design according to the ASME code is shown in Fig.4-5 [5] together with the measured curve of the fatigue life. This fatigue curve is the result of a half cycle stress test. On the other hand, the value of summing up the primary, the secondary and the peak stress, P_m+P_b+Q+F, is about 13 Kg/mm^2 according to the above mentioned analysis. However, a half value of the P_m+P_b+Q+F should be used when we try to evaluate the fatigue life using Fig.4-5, because this figure is the result of the half cycle stress test. Since P_m+P_b+Q+F is 6.5 Kg/mm^2, the fatigue life of the calorimeter is estimated to be 10^6 cycles.

5. Conclusion

The inertial cooling type calorimeter for the JT-60 NBI has been designed. It is safe from therml and mechanical troubles, and its fatgue life is estimated to be 10^6 cycles for the 0.5 sec beam pulse.

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1) H.Horiike, et al; to be submitted for publication.
2) W.D.Turner and M.Simon; "HEATING-3 -An IBM 360 Heat Conduction Program", ORNL-TM3208.
3) SAP-V.2, A Structural Analysis Program for Static and Dynamic Response of Linear Systems, Univ.South.Calif., (1972)
4) ASME Boiler and Pressure Vessel code, section 3, Nuclear power plant components(1977)
5) H.Horiike, et al, Private communication

Appendix

To estmated the mechanical safty factor, the stress is evaluated based on ASME code-sec 3 [4].

The following assumptions are made.

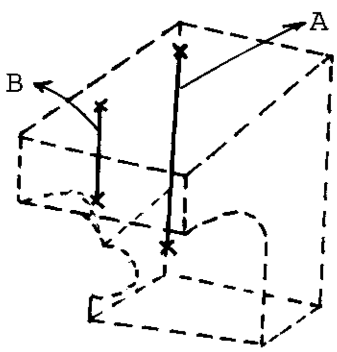
a. The primary stress which is generated from the internal pressure of cooling water was ignored because of its smallness.

b. The secondary stress was estimated as an equivalent linear stress which is calculated from the results of stress analysis. It is then assumed that $\sigma_x, \sigma_y, \sigma_z$ are the principal stress, and $\tau_{xy}=\tau_{yz}=\tau_{zx}=0$

The stress was evaluated at the two sections, namely,

A : x=1.5, 14.0<y< 36.0, z=1.5

B : x=1.5, 21.0<y<36.0, z=6.0



Case A:

a) Primary stress, P_m+P_b ; 0 kg/mm^2

b) Secondary stress, Q ; refering to table A-1,

the membrane stresses are given by

$$\sigma_x=\Sigma\ \sigma_x \Delta y/\Sigma\ \Delta y =0.697\ \text{Kg/mm}^2$$

$$\sigma_z=\Sigma\ \sigma_z \Delta y/\Sigma\ \Delta y =0.145\ \text{Kg/mm}^2$$

, the bending stresses are given by

$$\sigma_x=\pm\Sigma\ \sigma_x \Delta y\ 1/AL =\mp 0.896\ \text{Kg/mm}^2$$

$$\sigma_z=\pm\Sigma\ \sigma_z \Delta y\ 1/AL =\mp 0.507\ \text{Kg/mm}^2$$

where AL=242/3 .

Summing up the membrane stress and the bending stress, we obtain

$$\sigma_x=0.697+0.896= 1.593\ \text{Kg/mm}^2$$

$$\sigma_z=0.145+0.507= o.652\ \text{Kg/mm}^2$$

$$\sigma_y=0$$

The secondary stress is then given by
$Q=\sigma_x-\sigma_z=1.593$ Kg/mm^2.

Case B :

a) Primary stress; 0 Kg/mm^2

b) Secondary stress; refering to Table A-2, and in the same way as case A, $Q=3.079$ Kg/mm^2.

As a results of case A and B, the secondary stress is given by $Q=3.079$ Kg/mm^2, and hence

$$P_m+P_b+Q=3.079 \text{ Kg/mm}^2.$$

Table 3-1 The boundary condition of heat conduction calculation.

Heat flux ;	1 KW/cm^2
Water velocity ;	2 m/s
Heat transfer coefficient;	0.657 $w/cm^2 \cdot °C$
Cooling channel diameter;	1 cm

Table 3-2 The thermal properties of 0.2% silver content oxygen free copper.

Thermal conductivity	20°C	3.86 w/cm°C
	100°C	3.77
	300°C	3.66
Specific heat	20°C	385.2 J/Kg°C
	100°C	397.8
	300°C	414.5
Density		0.00896 Kg/cm^3

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;	1.68×10^{-5} 1/°C

ELEMENT NUMBER	Δy	LENGTH OF MOMENT ARM	σ_x	$\sigma_x \Delta y$	$\sigma_x \Delta y\ l$	σ_z	$\sigma_z \Delta y$	$\sigma_z \Delta y\ l$
20	3	-9.5	-2.33	-6.99	66.405	-0.753	-2.259	21.461
21	2	-7.0	-0.437	-0.874	6.118	-1.31	-2.62	18.34
22	2	-5.0	0.507	1.014	-5.07	-1.74	-3.48	17.4
23	2	-3.0	2.33	4.46	-13.38	-0.386	-0.772	2.32
24	2	-1.0	3.99	7.98	-7.98	1.85	3.70	-3.70
25	2	1.0	5.29	10.58	10.58	3.93	7.86	7.76
26	2	3.0	5.55	11.10	33.30	4.86	9.72	29.16
27	2	5.0	4.25	8.50	42.5	4.09	8.18	40.90
28	2	7.0	0.839	1.678	11.75	1.16	2.32	16.24
29	2	9.0	-5.26	-10.52	-94.68	-4.48	-8.96	-80.64
30	1	10.5	-11.60	-11.60	-121.80	-10.50	-10.50	-110.25
TOTAL				15.328	-72.26		3.19	-40.91

Table A-1 Calculation table of stress analysis (I)

ELEMENT NUMBER	Δy	LENGTH OF MOMENT ARM	σ_x	$\sigma_x \Delta y$	$\sigma_x \Delta y\ l$	σ_z	$\sigma_z \Delta y$	$\sigma_z \Delta y\ l$
120	2	-6.5	-3.31	-6.62	43.03	-4.89	-9.78	63.57
121	2	-4.5	1.64	3.28	-14.76	1.50	3.00	-13.50
122	2	-2.5	4.03	8.06	-20.15	3.33	6.66	-16.65
123	2	-0.5	4.89	9.78	-4.89	4.02	8.04	-4.02
124	2	1.5	3.96	7.92	11.82	3.40	6.80	10.20
125	2	3.5	0.93	1.86	6.51	1.23	2.46	8.61
126	2	5.5	-4.71	-9.42	-51.81	-3.16	-6.32	-34.76
127	1	7.0	-10.70	-10.70	-74.90	-8.05	-8.05	-56.35
TOTAL	15			4.16	-105.09		2.81	-42.90

Table A-2 Calculation table of stress analysis (II)

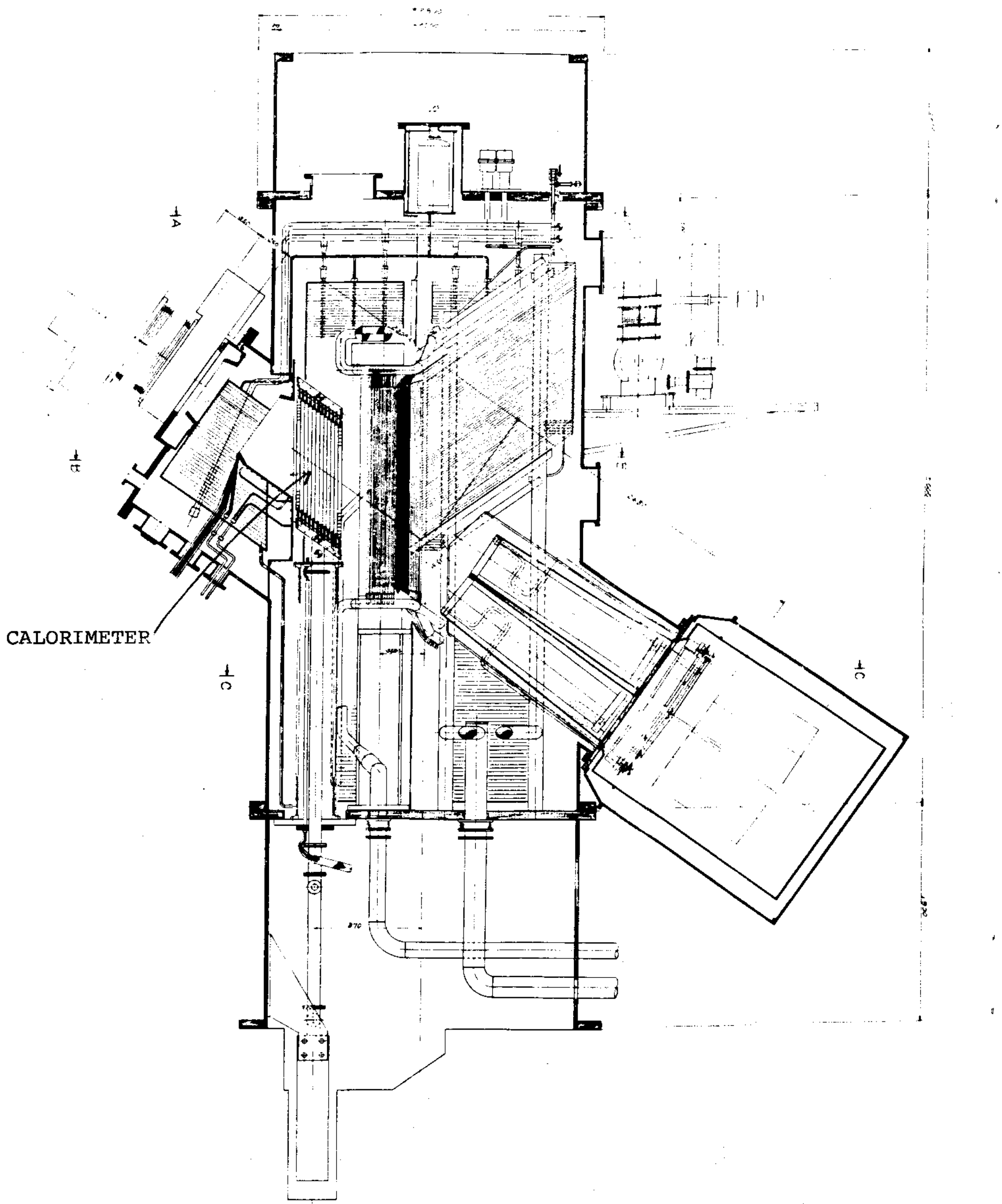


Fig.1-1 A view of the complete construction of the beam line.

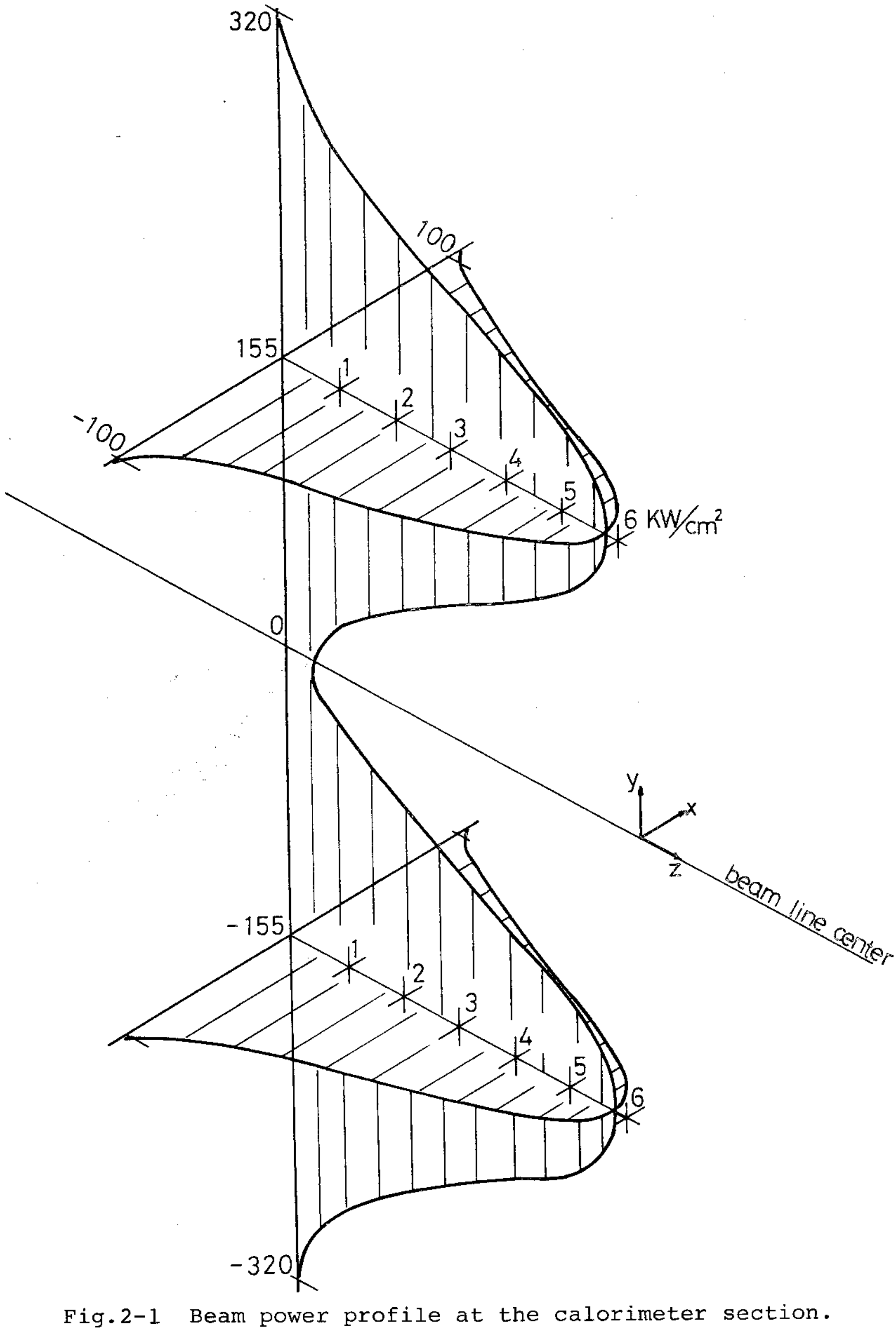


Fig.2-1 Beam power profile at the calorimeter section.

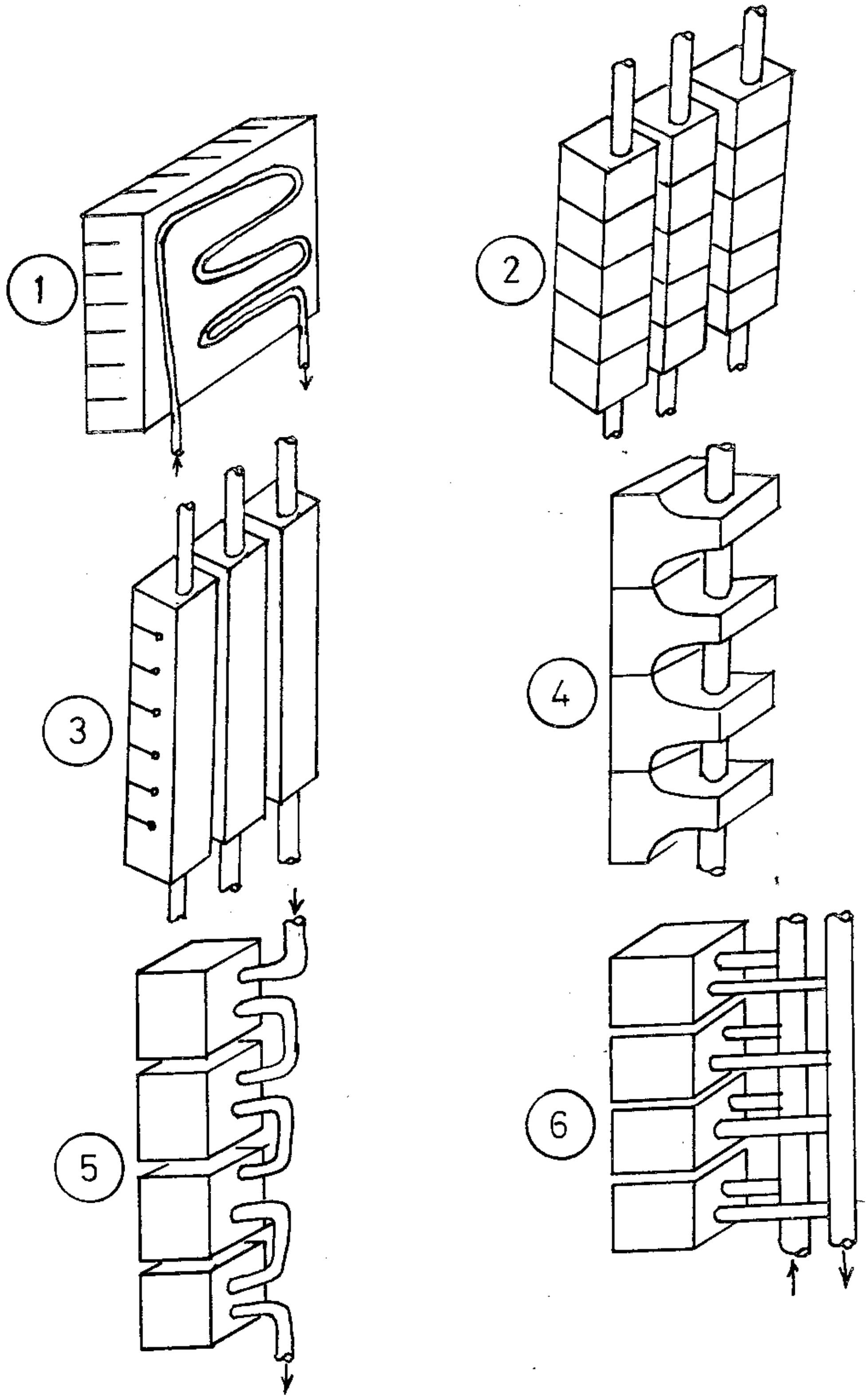


Fig.2-2 Cooling methods of the inertial cooling type dump.

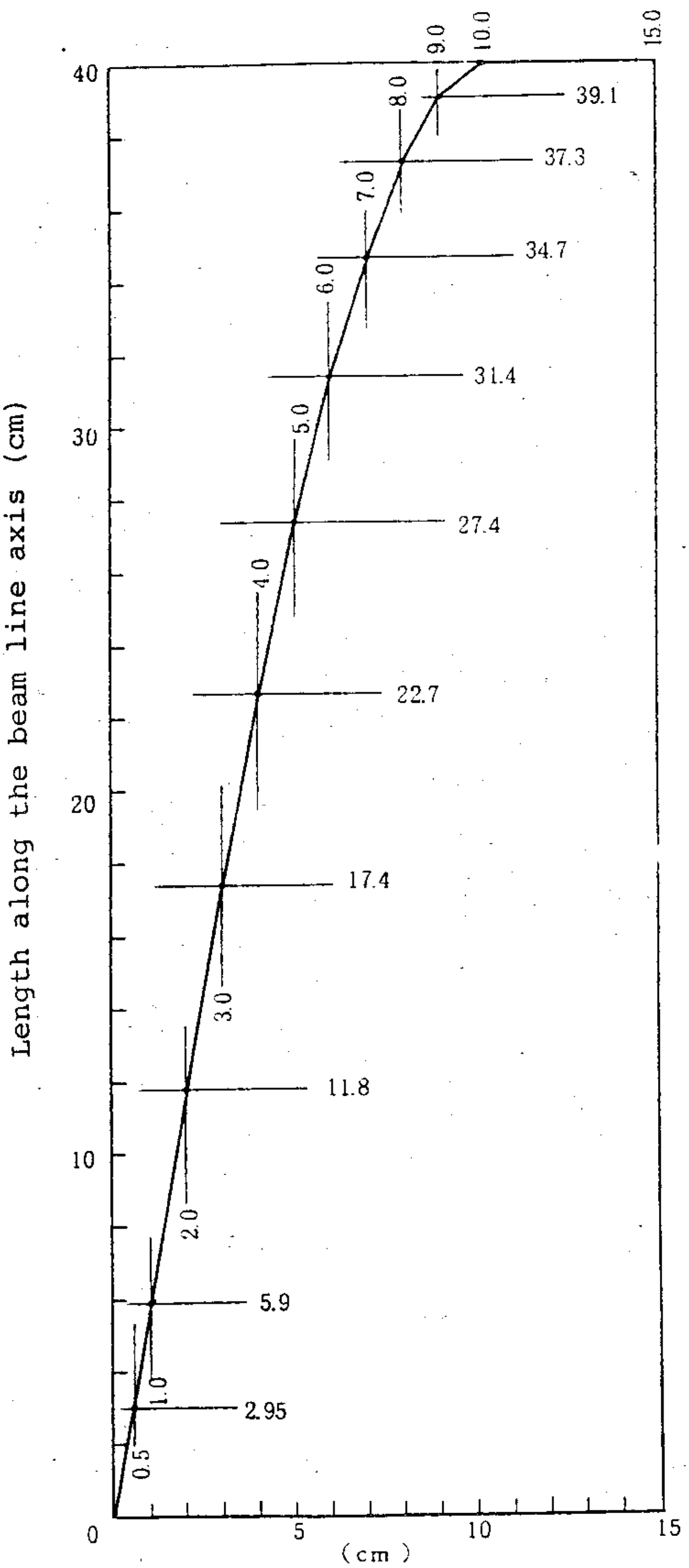


Fig.2-3 Shape of the dump surface along the beam axis.

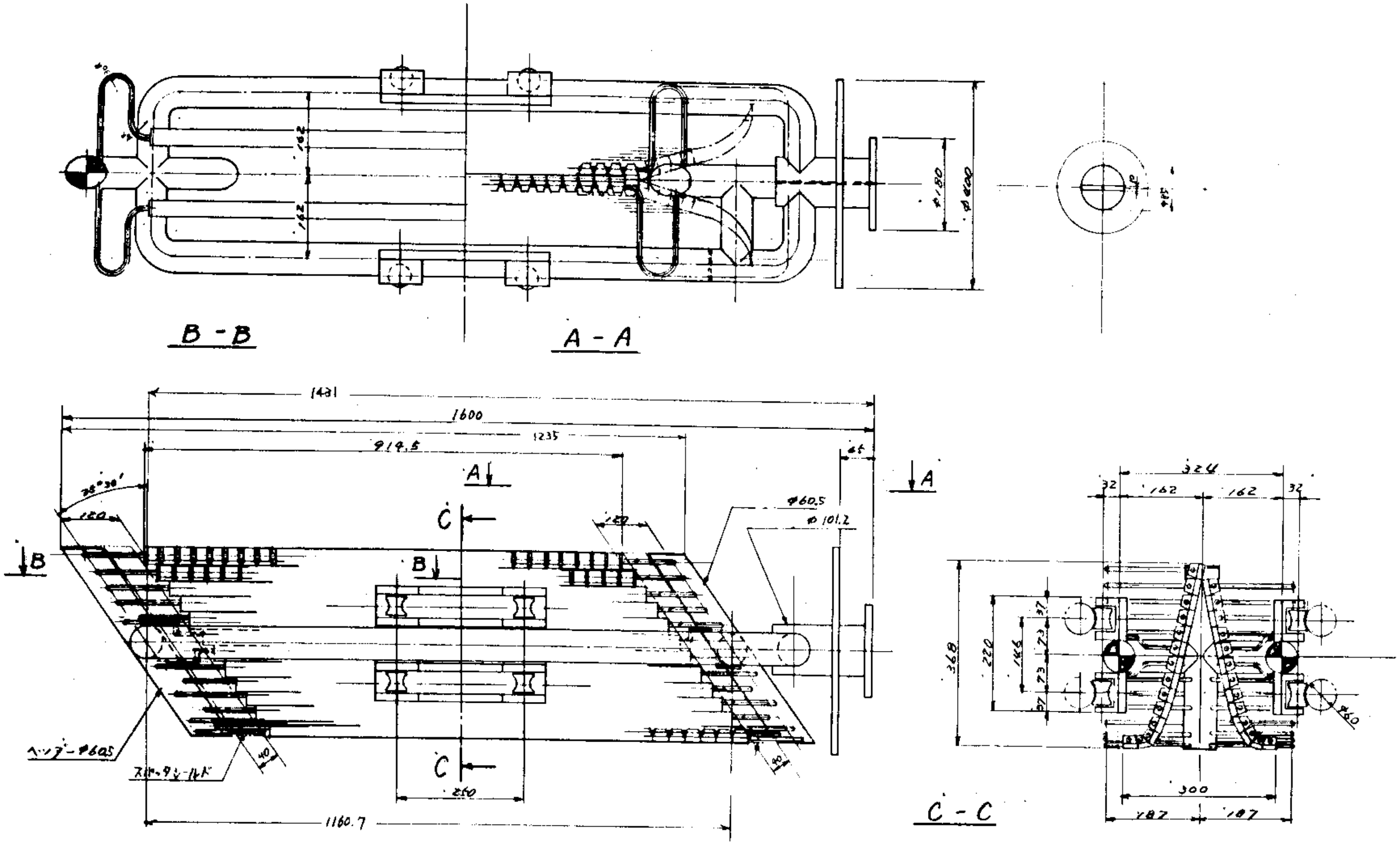


Fig.2-4 A view of the complete construction of the calorimeter.

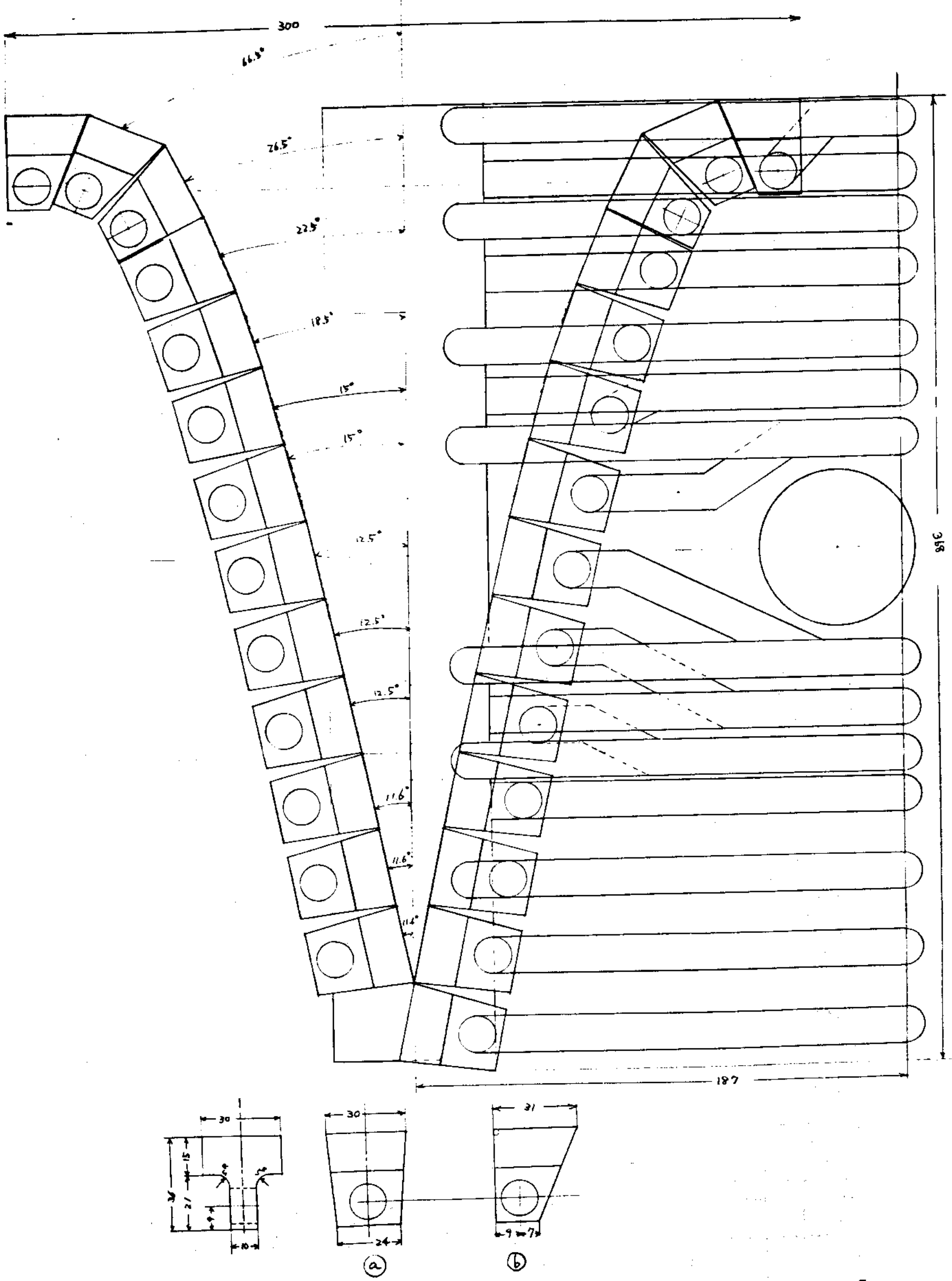


Fig.2-5 A cross-section view of the horizontal plane of the calorimeter.

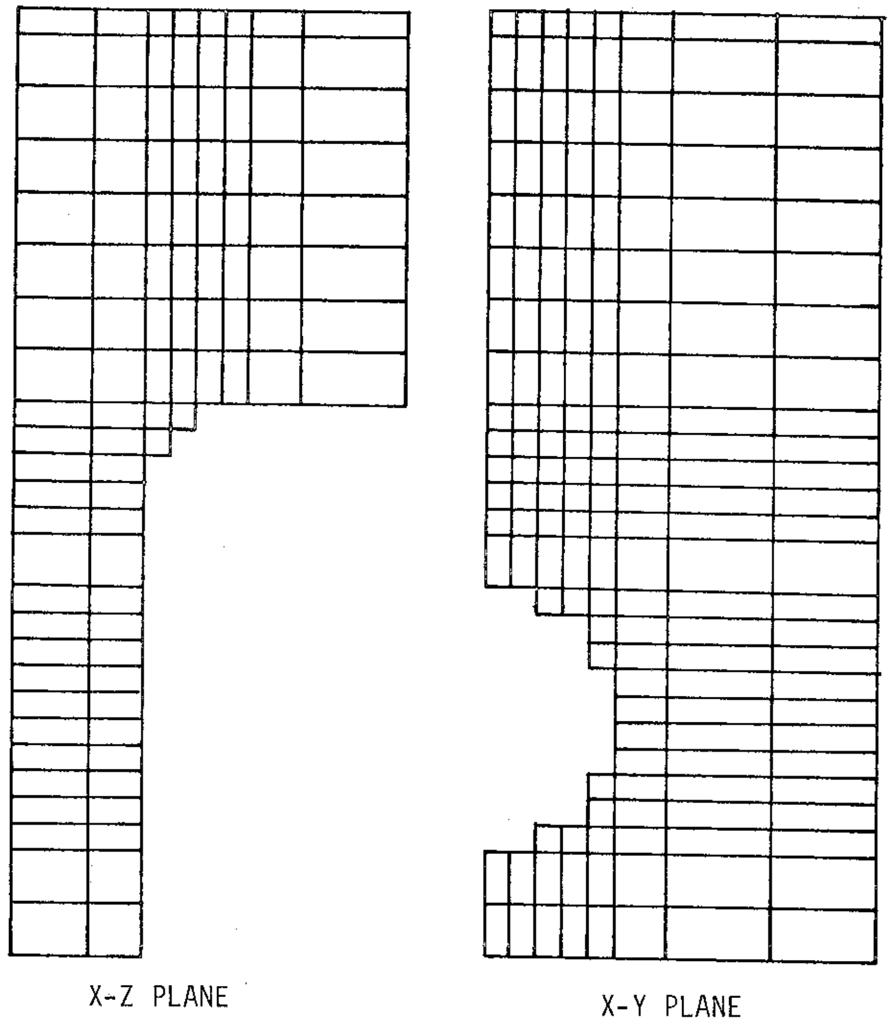


Fig.3-1 A calculation model of heat conduction

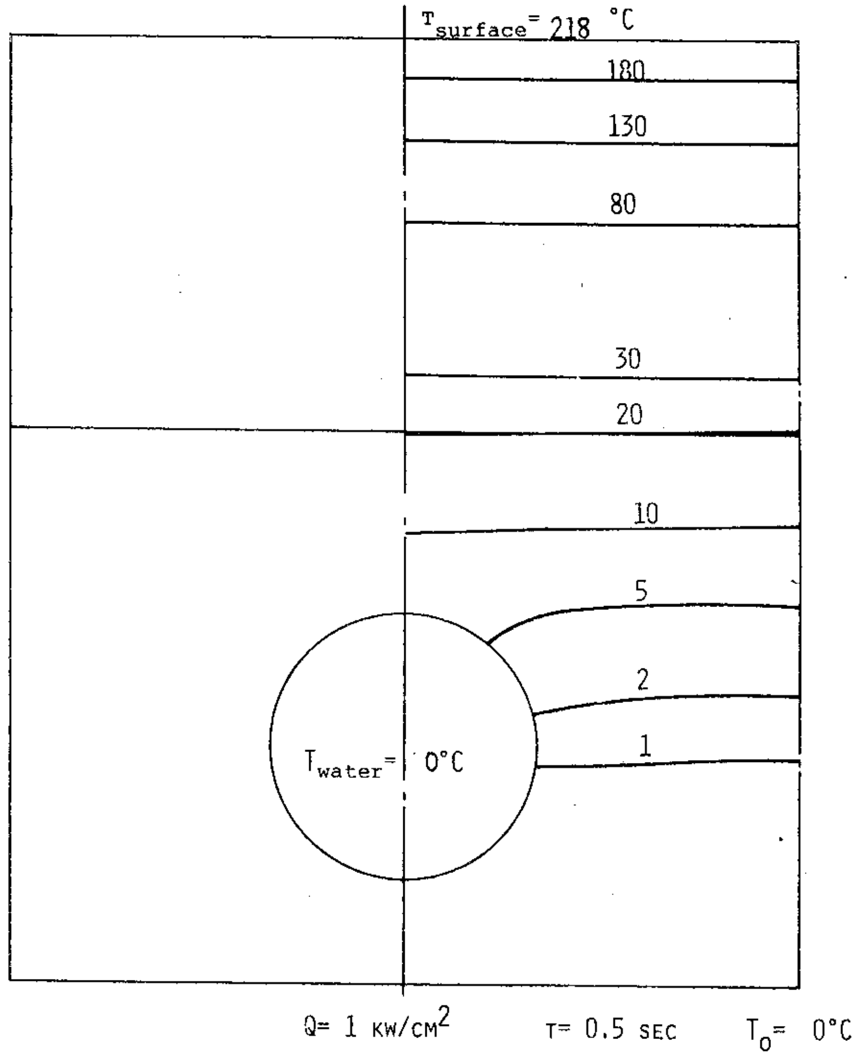


Fig.3-2 Elevated temperature distribution (I)

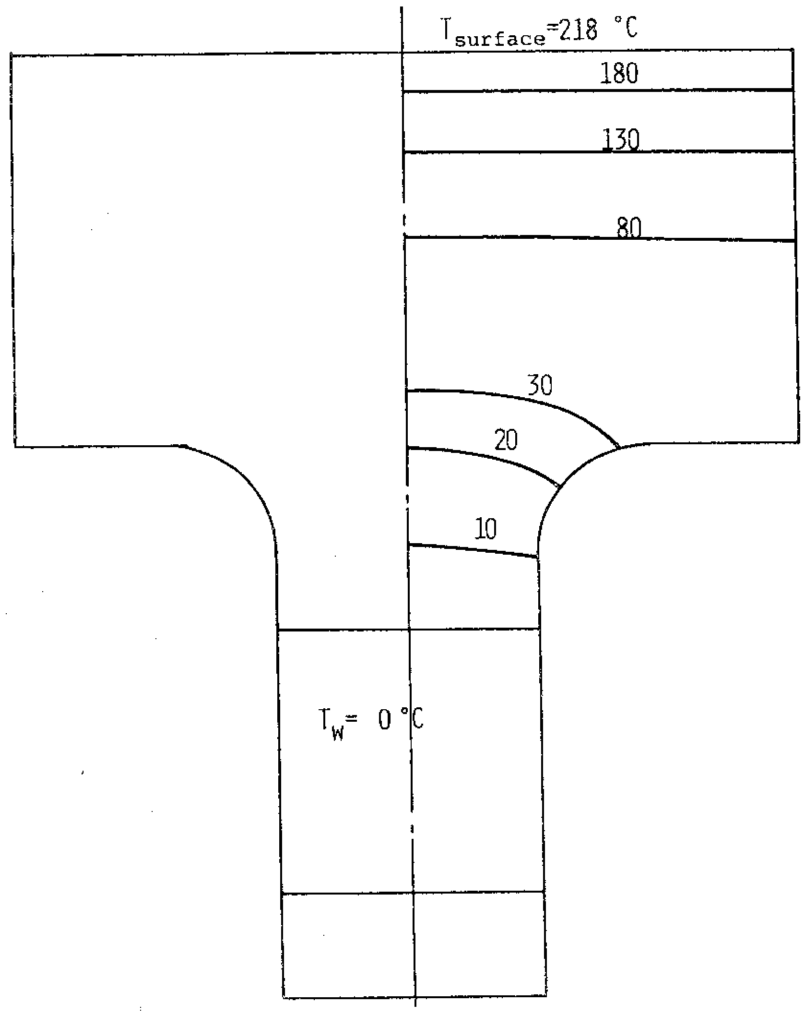


Fig.3-3 Elevated temperature distribution (II)

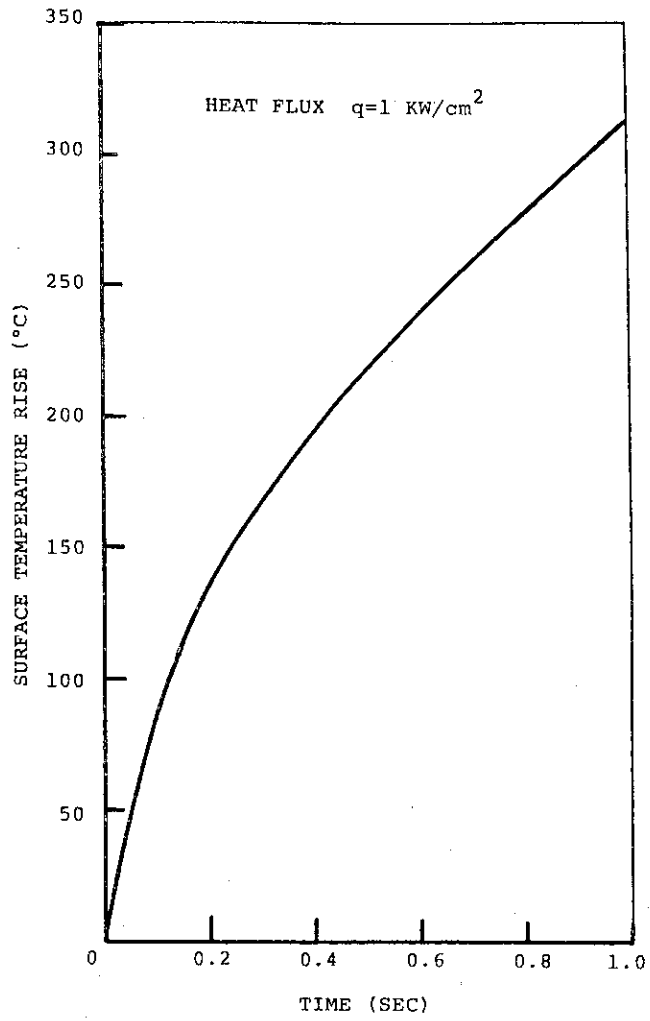


Fig.3-4 Transient temperature of the dump surface.

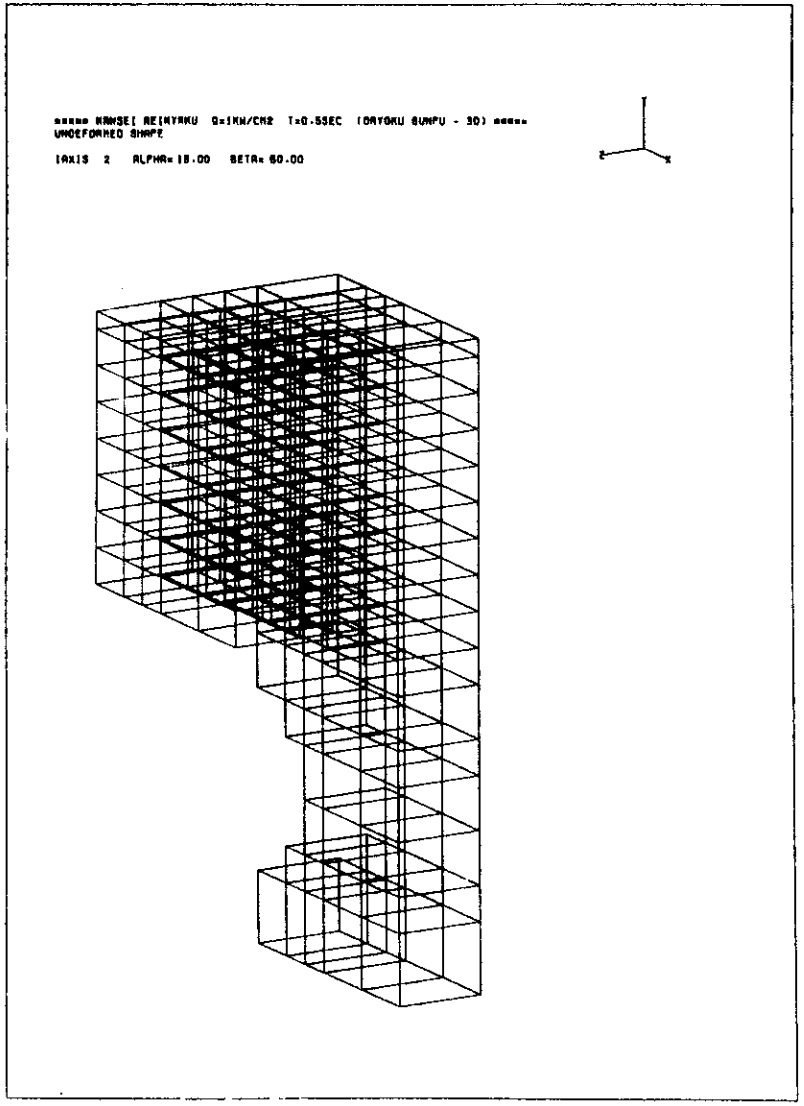


Fig.4-1 The calculation model for stress analysis.

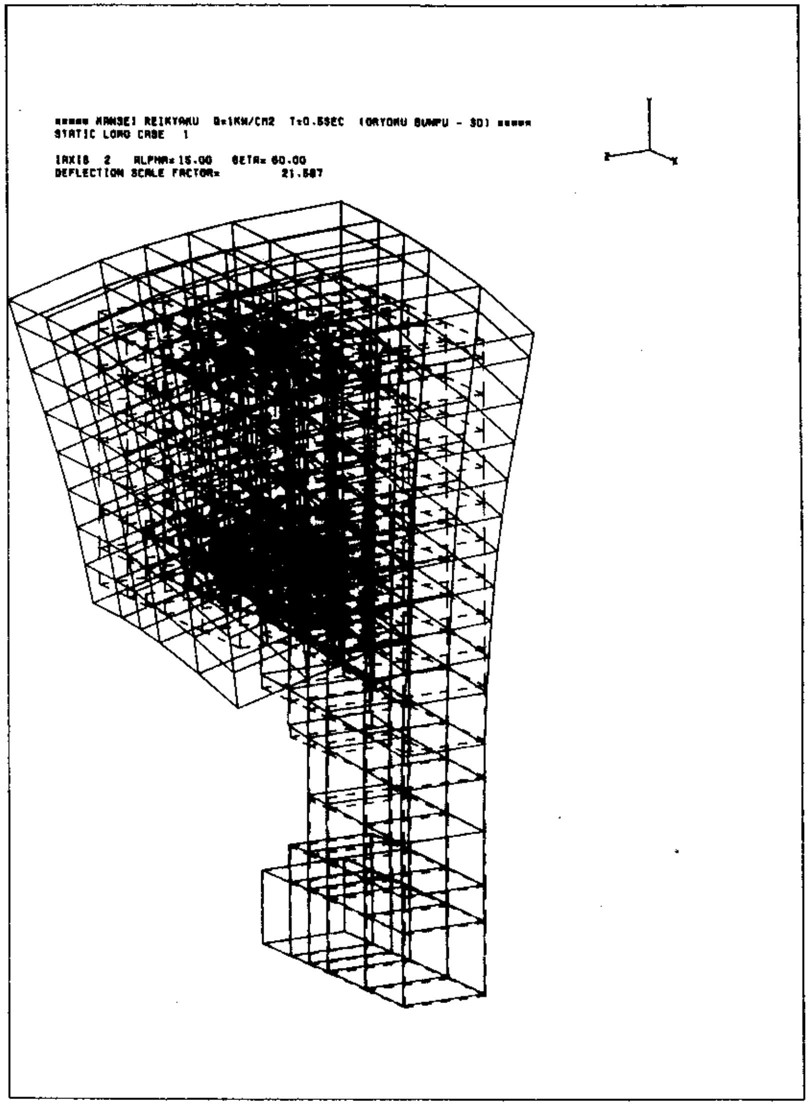


Fig.4-2 The deformation figure of the dump.

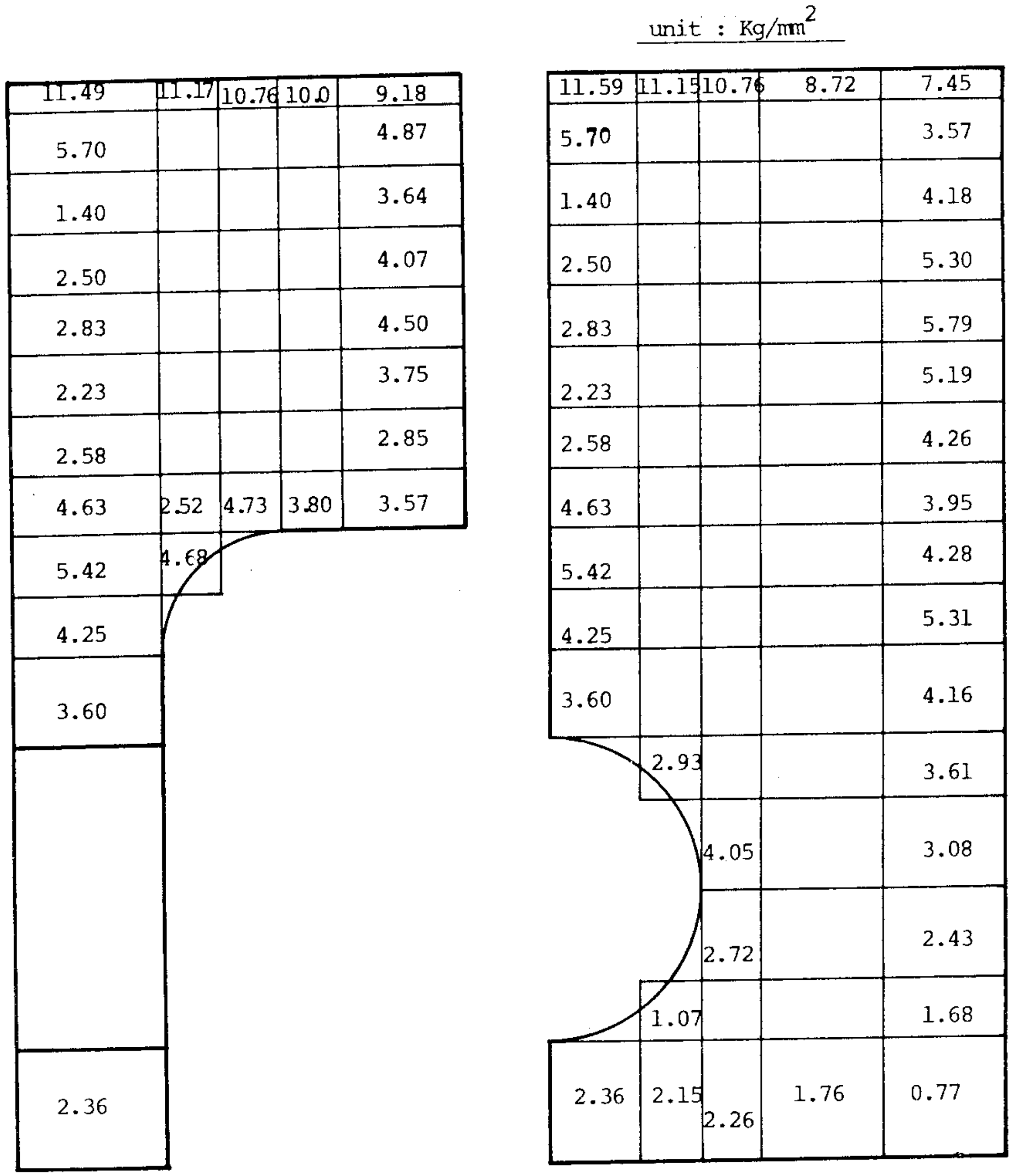


Fig.4-3 The stress intensity distribution

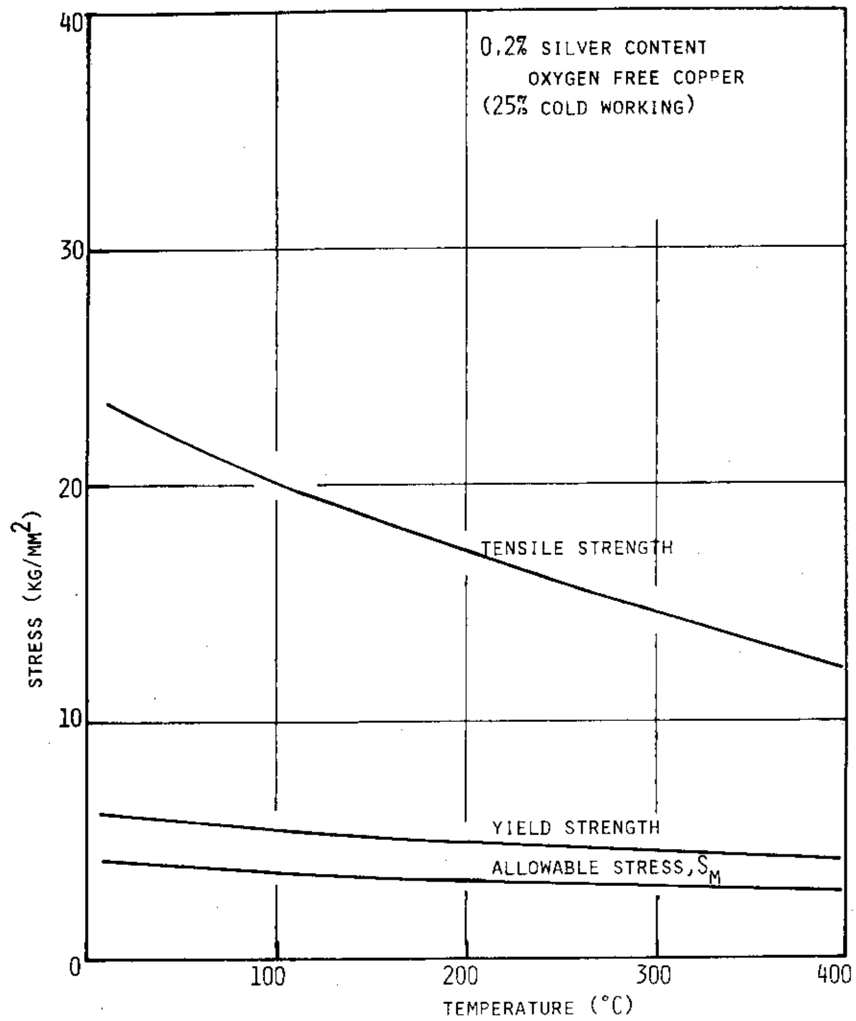


Fig.4-4 The mechanical strength of 0.2% silver content oxygen free copper.

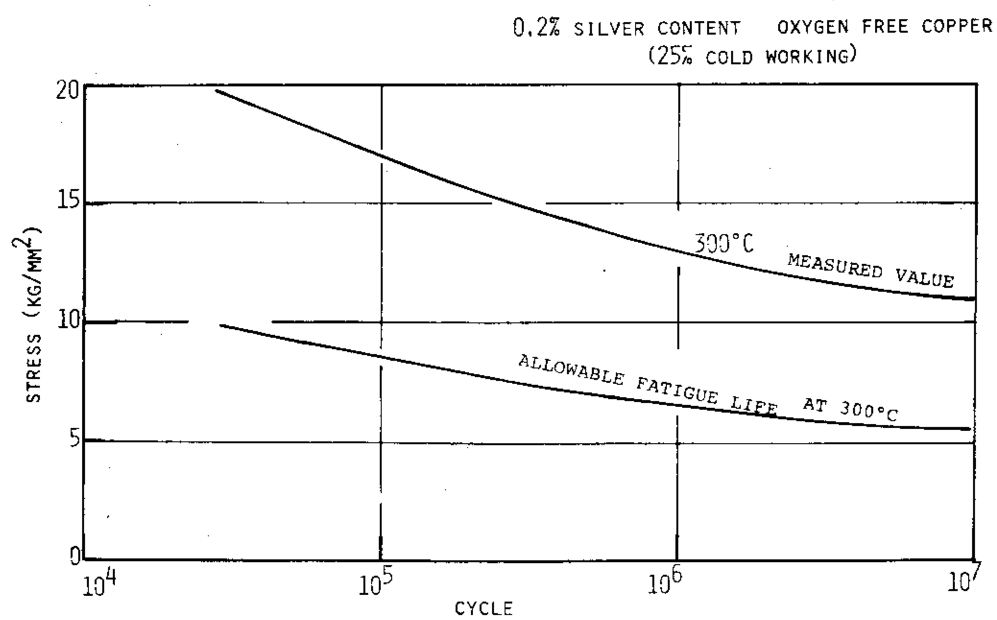


Fig.4-5 The fatigue life curve of 0.2% silver content oxygen free copper.