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TRANSIENT THERMAL AND STRESS ANALYSES OF THE ITER SHIELDING BLANKET/FIRST WALL UNDER OFF-NORMAL CONDITIONS

September 1995

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(Received August 17, 1995)

Transient thermal and stress analyses have been conducted with the following three off-normal conditions for the shielding blanket and first wall (FW) structure of International Thermonuclear Experimental Reactor (ITER).

-Loss of Flow Accident (LOFA)

-Loss of Coolant Accident (LOCA)

-Power Excursion Condition (PEC)

The main results obtained are as follows:

1) In case of FW LOFA/LOCA, time to reach 400℃ is 18 s at Beryllium surface, in case of shield LOFA/LOCA, time to reach 400℃ is 90 s at 316SS internal rib, and in case of FW and shield LOFA/LOCA, time to reach 400℃ is 17 s at Beryllium surface.

2) In case of FW LOFA/LOCA, maximum temperatures to satisfy 3Sm limits are 280℃ for FW Cu alloy and 285℃ for 316SS internal rib and in case of shield LOFA/LOCA, maximum temperatures to satisfy 3Sm limits are 248℃ for FW Cu alloy and 170℃ for 316SS internal rib. However, detail design guideline for

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.D11).

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off-normal conditions should be established and the stress should be reevaluated in future.

3) In case of FW LOFA/LOCA, plasma must be shut-down in a few seconds after the initiation of these events so as to prevent excursion of FW temperature and stress, while plasma shut-down requirement could be relatively relaxed in case of shield LOFA/LOCA.

4) Stresses and displacements during FW LOFA and FW LOCA are nearly equal. So are those during shield LOFA and LOCA.

5) Power excursion up to 1.8 GW shows no problem.

Keywords : ITER, Shielding Blanket, Thermal Analysis, Stress Analysis, LOFA, LOCA, PEC

非正常時におけるＩＴＥＲ遮蔽ブランケット過渡熱・応力解析

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（1995年８月17日受理）

核融合実験炉ブランケット構造体の非正常時における構造健全性を確認するために，以下の３ケースに関して熱及び熱応力解析を行った。

-Loss of Flow Accident (LOFA)：冷却材流動停止事故

-Loss of Coolant Accident (LOCA)：冷却材損失事故

-Power Excursion Condition (PEC)：過出力状態

これらの現象が生じた場合について今回得られた主な結果は以下の通りである。

１）ブランケット構造体各部位が400℃に達するまでの時間は，第一壁のＬＯＦＡ／ＬＯＣＡ時の場合，ベリリウム表面が最も早く18秒。シールド部のＬＯＦＡ／ＬＯＣＡ時の場合，中央リブＳＵＳ部が最も早く90秒。第一壁とシールド部のＬＯＦＡ／ＬＯＣＡ時の場合，ベリリウム表面が最も早く17秒。

２）ブランケット構造体の構造健全性（３Ｓｍ）を満足する最高温度は，第一壁のＬＯＦＡ／ＬＯＣＡ時では第一壁Ｃｕ部で280℃，中央リブＳＵＳ部285℃である。また，シールド部のＬＯＦＡ／ＬＯＣＡでは第一壁Ｃｕ部で248℃，中央リブＳＵＳ部170℃である。

３）第一壁のＬＯＦＡ／ＬＯＣＡ時の場合，第一壁温度及び応力の過度な上昇を防ぐ為にＬＯＦＡ／ＬＯＣＡ発生後数秒間にプラズマを停止する必要がある。遮蔽領域のＬＯＦＡ／ＬＯＣＡ時の場合，プラズマ停止条件は比較的緩和される。

４）第一壁のＬＯＦＡ時とＬＯＣＡ時との比較，及びシールド部のＬＯＦＡ時とＬＯＣＡ時との比較では，どちらの場合も発生応力及び変位量の差はほとんど無い。

５）1.8ＧＷまでのＰＥＣ時における過渡熱及び熱応力がブランケット構造体に与える影響については特に問題ない。

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年設計作業計画（Task No.G16TD12, IDNo.D11）に基づいて実施した。

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1 BACKGROUND AND OBJECTIVE

Modular type shield blanket for ITER is composed of first wall (FW) and shield. FW and shield are equipped with independent cooling systems to remove surface heat flux from plasma and nuclear heating by water. Defailed design description and thermo-mechanical performances under normal operation conditions were reported(1). In case of coolant pump or cooling pipe failure, heat cannot be removed, and as a result, integrity of the blanket structure is seriously affected due to temperature rise and stress increase. The following three off-normal conditions possibly to occur to the blanket structure were assumed here.

- Loss of Flow Accident (LOFA)
- Loss of Coolant Accident (LOCA)
- Power Excursion Condition (PEC)

LOFA means that circulation of coolant in the FW or shield is stopped. LOCA means that coolant in the FW or shield is lost. In case of these accidents, thermal stress will increase by temperature rise due to insufficiency of cooling. PEC means a shot time (10 s) increase of fusion power. In case of PEC, surface heat flux to FW and nuclear heating in in-vessel components increase resulting in the increase of thermal stress. Transient thermal and stress analyses have been performed so as to investigate the behavior of the blanket structure during these events. Inboard blanket at mid plane has been taken for the analyses. Two analysis models were prepared. One is a model of horizontal cross-section of blanket to investigate the behavior of the blanket box structure such as thermal stress based on the difference between FW and Shield temperatures, and the other a zoomed-up model of vertical cross-section of FW to grasp the local response. Analysis method and results are described in chapter 2 and 3, respectively. Stress evaluation and conclusion are described in chapter 4 and 5, respectively.

2 ANALYSIS METHOD

2.1 Analysis model

<MODEL-1>

The analysis model (MODEL-1) is shown in Fig.1, which is a cross-section of the inboard blanket at midplane. The whole meshes are shown in Fig.2, and detailed meshes at FW part in Fig.3. FW materials are 316SS as structural material and Cu alloy as heat sink material. Beryllium is coated on Cu alloy as plasma facing material.

<MODEL-2>

The analysis model (MODEL-2) for local FW is shown in Fig.4 and meshes are shown in Fig.5. FW consists of 316SS structural

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2.2 Analysis condition

Analysis conditions for normal operation (steady state), LOFA/LOCA and PEC are shown in Table 1, Table 2 and Table 3, respectively. Thermal boundary conditions for normal operation (steady state), FW LOFA/LOCA, Shield LOFA/LOCA, FW and shield LOFA/LOCA and PEC are shown in Fig.6, Fig.7, Fig.8, Fig.9 and Fig.10, respectively and stress boundary conditions are shown in Fig.11. Heat transfer coefficient used in MODEL-1 is 12000 W/m2/k, while heat transfer coefficient used in MODEL-2 is modified to 17300 W/m2/k in order to obtain Beryllium maximum temperature matched with that of MODEL-1. MODEL-1 corresponds to more detail FW geometry hence more appropriate to examine temperature distribution in FW. In case of LOFA/LOCA, three cases each are considered as follows:

-LOFA

1) shield cooling system alive, FW coolant flow stopped
2) FW cooling system alive, shield coolant flow stopped
3) Both of FW and shield coolant flow stopped

-LOCA

1) shield cooling system alive, FW coolant lost
2) FW cooling system alive, shield coolant lost
3) Both of FW and shield coolant lost

In case of LOCA, coolant pressure is also lost, while coolant pressure (2 MPa) is kept during LOFA. For both of LOFA and LOCA analyses, heat transfer coefficients are stepped down to 0 W/m2/k at their start. Fusion power during PEC (for 10 s) is increased by 20% from the normal operating condition. All of the above events are assumed to initiate from the steady state under normal operation condition.

3 ANALYSIS RESULTS

3.1 Thermal transient analysis

Steady state operation condition

Temperature distributions in FW and shield are shown in Fig.12 and Fig.13, respectively. The maximum temperature of 266°C occurs at Beryllium surface. Temperatures at the boundary of Beryllium and Cu alloy, at the corner of 316SS cooling channel near plasma and at 316SS center rib near FW are 247°C, 238°C and 252°C, respectively.

LOFA/LOCA conditions

<u>LOFA/LOCA at FW</u>

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<u>LOFA/LOCA at FW</u>

Responses of FW and shield temperatures are shown in Figs.14~18. Temperature distributions are shown in Figs.19~21. Temperatures of FW rise after LOFA/LOCA occurs. The maximum temperature response occurs at Beryllium surface, and the time to reach 400°C, which would be an allowable design limit, is about 18 s. As for ribs in the shield, there is little temperature change from the steady state condition because of the cooling inside the shield kept.

LOFA/LOCA at shield

Responses of shield and FW temperatures are shown in Figs.22~26. Temperature distributions are shown in Figs.27~29. Temperatures of rib-a and rib-b (rib-a and rib-b are shown in Fig.2) rise after LOFA/LOCA occurs. The time for rib-a and rib-b temperatures to reach 400°C is about 90 s. On the other hand, shield-side 316SS temperature of FW almost saturates at 60 s after LOFA/LOCA occurs. The maximum temperature of FW is about 276°C at Beryllium surface.

LOFA/LOCA at FW and shield

Response of FW temperature is shown in Fig.30. Temperature distribution is shown in Fig.31. Temperatures of FW increase linearly as a function of time after LOFA/LOCA occurs. Temperature at Beryllium surface is the highest. It takes about 17 s for Beryllium surface temperature to reach 400°C.

PEC condition

Responses of FW and shield temperatures are shown in Fig.32 and Fig.33, respectively. Temperature distribution in FW and shield are shown in Fig.34 and Fig.35, respectively. FW temperature increases slightly during PEC due to the increase of fusion power for 10 s. Then the temperature decreases to be constant at about 10 s after steady state operation is recovered. The maximum temperature at the Beryllium surface at 10 s after PEC is about 283°C which is 17°C higher than that during normal operation. Temperatures of ribs in the shield are little changed.

3.2 Thermal stress analysis

The back plate also expands due to its temperature rise. Thus, an average temperature and thermal expansion at the blanket leg of the back plate were assumed to be 200°C and 0.676 mm, respectively, in the present analyses. Stresses of FW and the legs of the blanket is shown in Fig.36 as a function of back plate temperature.

Normal operation condition

The maximum stress due to coolant pressure (2 MPa) alone is 29 MPa. Stress distribution during normal operation (steady state) is shown in Fig.37. The maximum stress in the Cu alloy is 166 MPa, and the maximum stress in the 316SS is 202 MPa at center rib. The maximum displacements are 0.94 mm in the toroidal direction and 1.36 mm in the radial direction.

LOFA/LOCA conditions

FW LOFA

Stress distribution is shown in Fig.38. The temperature distribution at 10 s after FW LOFA is applied here. The maximum stress is 763 MPa at plasma-side cooling channel of 316SS. The maximum displacements are 1.05 mm in the toroidal direction and 1.64 mm in the radial direction.

FW LOCA

Stress distribution is shown in Fig.39, for which the temperature distribution at 10 s after FW LOCA is applied. The maximum stress is 763 MPa at plasma-side cooling channel of 316SS. The maximum displacements are 1.04 mm in the toroidal direction and 1.64 mm in the radial direction. The difference of stresses and displacements during FW LOFA (with coolant pressure) and FW LOCA (without coolant pressure) is small, because the thermal load is dominant for both responses.

Shield LOFA

Stress distribution is shown in Fig.40. The temperature distribution at 50 s after shield LOFA is applied in the analysis. The maximum stress is 505 MPa at plasma-side cooling channel of 316SS. The maximum displacements are 1.19 mm in the toroidal direction and 1.35 mm in the radial direction.

Shield LOCA

Stress distribution is shown in Fig.41. The temperature distribution at 50 s after shield LOCA is applied here. The maximum stress is 509 MPa at plasma side cooling channel of 316SS. The maximum displacements are 1.18 mm in the toroidal direction and 1.30 mm in the radial direction.

The difference of stresses and displacements during shield LOFA (with coolant pressure) and shield LOCA (without coolant pressure) is small, because the thermal load is dominant for both responses.

PEC condition

Stress distribution is shown in Fig.42. The temperature distribution 10 s after initiation of PEC is applied for this analysis. The maximum stress is 232 MPa in Cu alloy of FW. In the shield region, the maximum stress 210 MPa in 316SS center rib. The maximum displacements are 1.11 mm in the toroidal direction and 1.37 mm in the radial direction.

4 EVALUATION

Preliminary thermal and stress evaluation is performed here based on the results obtained above. Stress intensity, such as in ASME section III, is approximately defined as follows:

$Sm = \min. (1/3\ \sigma_u, 2/3\ \sigma_y)$

, where σ_u and σ_y are Ultimate tensile strength and Yield strength, respectively.

A conservative guideline for the maximum stress due to coolant pressure and thermal loads is to satisfy the following condition.

$\sigma_{max} < 3\ Sm$

The maximum allowable design temperature of 316SS would be 400°C.

LOFA/LOCA conditions

FW LOFA/LOCA

The time evolution of the stresses and temperatures at the point of maximum stresses in Cu alloy and 316SS in case of FW LOFA/LOCA is shown in Fig.43. The maximum temperatures and the times to reach the maximum temperatures which satisfy "$\sigma_{max} < 3$ Sm" are 280°C (in about 2 s) for Cu alloy and 285°C (in about 3 s) for 316SS, which shows that plasma must be shut-down in a few seconds after the initiation of FW LOFA/LOCA events so as to prevent the excursion of the FW temperature and stress.

Shield LOFA/LOCA

The time evolution of the stresses and temperatures at the point of maximum stresses in Cu alloy and 316SS in case of shield LOFA and LOCA is shown in Fig.44. Fig.44 shows that thermal stress at FW (Cu) decrease once because temperature differentials between FW and shield is relieved due to a rise of the temperature at shield but after that, thermal stress at FW (Cu) is risen again following with time due to more a increase of the temperature at shield. The maximum temperatures and the times to reach the maximum temperatures which satisfy "$\sigma_{max} < 3$ Sm" are 248°C (in about 90 s) for Cu alloy and 170°C (in about 35 s) for 316SS. Plasma shut-down requirement is relatively relaxed in comparison with the case of FW LOFA/LOCA. Although the stresses are conservatively evaluated based on 3 Sm guideline, the detail design guideline for off-normal events such as LOFA and LOCA should be established in future, and stress evaluation should be revisited based on it. For instance, the limits of temperature and stress should be carefully decided from the view point of the number of events, the melting and the reuse of materials and so forth.

PEC condition

The maximum temperatures and stress of Cu alloy and 316SS during PEC and the allowable stresses are as follows:

Component	σ_{max} (MPa)	Temperature (°C)	Sm (MPa)	3 Sm (MPa)
Cu	232	267	101	303
316SS	210	257	124	378

Based on the results shown above, PEC up to 1.8 GW causes no problem.

5 CONCLUSION

Transient thermal and stress analyses of the ITER FW and shield blanket have been carried out for off-normal conditions. The results obtained are as follows:

(1)In case of FW LOFA/LOCA, time to reach 400°C is 18 s at Beryllium surface, in case of shield LOFA/LOCA, time to reach 400°C is 90 s at 316SS internal rib, and in case of FW and shield LOFA/LOCA, time to reach 400°C is 17 s at Beryllium surface.

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(3)In case of FW LOFA/LOCA, plasma must be shut-down in a few seconds after the initiation of these events so as to prevent excursion of FW temperature and stress, while plasma shut-down requirement could be relatively relaxed in case of shield LOFA/LOCA.

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ACKNOWLEDGMENT

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REFERENCE

(1) S. Sato, et al. : "Conceptual Design of ITER Shielding Blanket," JAERI-tech 95-019 (1995)

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Table 1 Thermal and stress analysis conditions for normal operation

Surface heat flux	0.5 MW/m2
Nuclear heating	
Beryllium	7.7 MW/m2
Copper alloy	17.6 MW/m2
316SS	13.8 MW/m2
Heat transfer coeff.	
at the FW cooling channel	17. kW/m2
at the shield wall	3.9 kW/m2
Uniform bulk coolant temp.	150°C
Coolant pressure	2 MPa

Table 2 Thermal and stress analysis conditions for LOFA／LOCA

FW cooling system trip
heat transfer coeff.(FW) is changed.
17. kW/m2 to 0 kW/m2

Shield cooling system trip
heat transfer coef.(Shield) is changed.
3.9 kW/m2 to 0 kW/m2

FW and shield cooling systems are tripped
both heat transfer coeff. are changed.
FW : 17. kW/m2 to 0kW/m2
Shield : 3.9 kW/m2 to 0 kW/m2

- Surface heat flux and nuclear heating are same as steady state
- In case of LOCA, coolant pressure is changed 2 MPa to 0 MPa

Table 3 Thermal and stress analysis conditions for PEC

Surface heat flux		0.6 MW/m^2
Nuclear heating		
	Beryllium	9.24 MW/m^2
	Copper alloy	21.1 MW/m^2
	316SS	16.6 MW/m^2
Heat transfer coeff.		
	at the FW cooling channel	17. kW/m^2
	at the shield wall	3.9 kW/m^2

- Surface heat flux and nuclear heating are 1.2 times higher than of steady state for 10 sec..
- Cooling conditions are same as steady state (2 MPa)

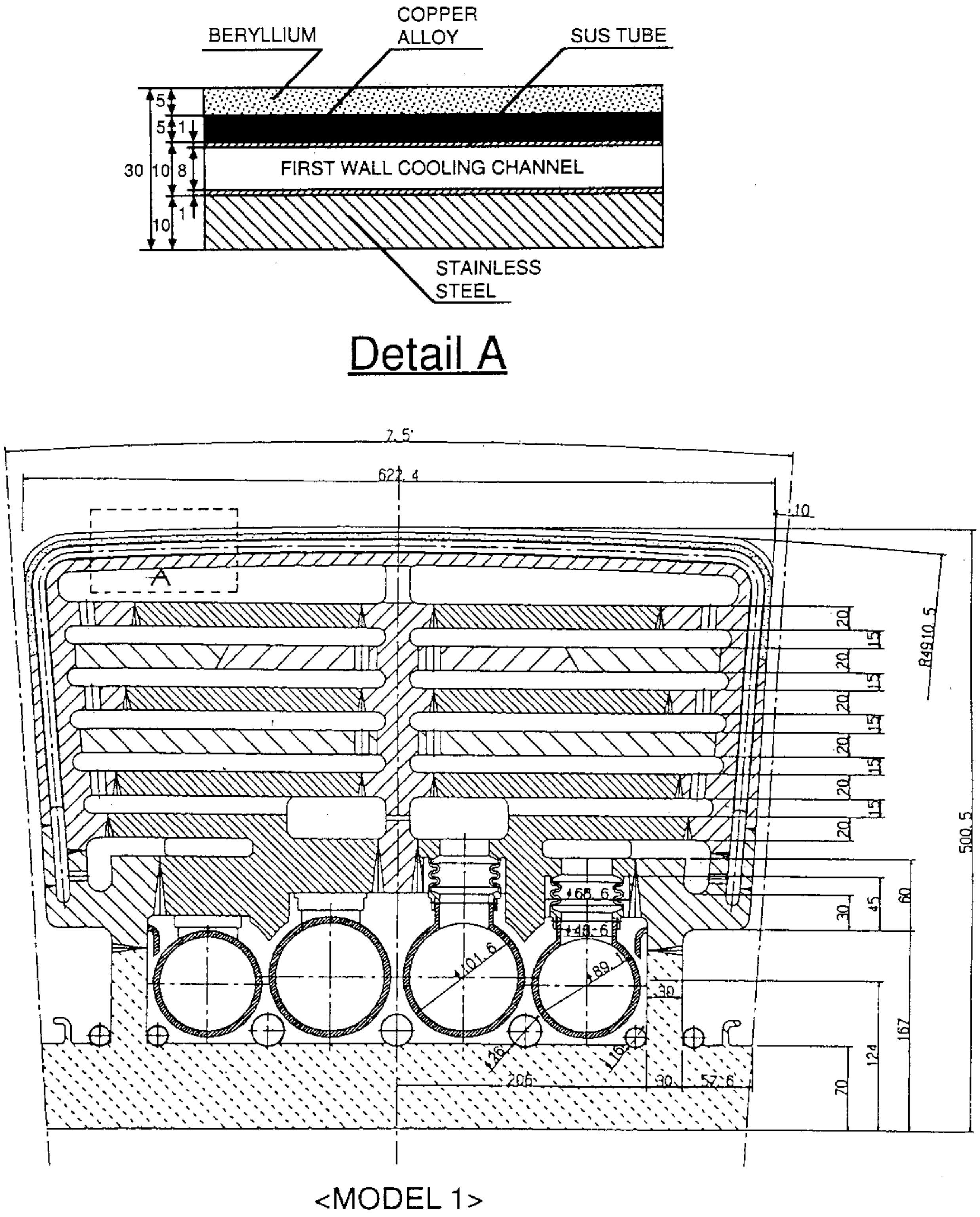


Fig. 1 Cross-Section of the inboard blanket at mid plane

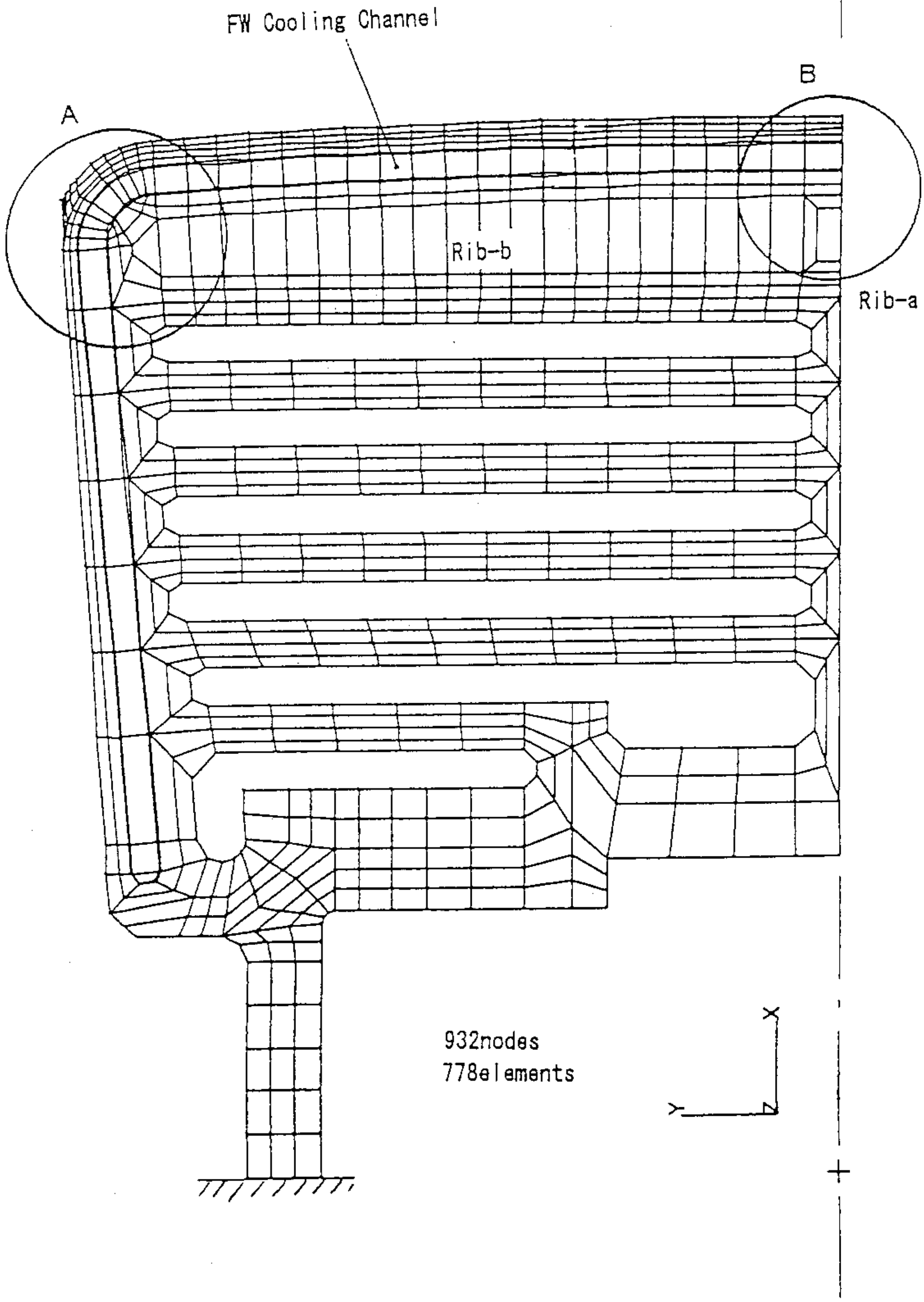
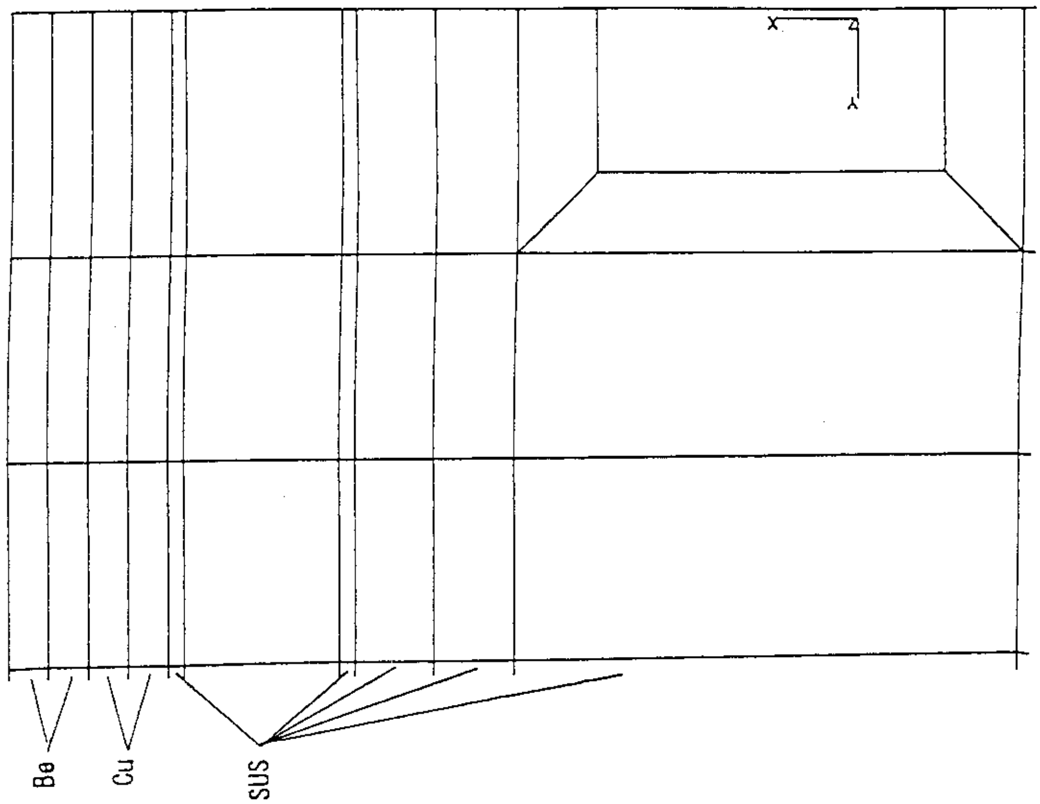
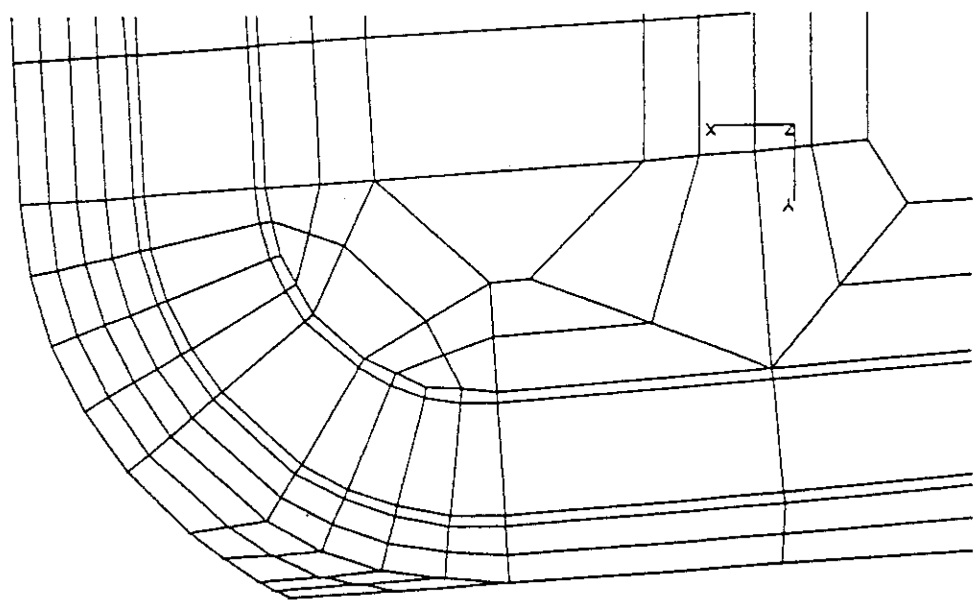


Fig. 2 The Whole Meshes



Mesh Model (Detail B)



Mesh Model (Detail A)

Fig. 3 Meshes at FW Part

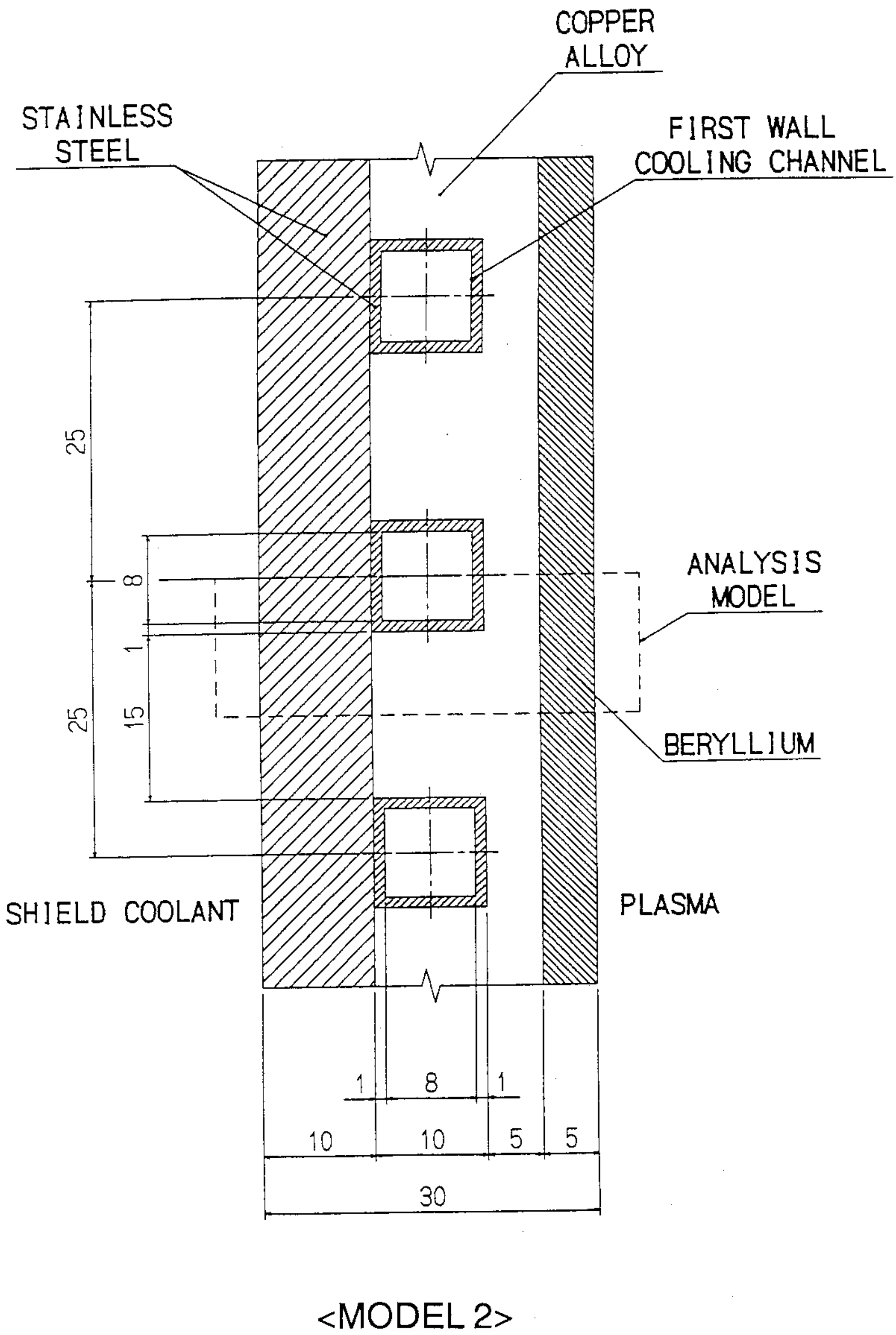


Fig. 4 Cross-Section of Local FW

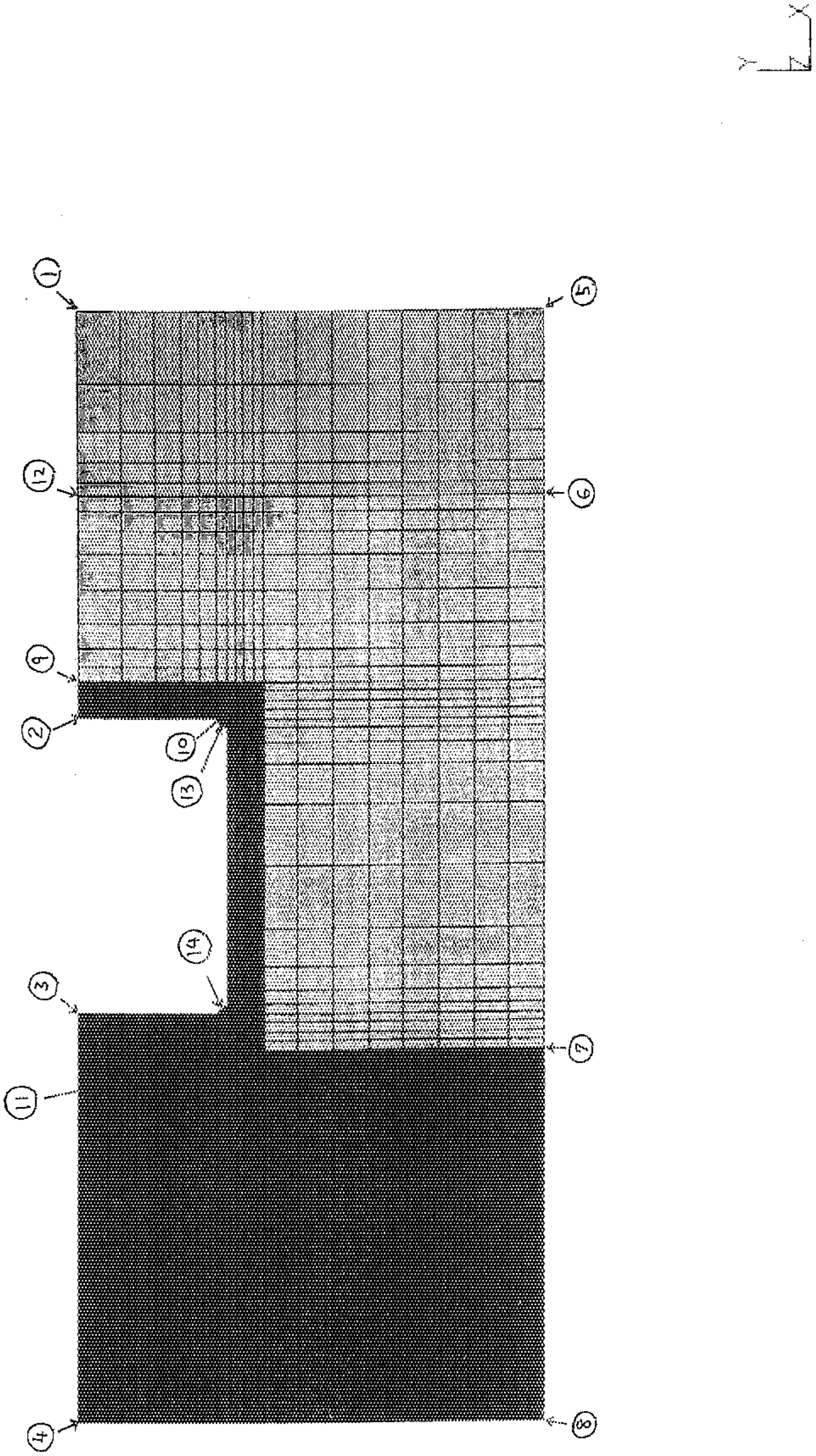


Fig. 5 Mesh Model of FW

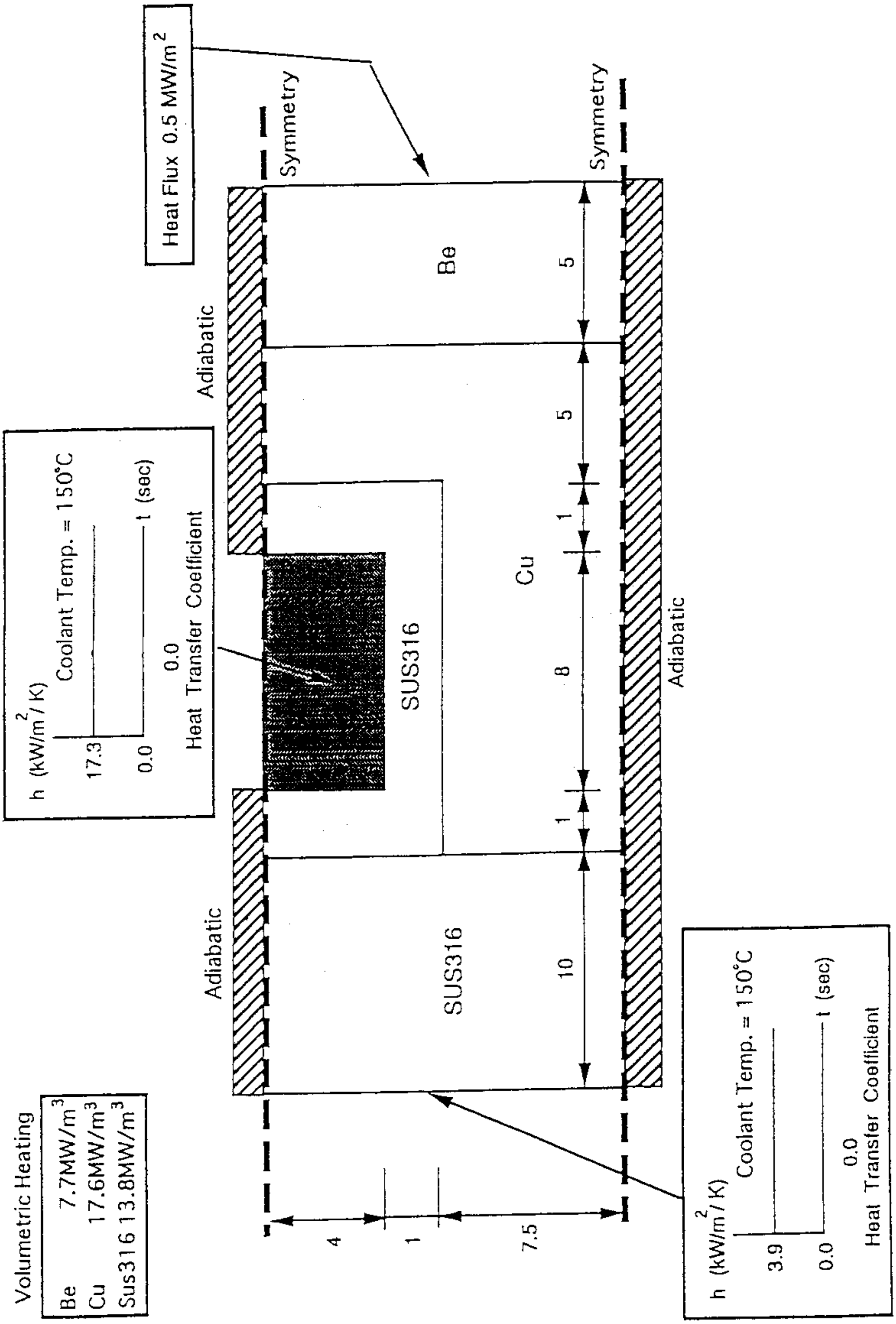


Fig. 6 Thermal Boundary Condition (steady state operation)

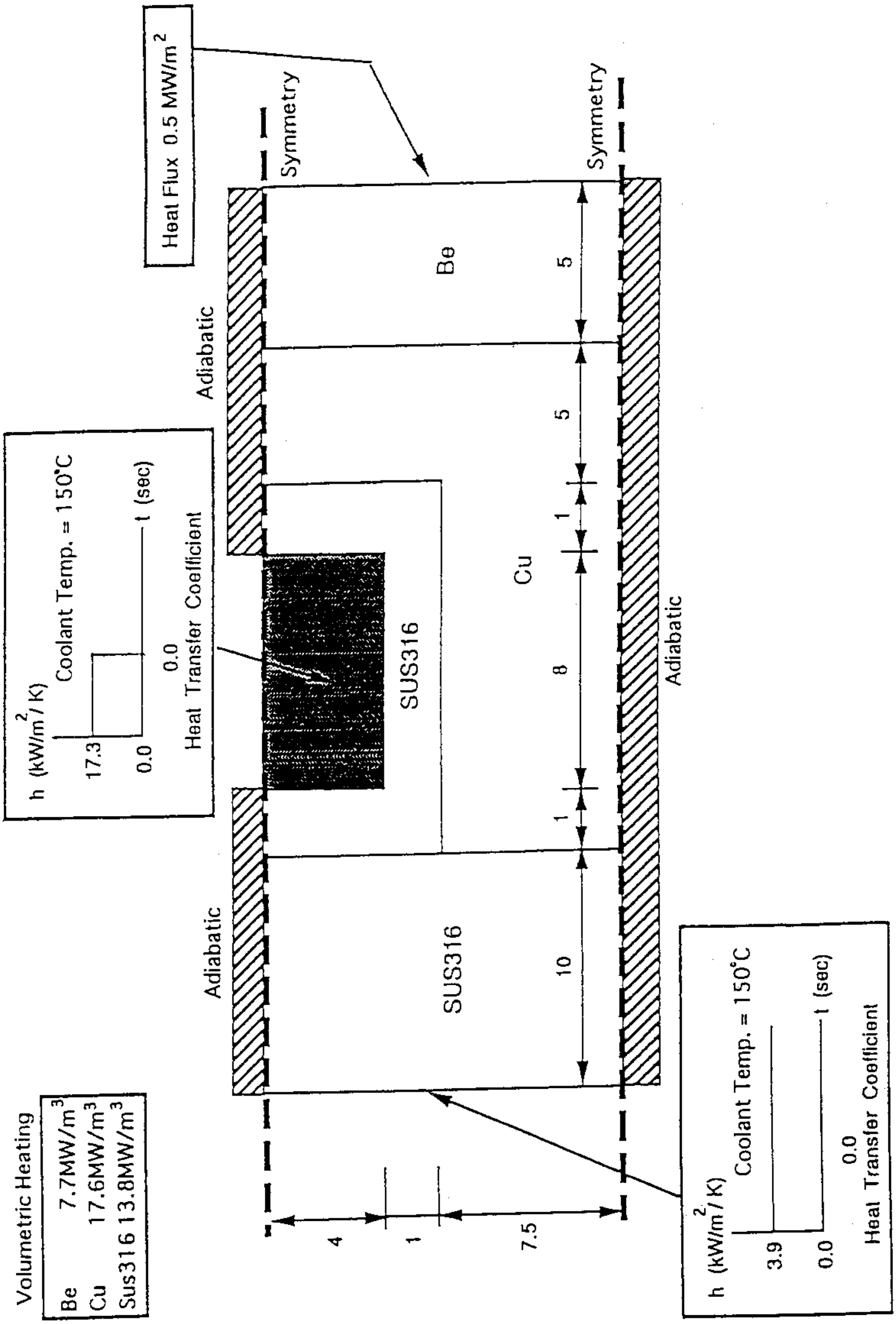


Fig. 7 Thermal Boundary Condition (FW LOFA/LOCA)

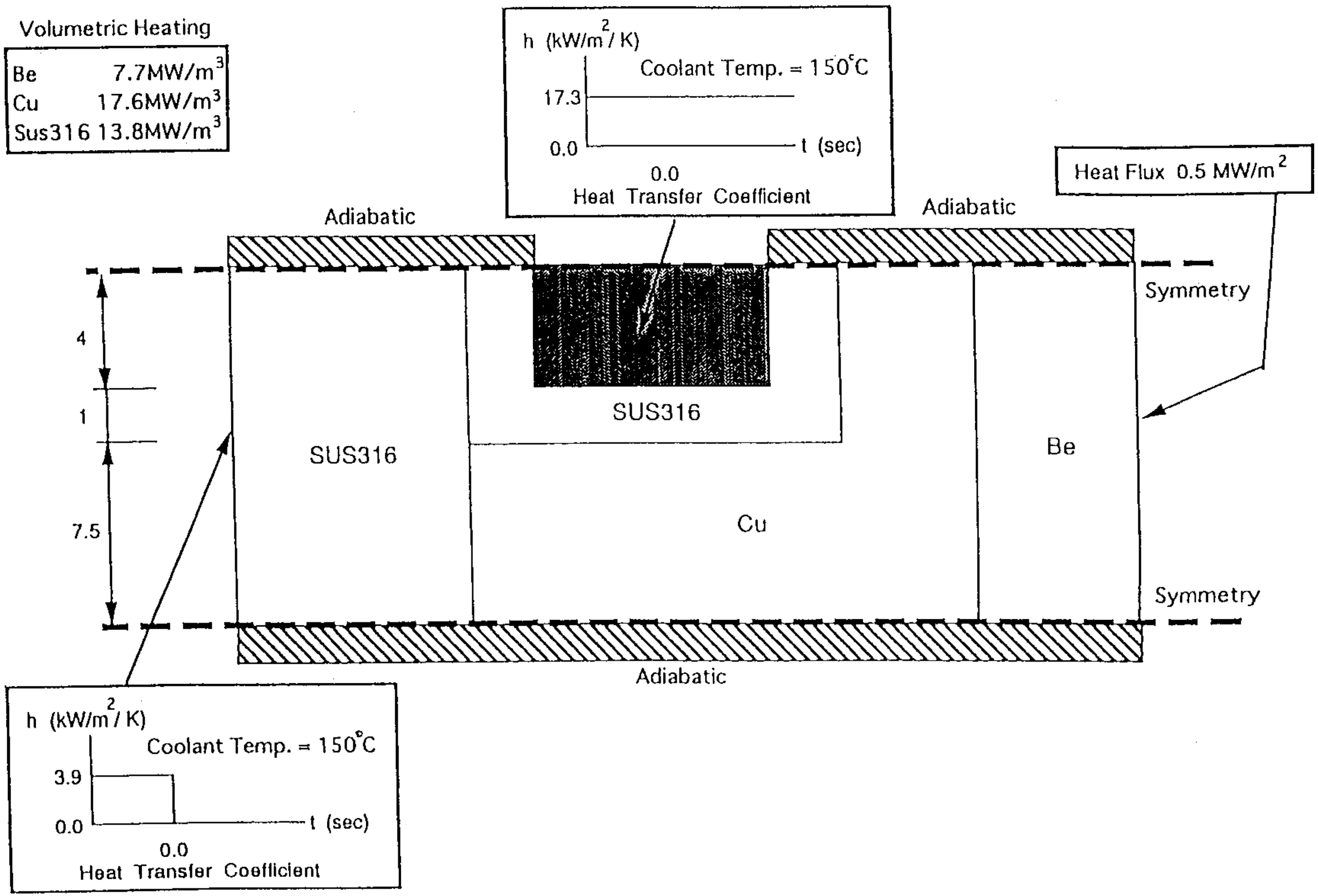


Fig. 8 Thermal Boundary Condition (Shield LOFA/LOCA)

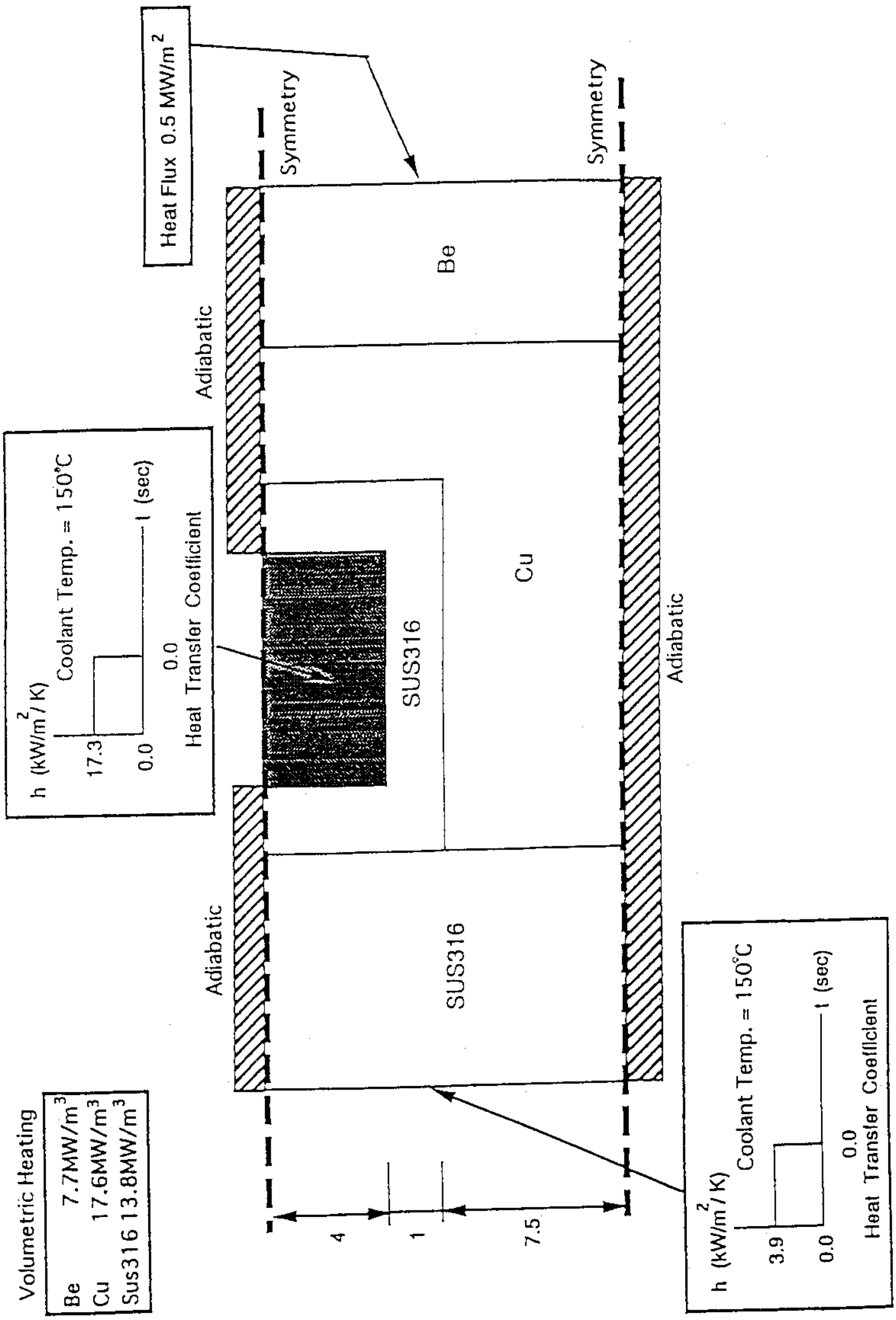


Fig. 9 Thermal Boundary Condition (FW and shield LOFA/LOCA)

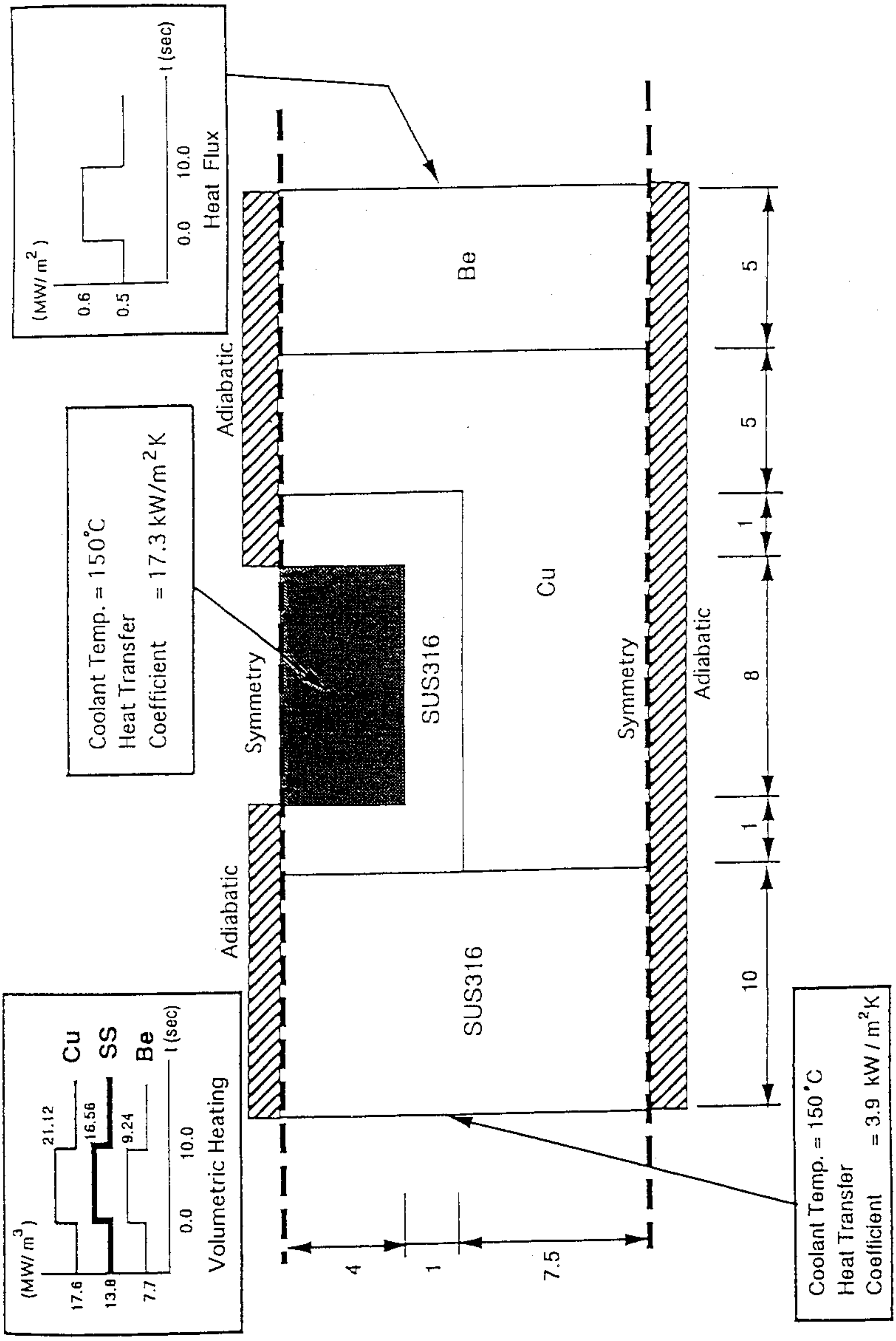


Fig. 10 Thermal Boundary Condition (PEC)

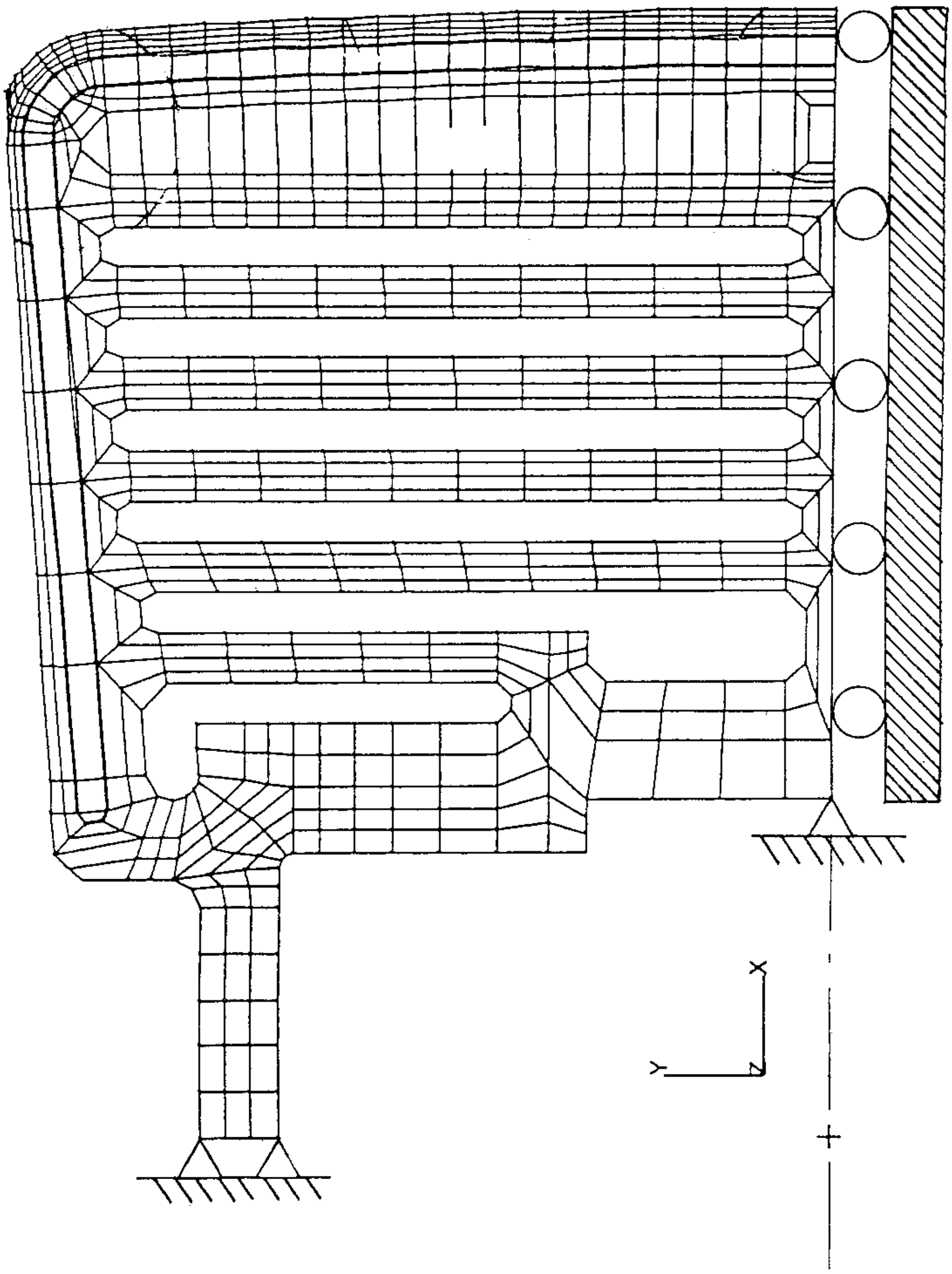


Fig. 11 Stress Boundary Condition

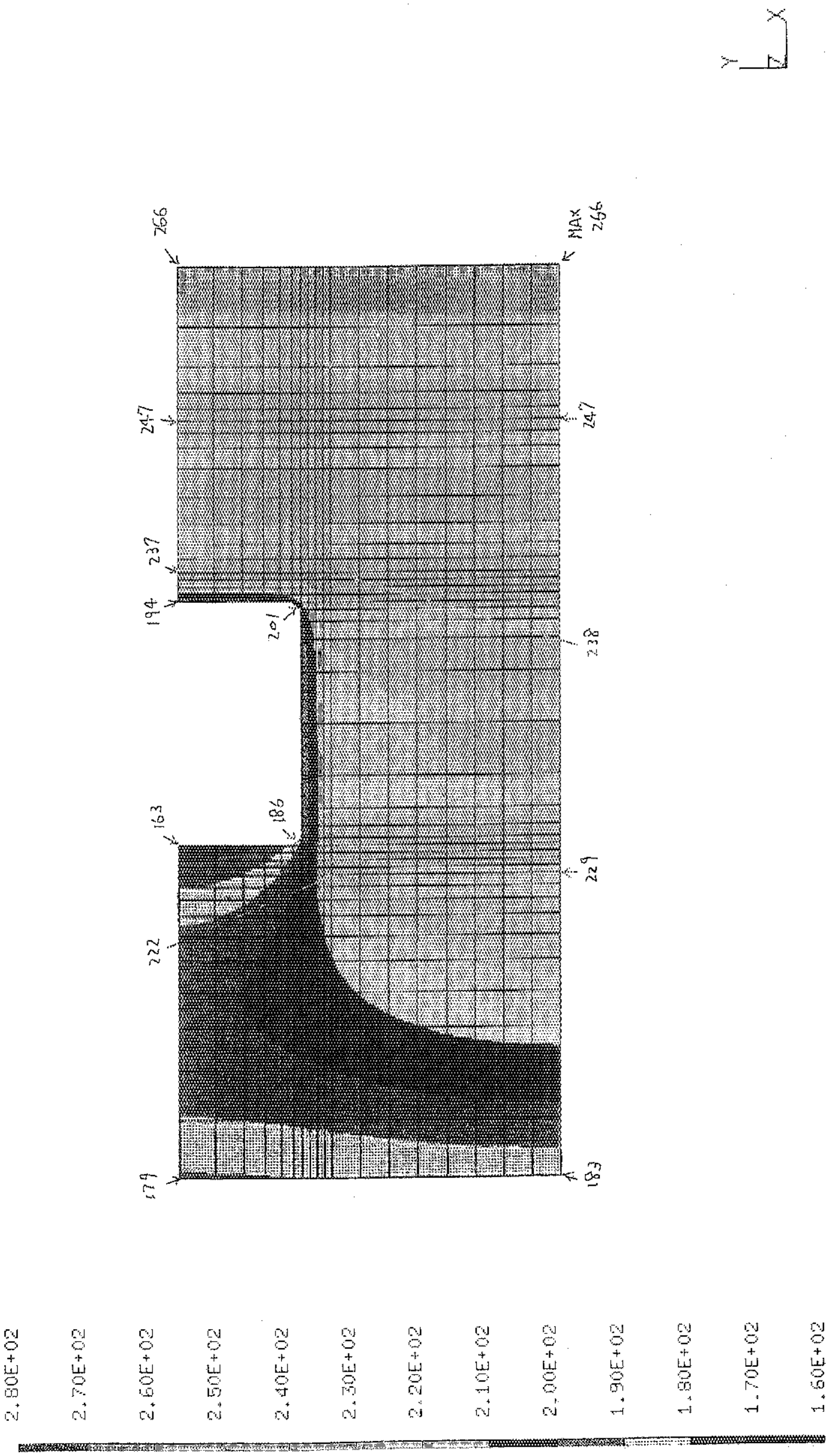


Fig. 12 Temperature Distributions in FW at Steady State Operation

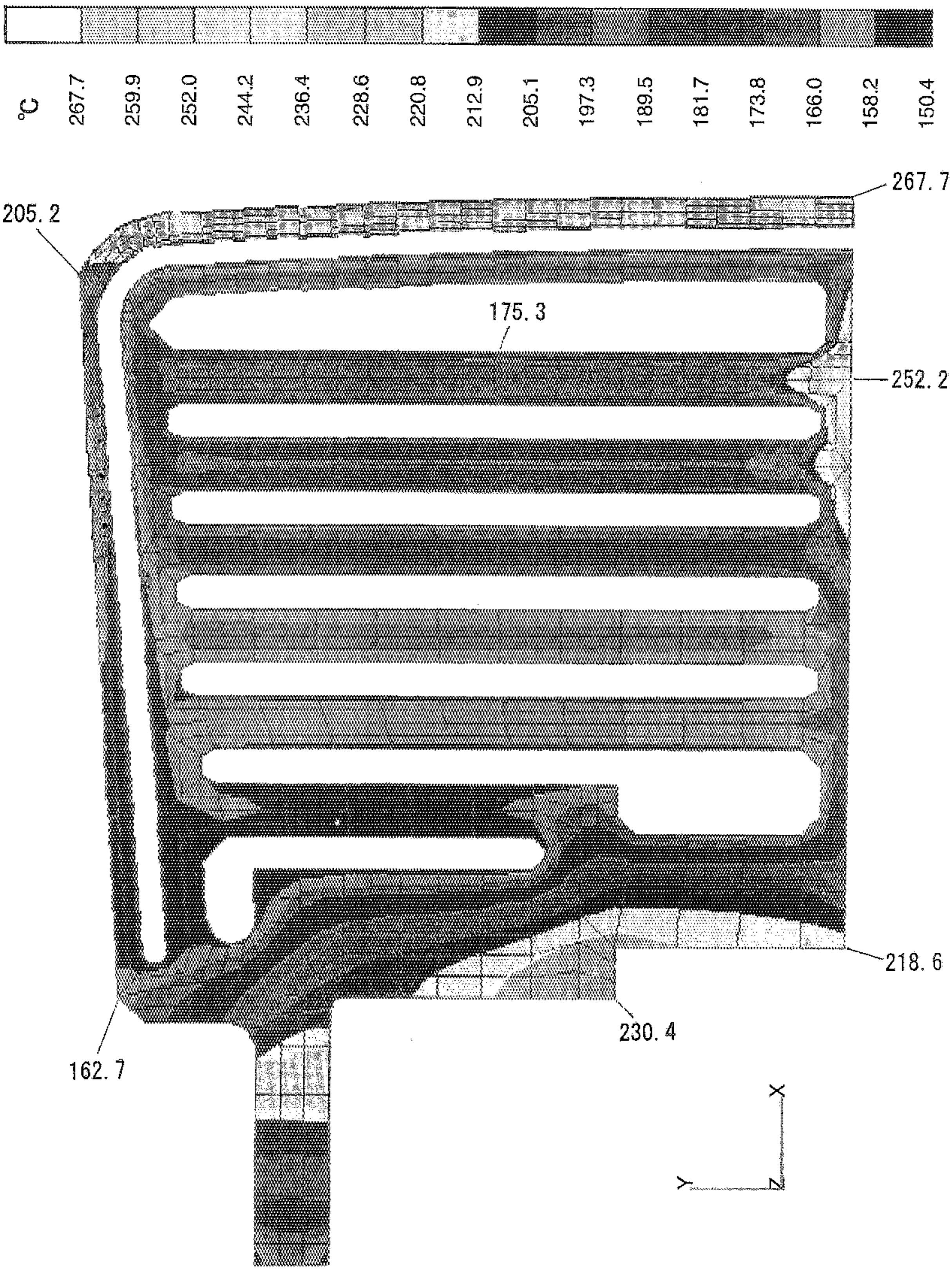


Fig. 13 Temperature Distributions in Shield at Steady State Operation

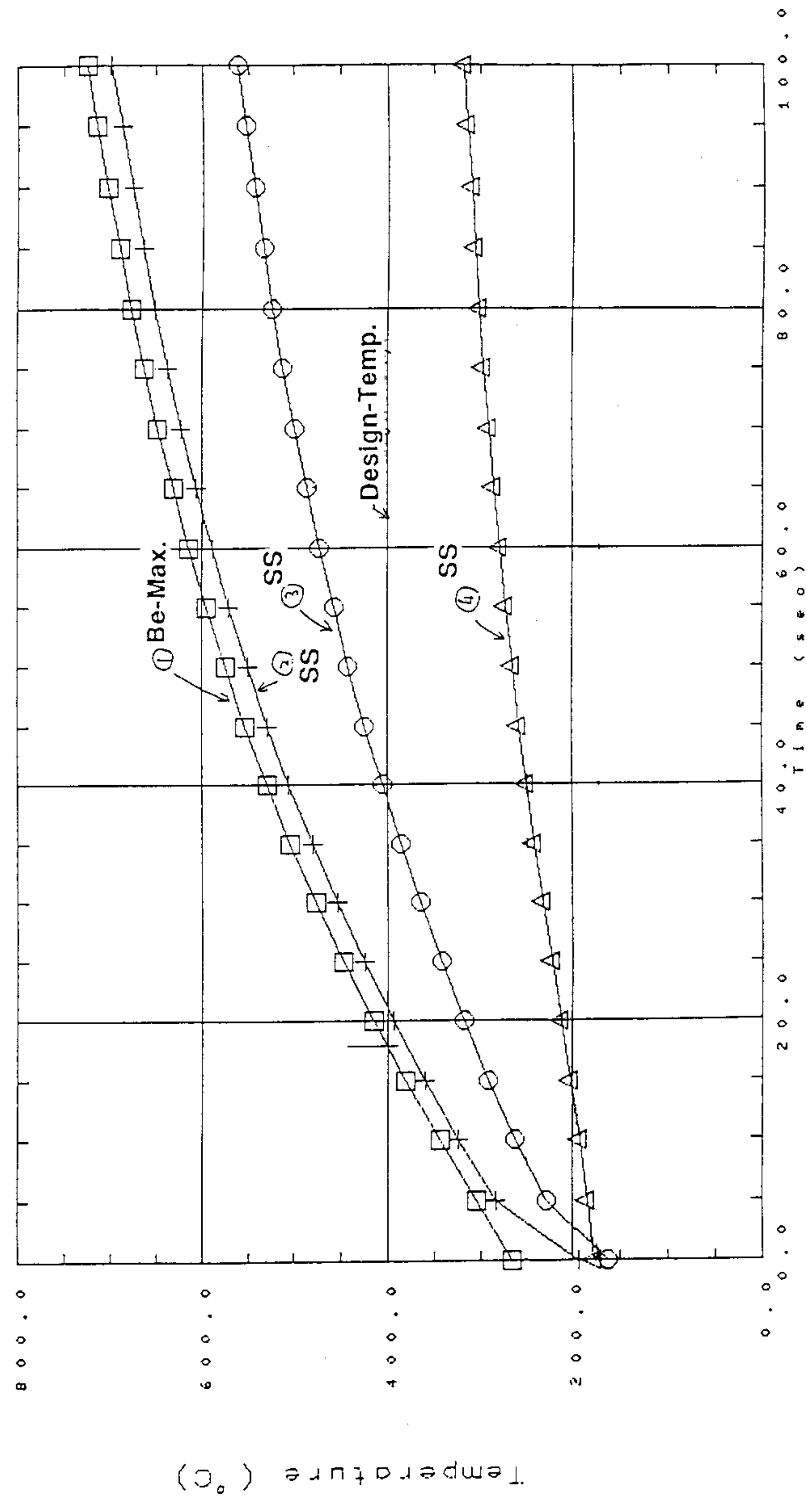


Fig.14 Responses of FW Temperature at FW LOFA/LOCA
(the numbers 1~4 : refer to Fig.5)

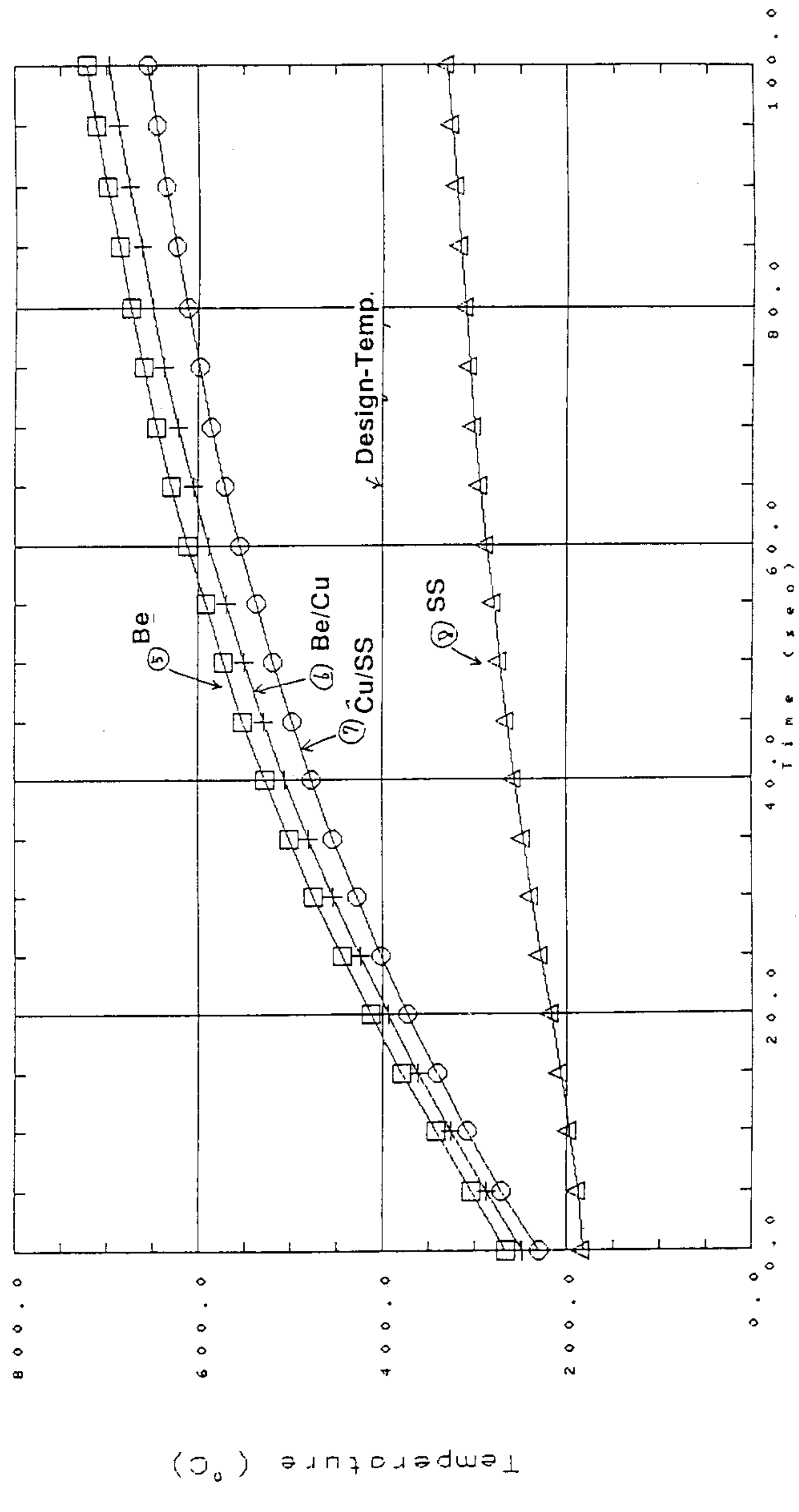


Fig. 15 Responses of FW Temperature at FW LOFA/LOCA
(the numbers 5~8 : refer to Fig. 5)

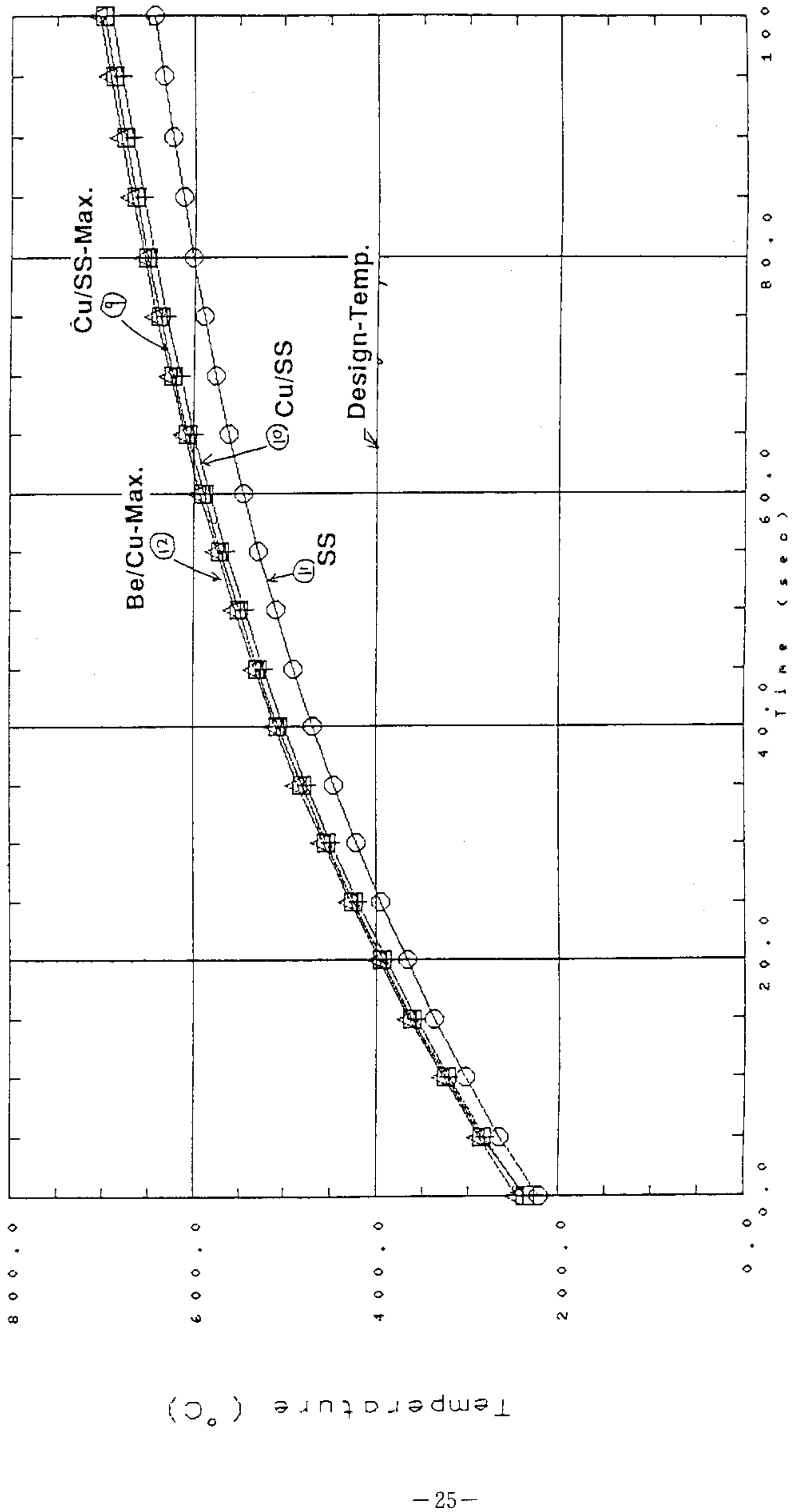


Fig.16 Responses of FW Temperature at FW LOFA／LOCA
(the numbers 9~12 : refer to Fig.5)

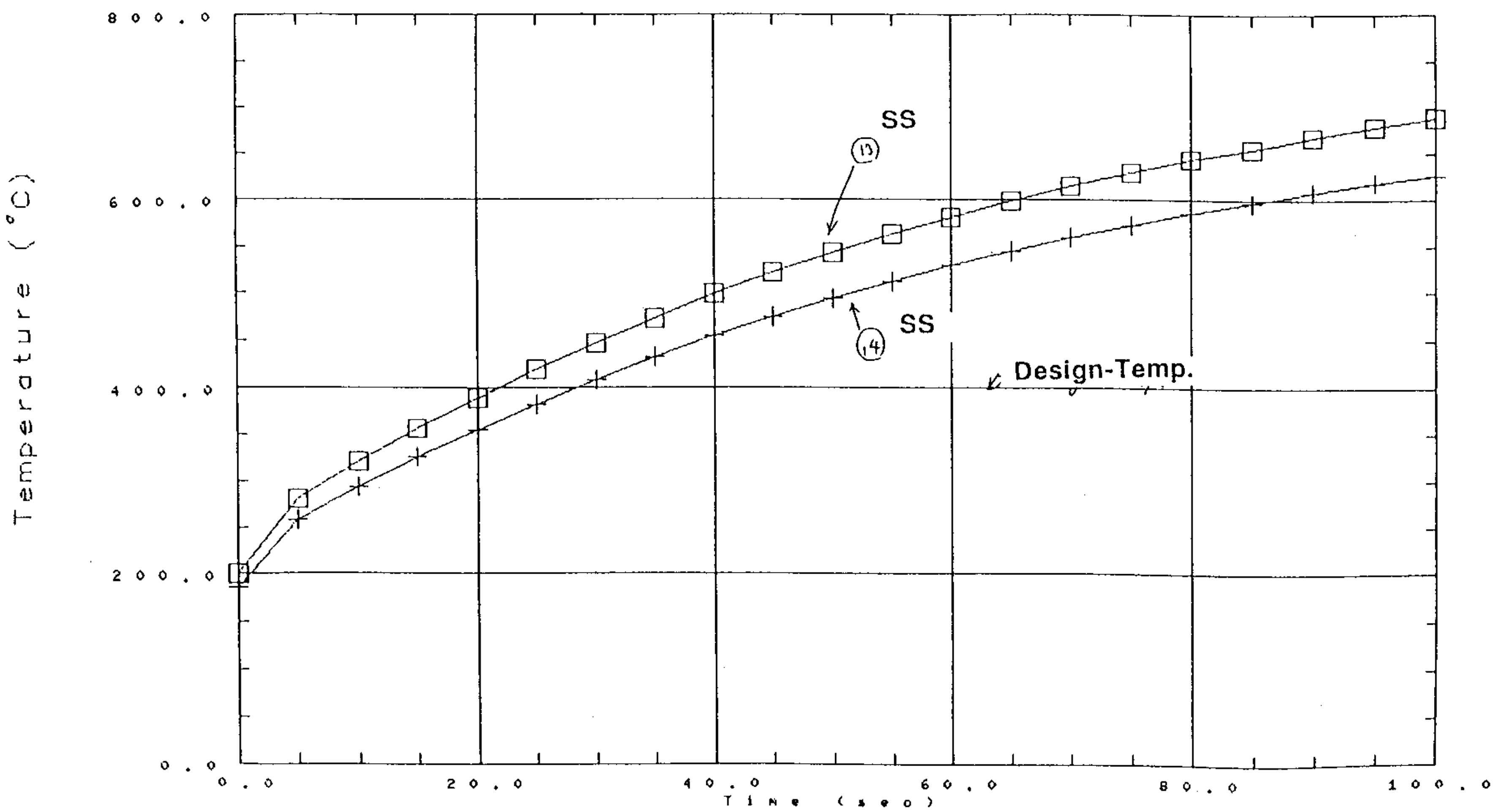


Fig. 17 Responses of FW Temperature at FW LOFA／LOCA
(the numbers 13~14 : refer to Fig. 5)

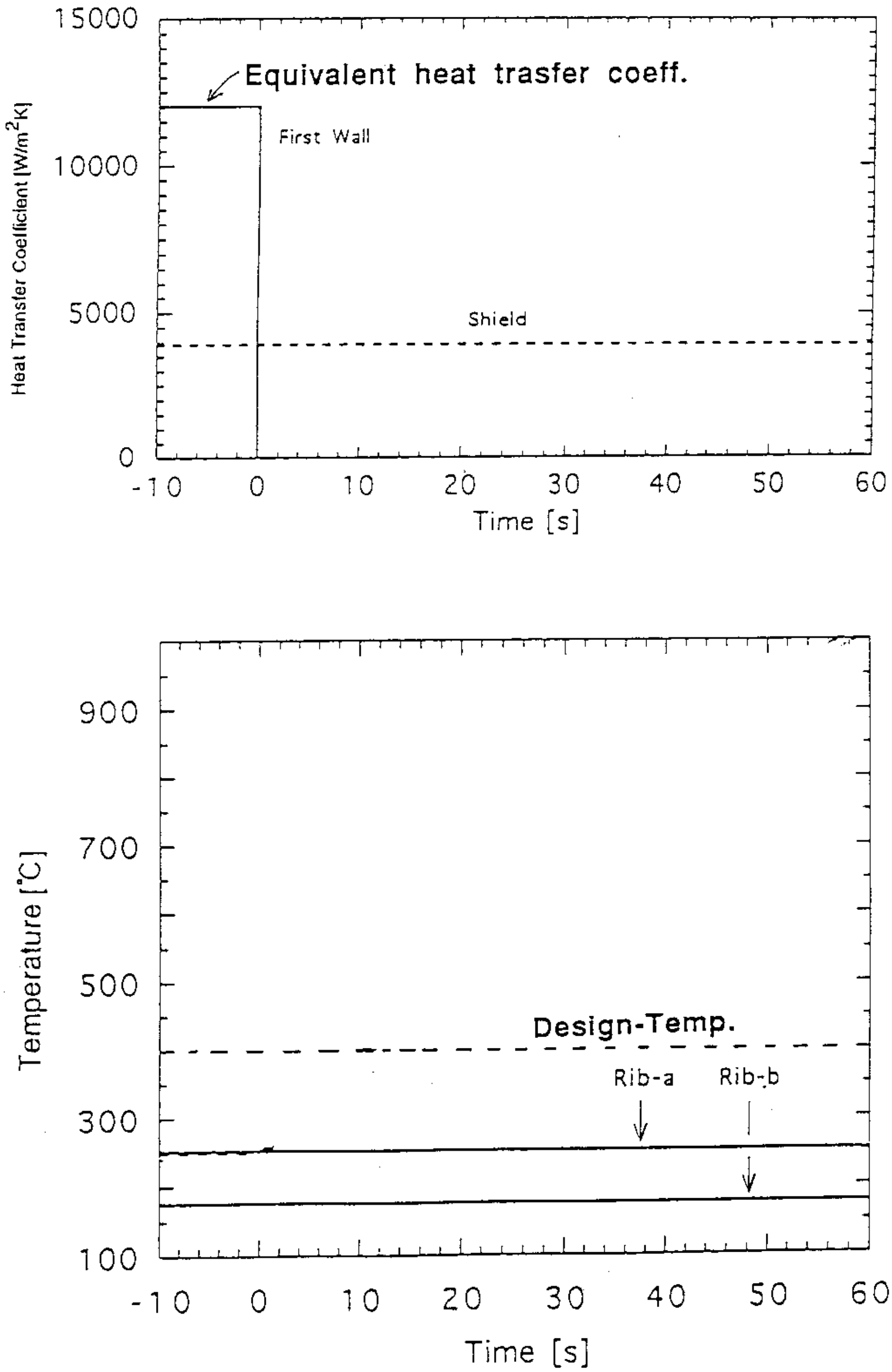


Fig. 18 Responses of Shield Temperature at FW LOFA/LOCA (MODEL−1)

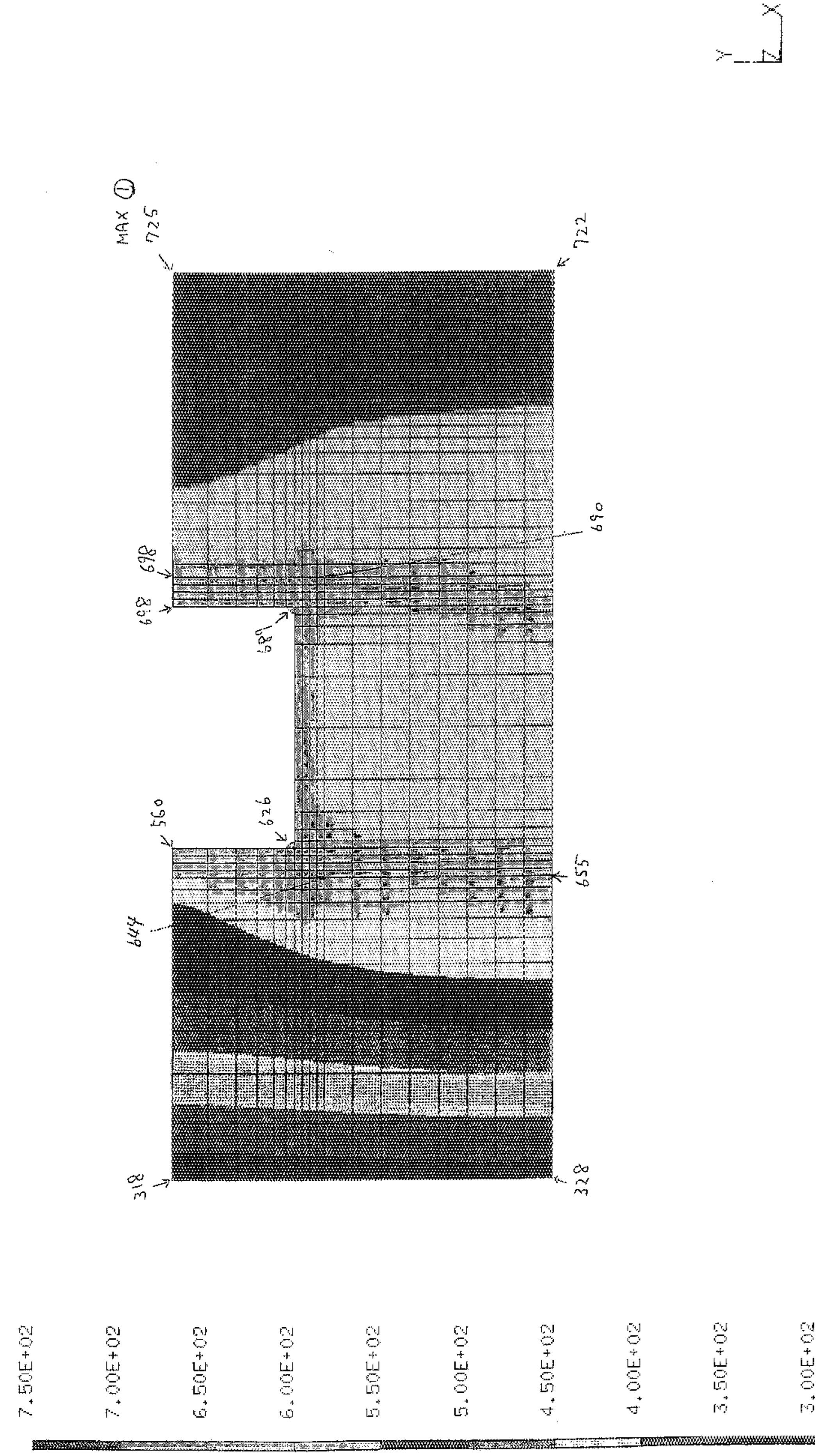


Fig. 19 Temperature Distributions in FW at FW LOFA/LOCA (after 100s)

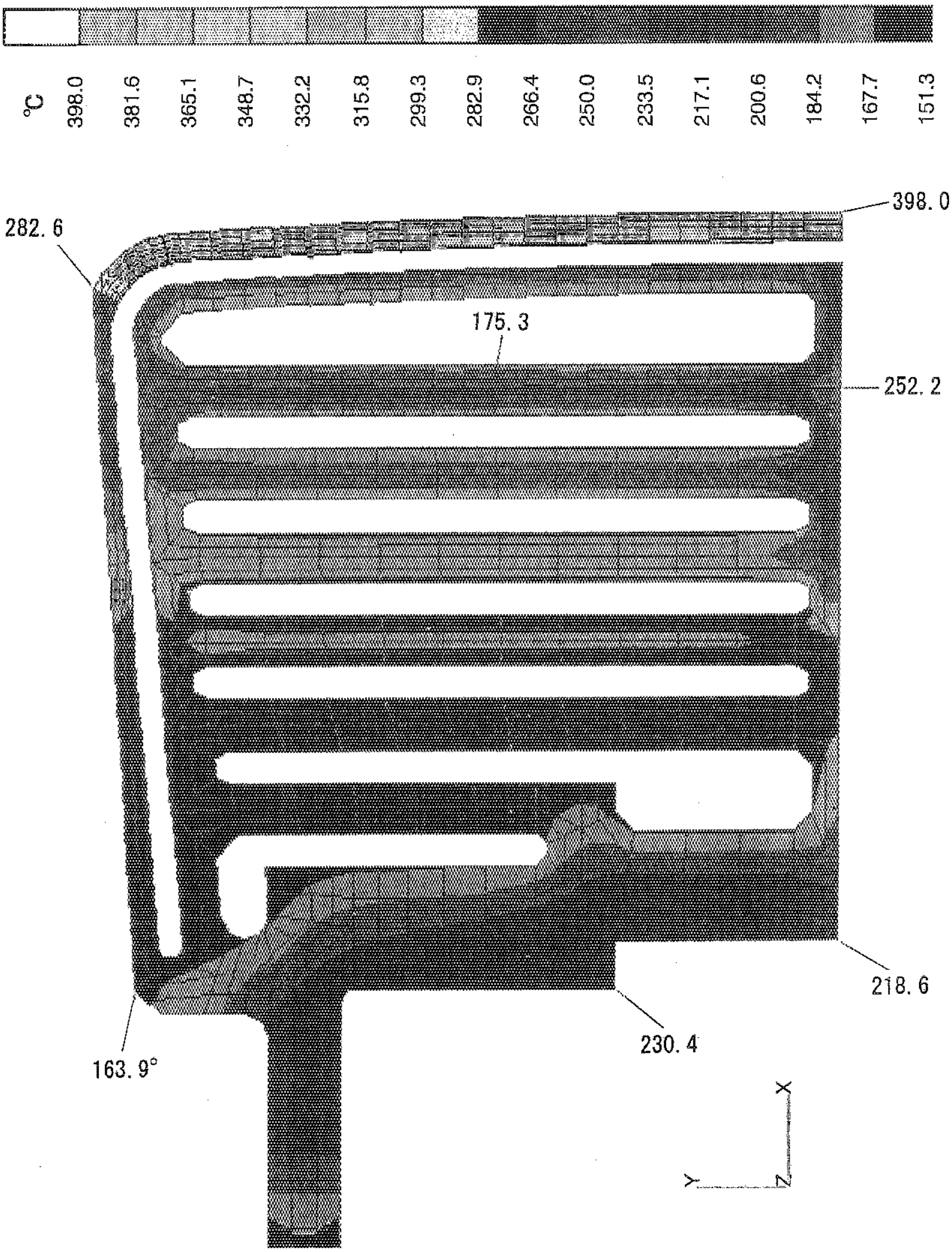


Fig. 20 Temperature Distributions in Shield at FW LOFA／LOCA (after 10s)

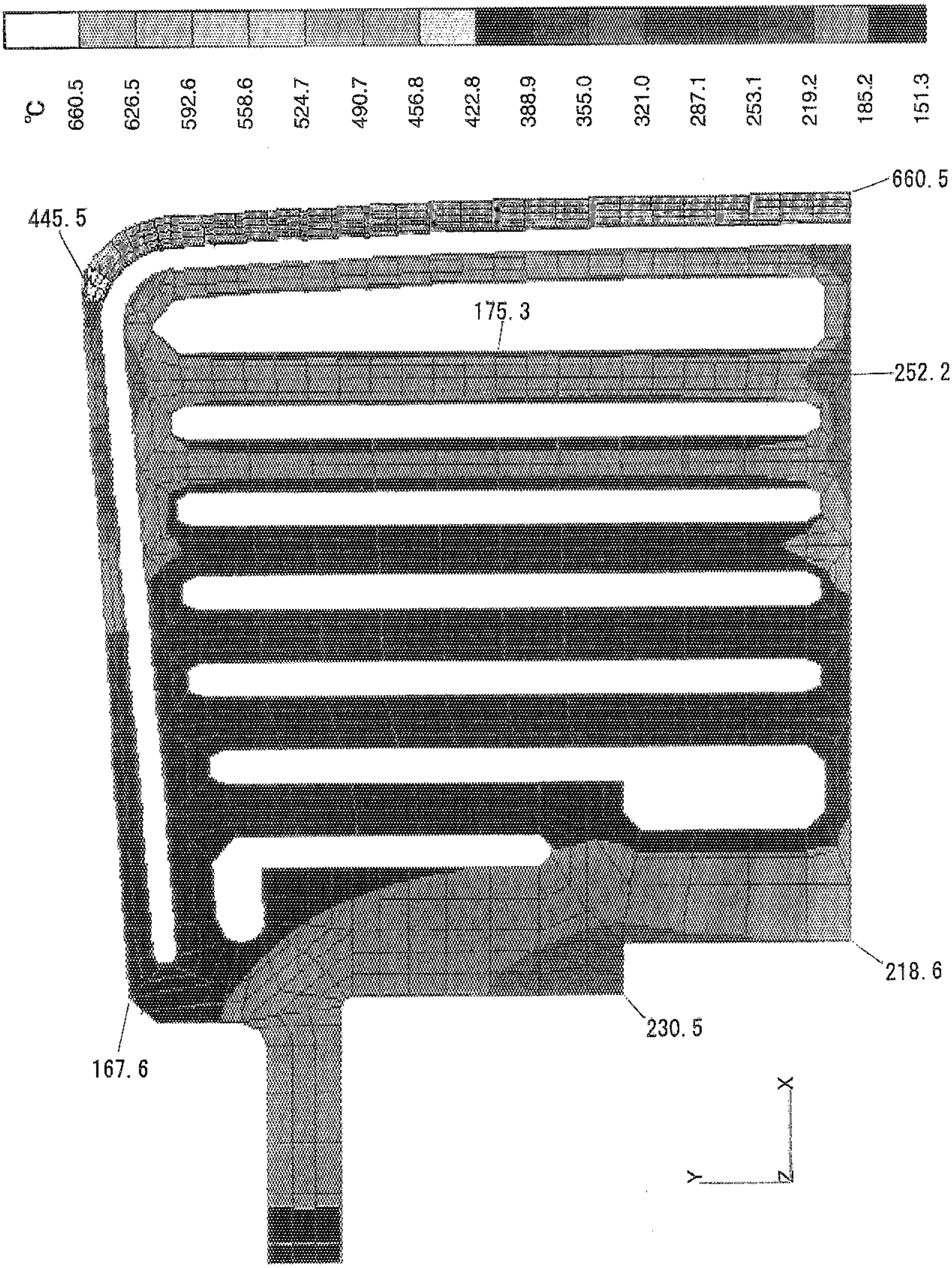


Fig. 21 Temperature Distributions in Shield at FW LOFA／LOCA (after 30s)

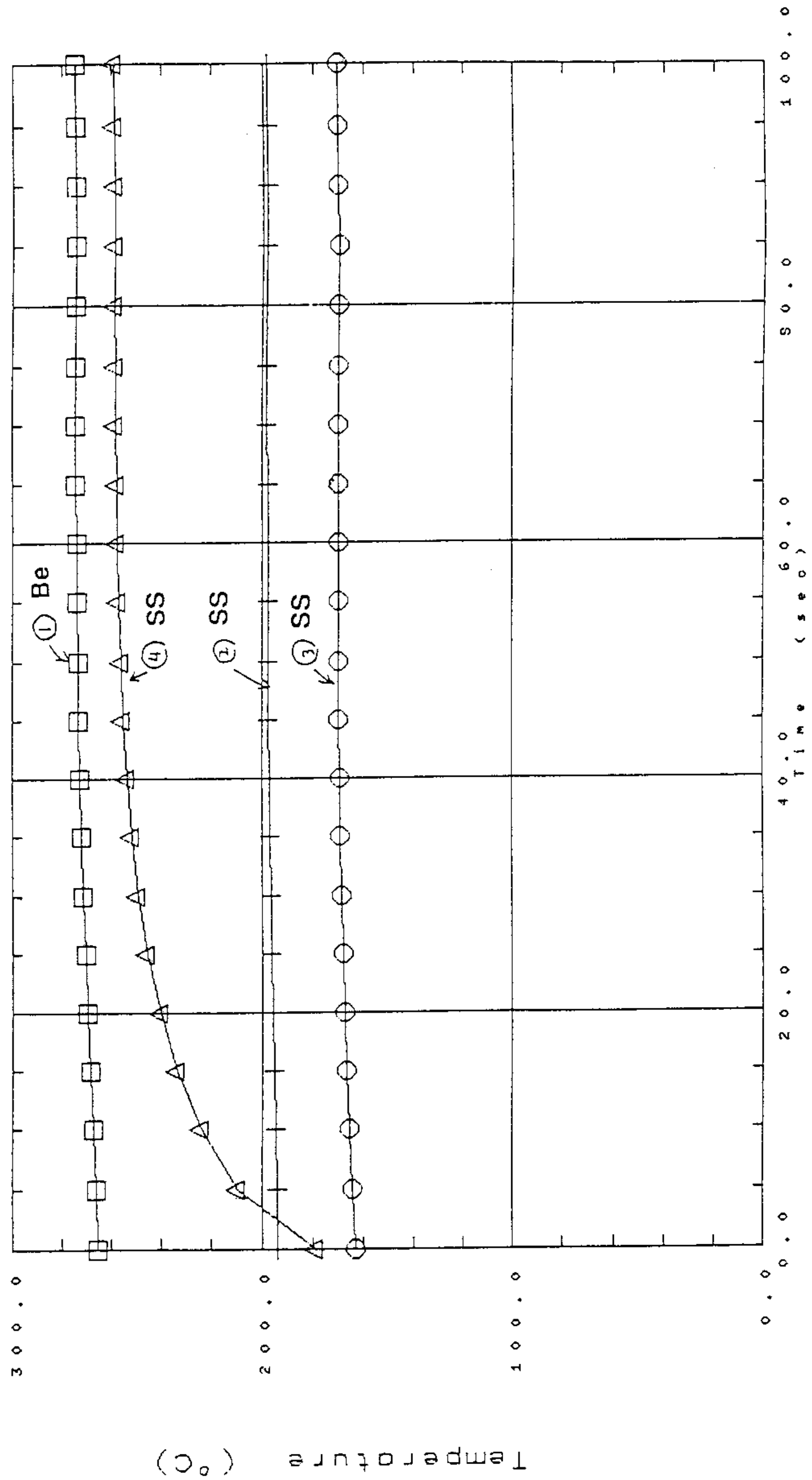


Fig. 22 Responses of FW Temperature at Shield LOFA／LOCA
(the number 1~4 : refer to Fig. 5)

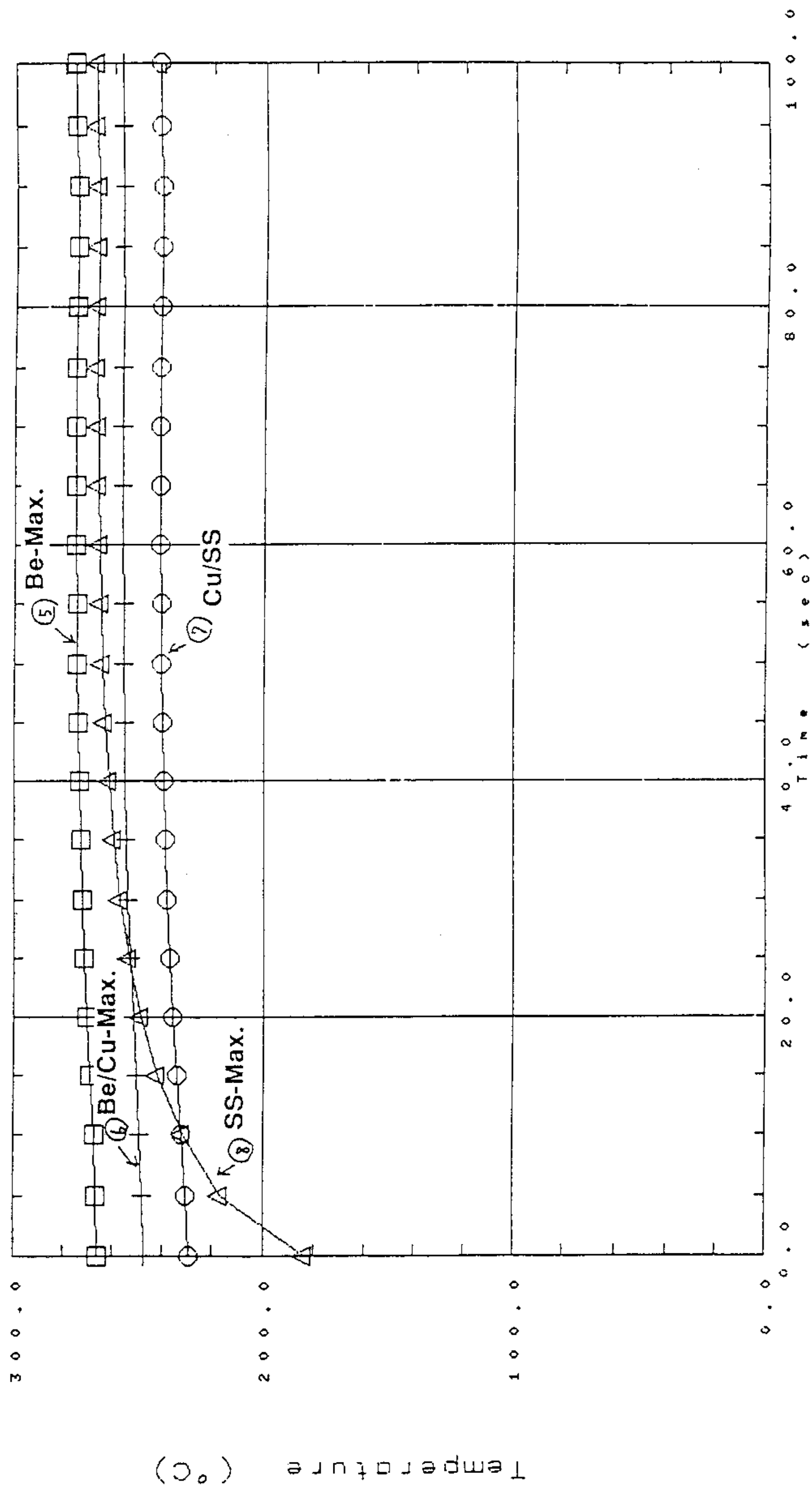


Fig. 23 Responses of FW Temperature at Shield LOFA／LOCA
(the number 5~8 : refer to Fig. 5)

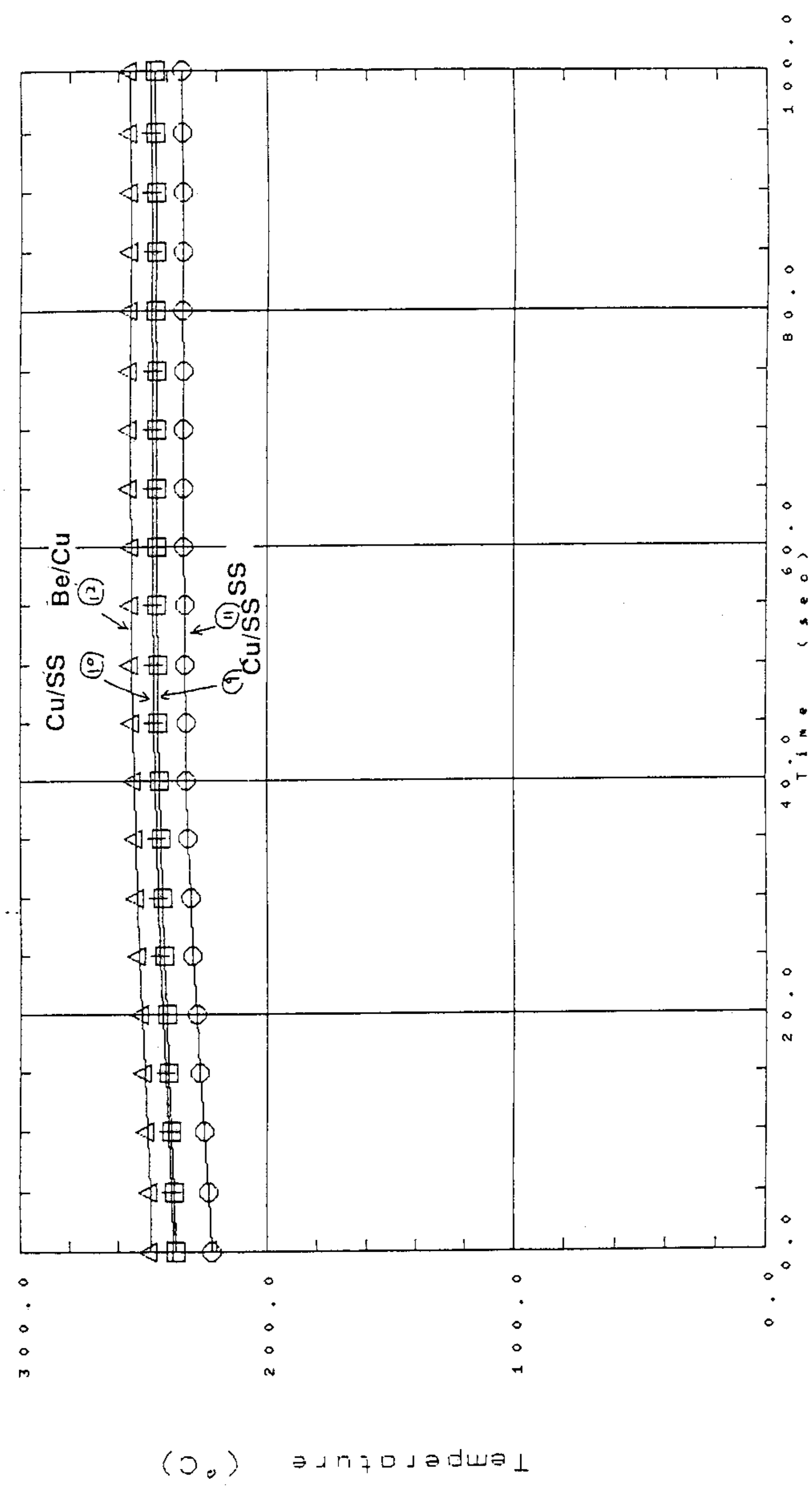


Fig. 24 Responses of FW Temperature at Shield LOFA/LOCA
(the number 9~12 : refer to Fig. 5)

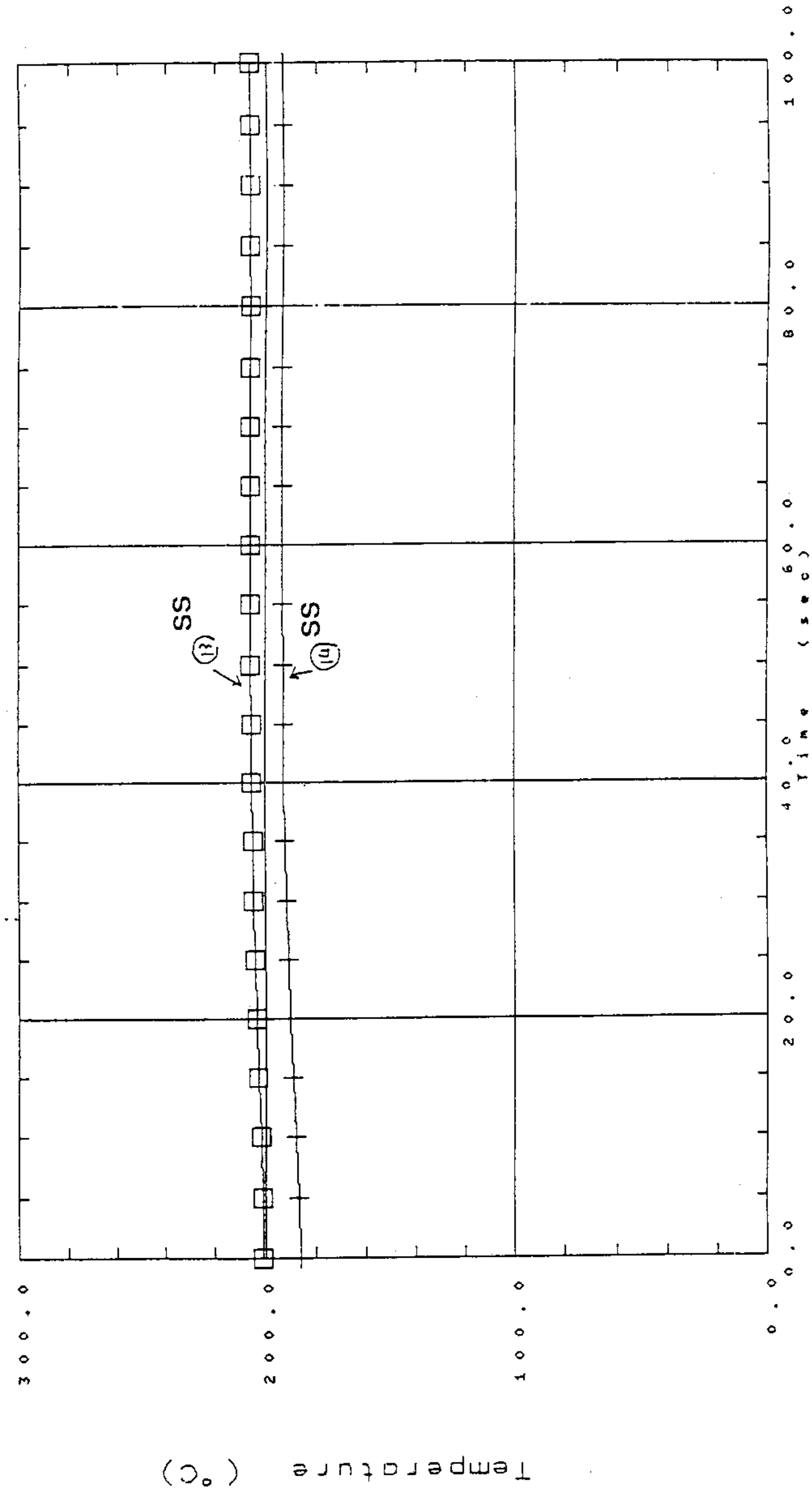
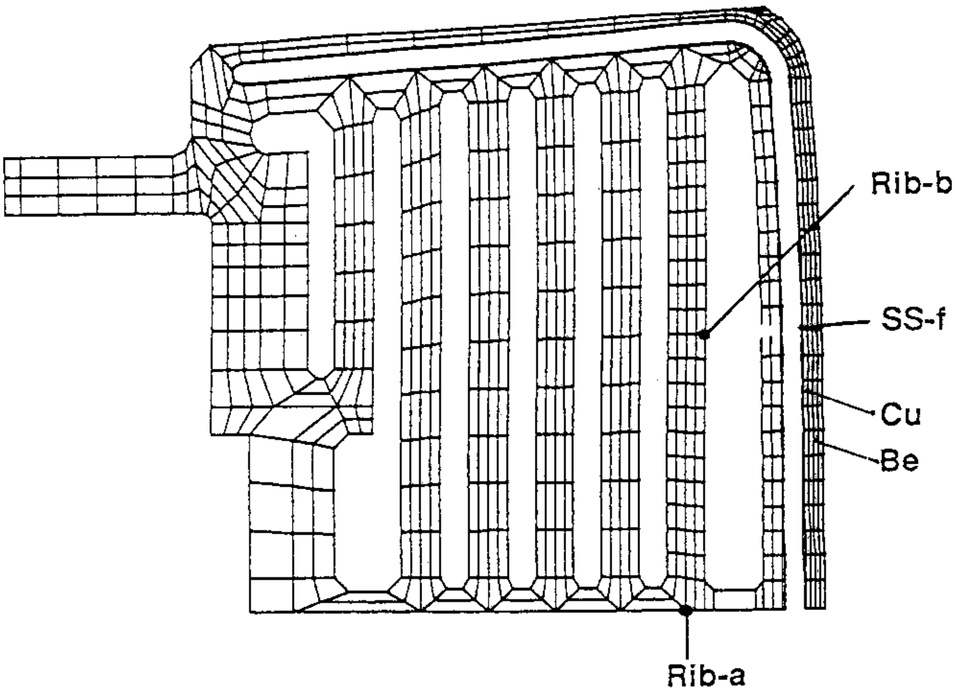


Fig. 25 Responses of FW Temperature at Shield LOFA／LOCA
(the number 13~14 : refer to Fig. 5)



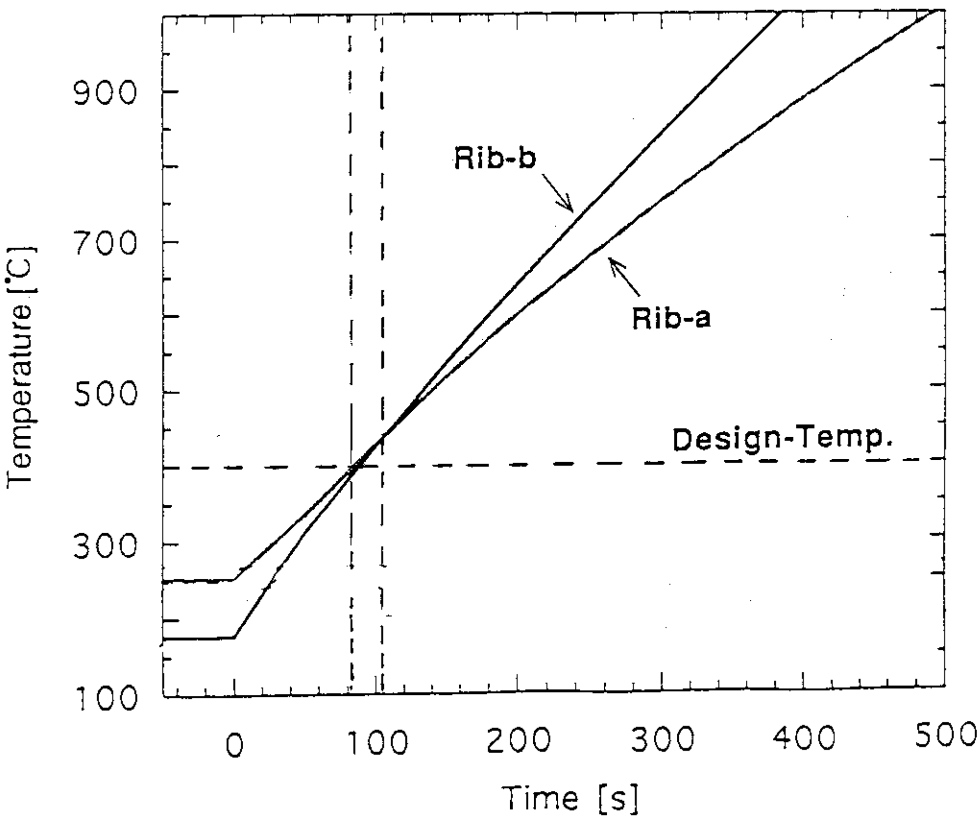


Fig. 26 Responses of Shield Temperature at Shield LOFA/LOCA (MODEL-1)

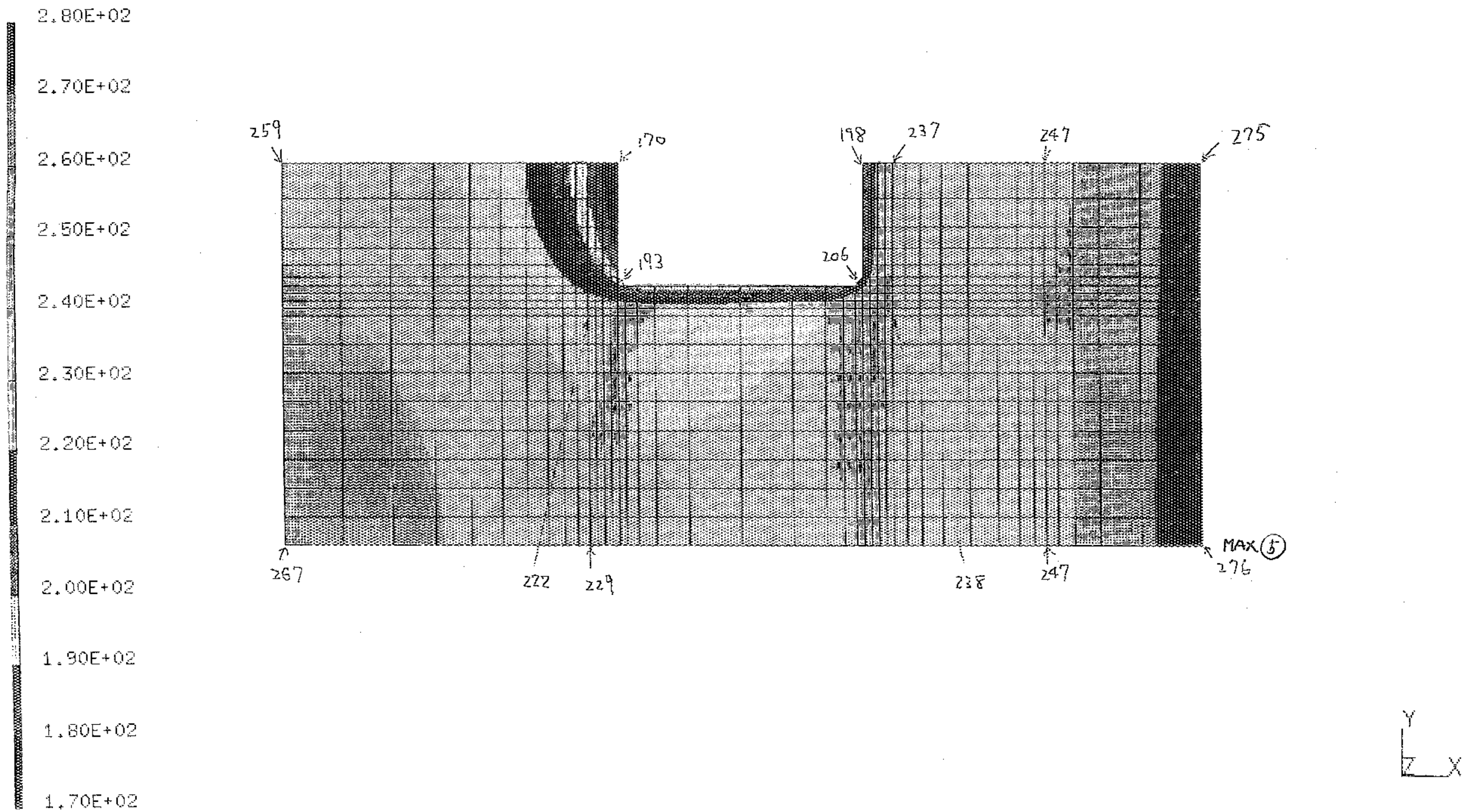


Fig. 27 Temperature Distributions in FW at Shield LOFA/LOCA (after 100s)

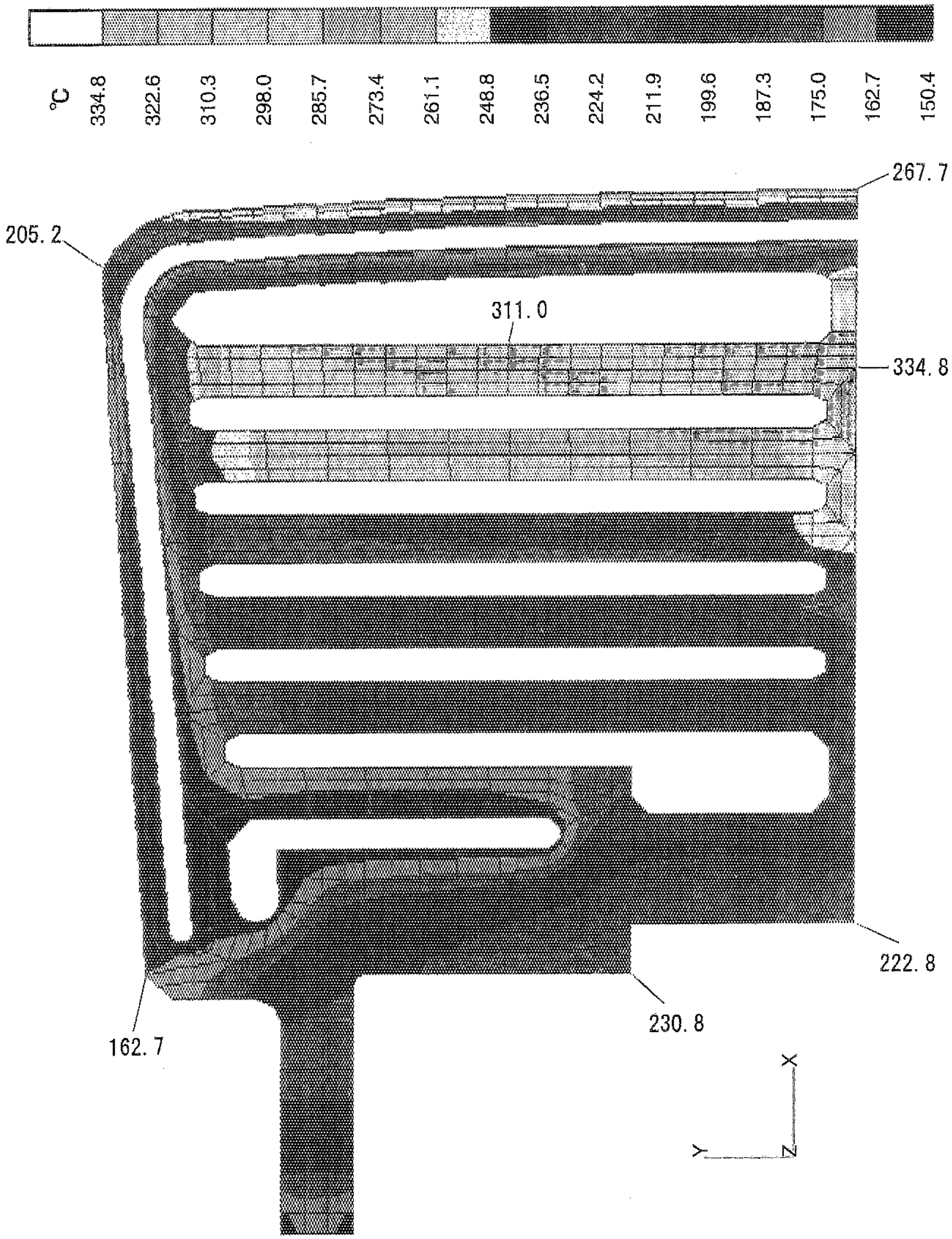


Fig. 28 Temperature Distributions in Shield at Shield LOFA／LOCA (after 50s)

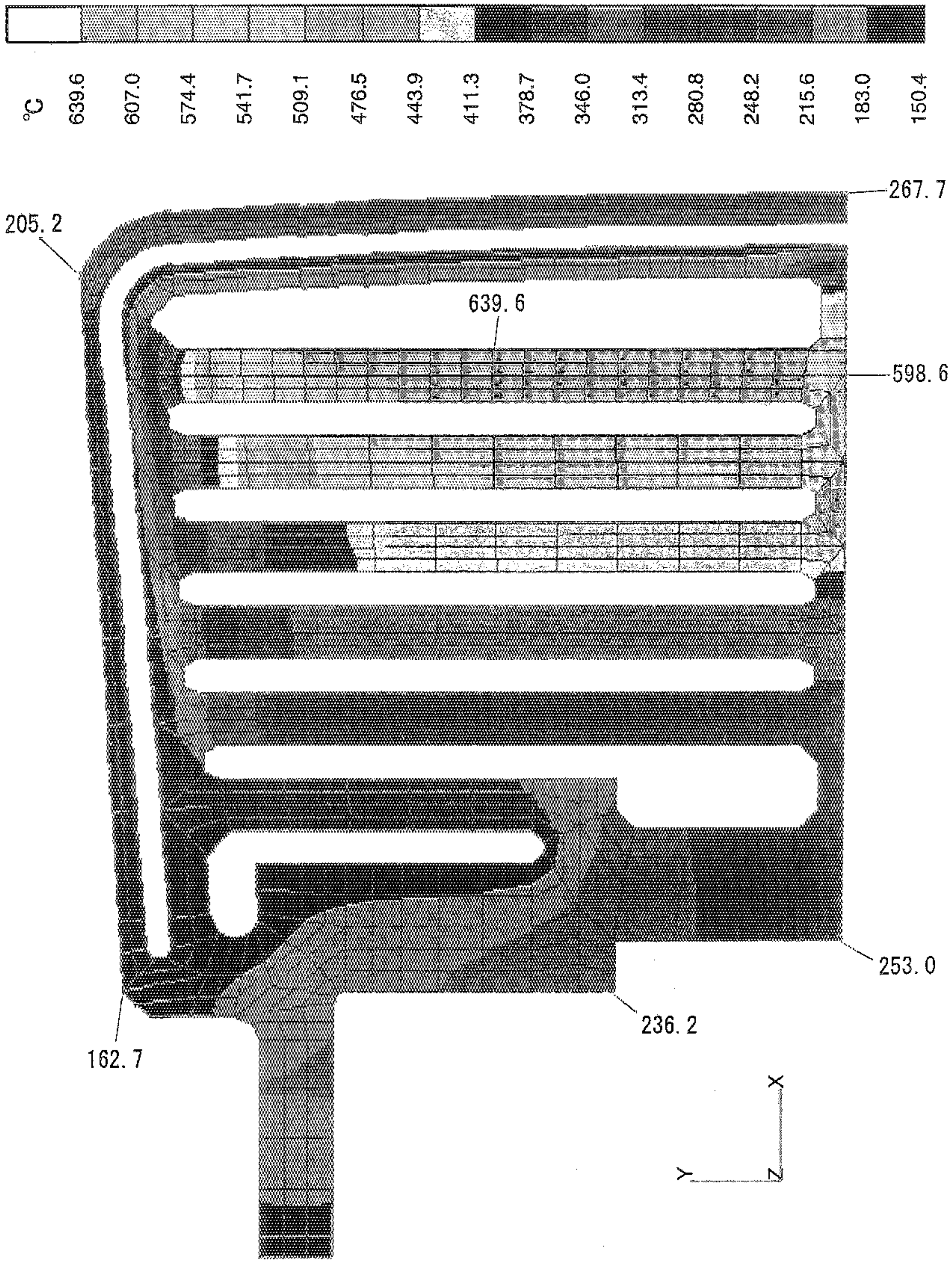


Fig. 29 Temperature Distributions in Shield at Shield LOFA/LOCA (after 200s)

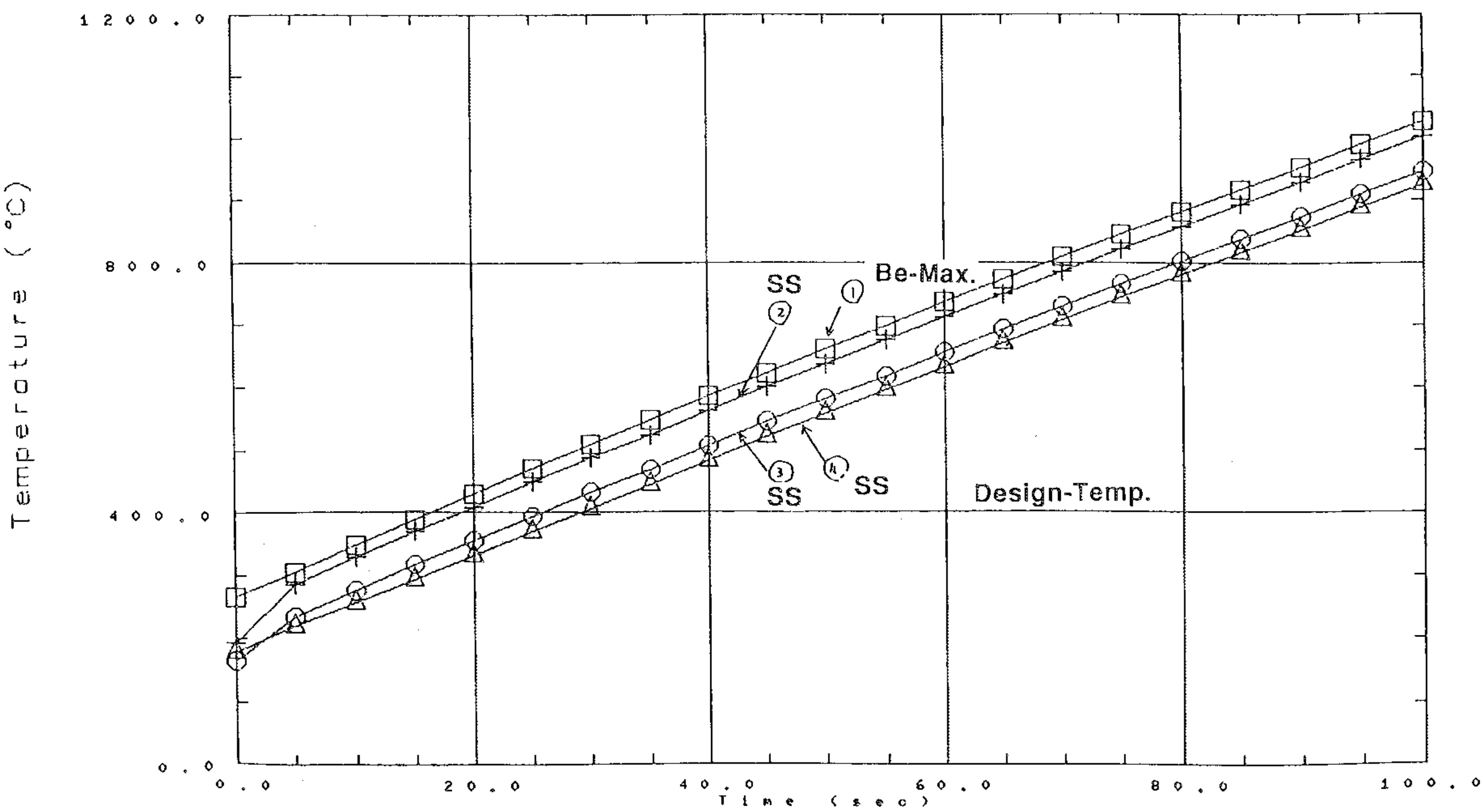


Fig. 30 Responses of FW Temperature at FW and Shield LOFA/LOCA
(the number 1~4 : refer to Fig. 5)

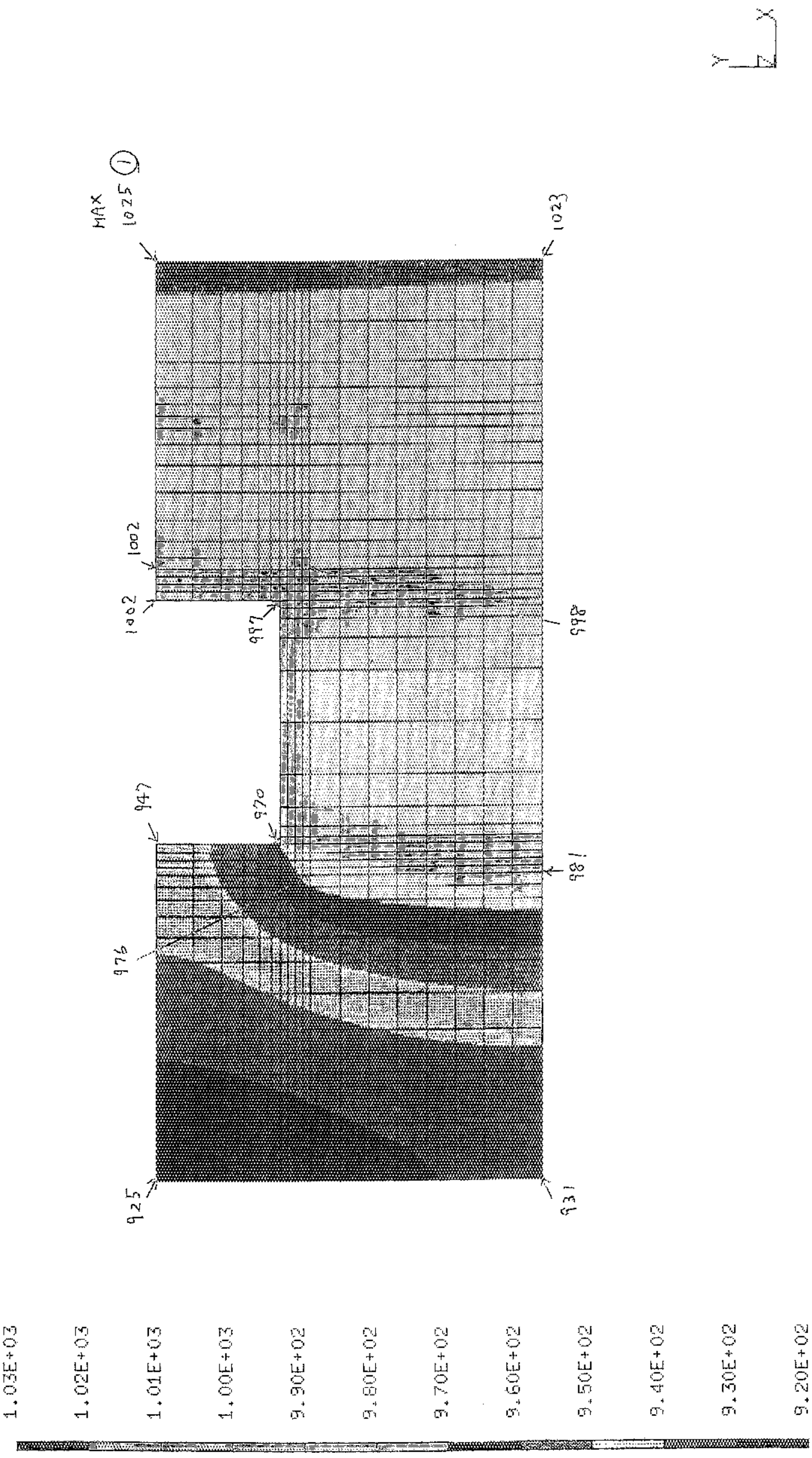


Fig.31 Temperature Distributions in FW at FW and Shield LOFA/LOCA (after 100s)

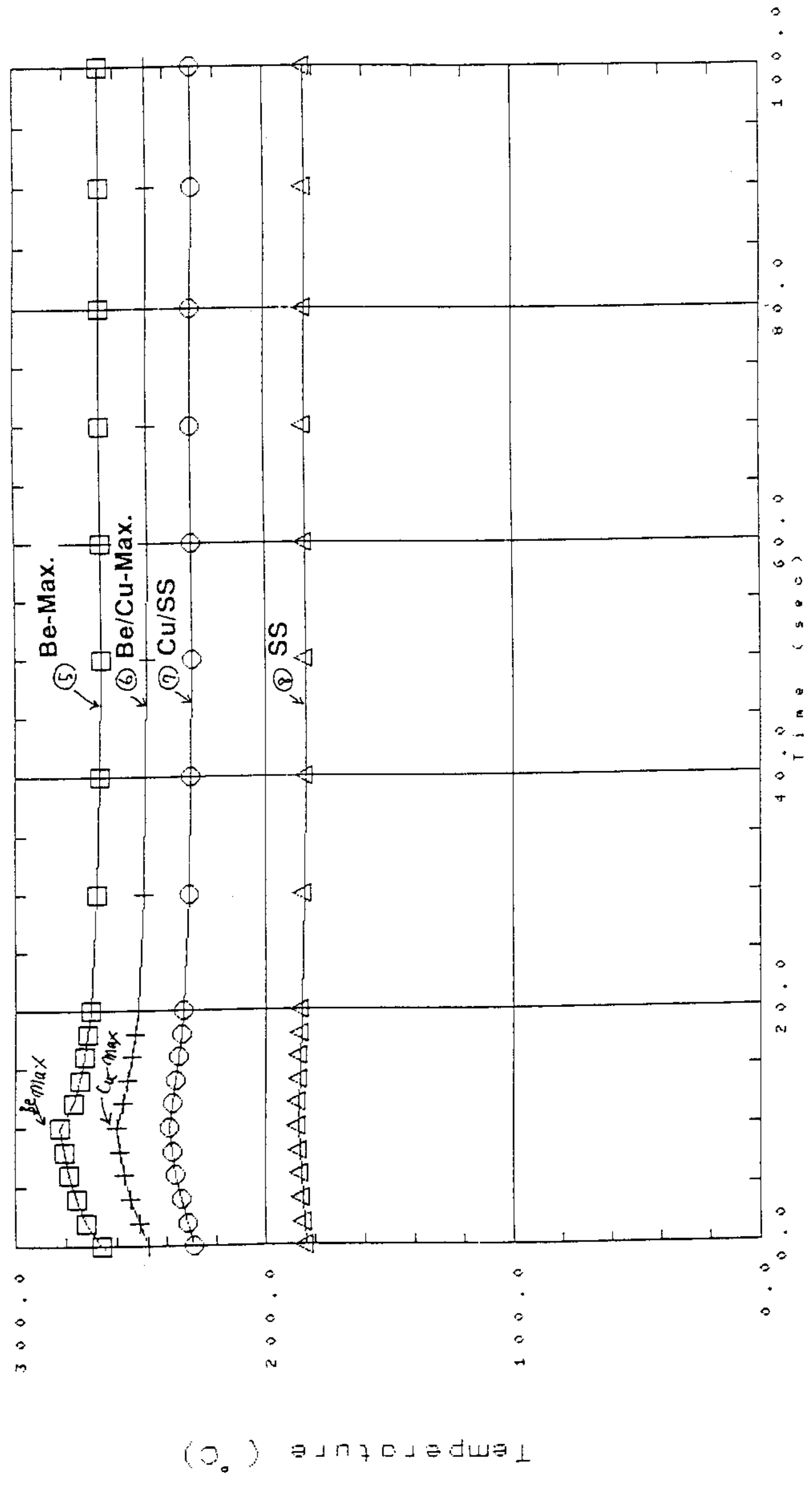


Fig. 32 Responses of FW Temperature at PEC (the number 5~8 : refer to Fig. 5)

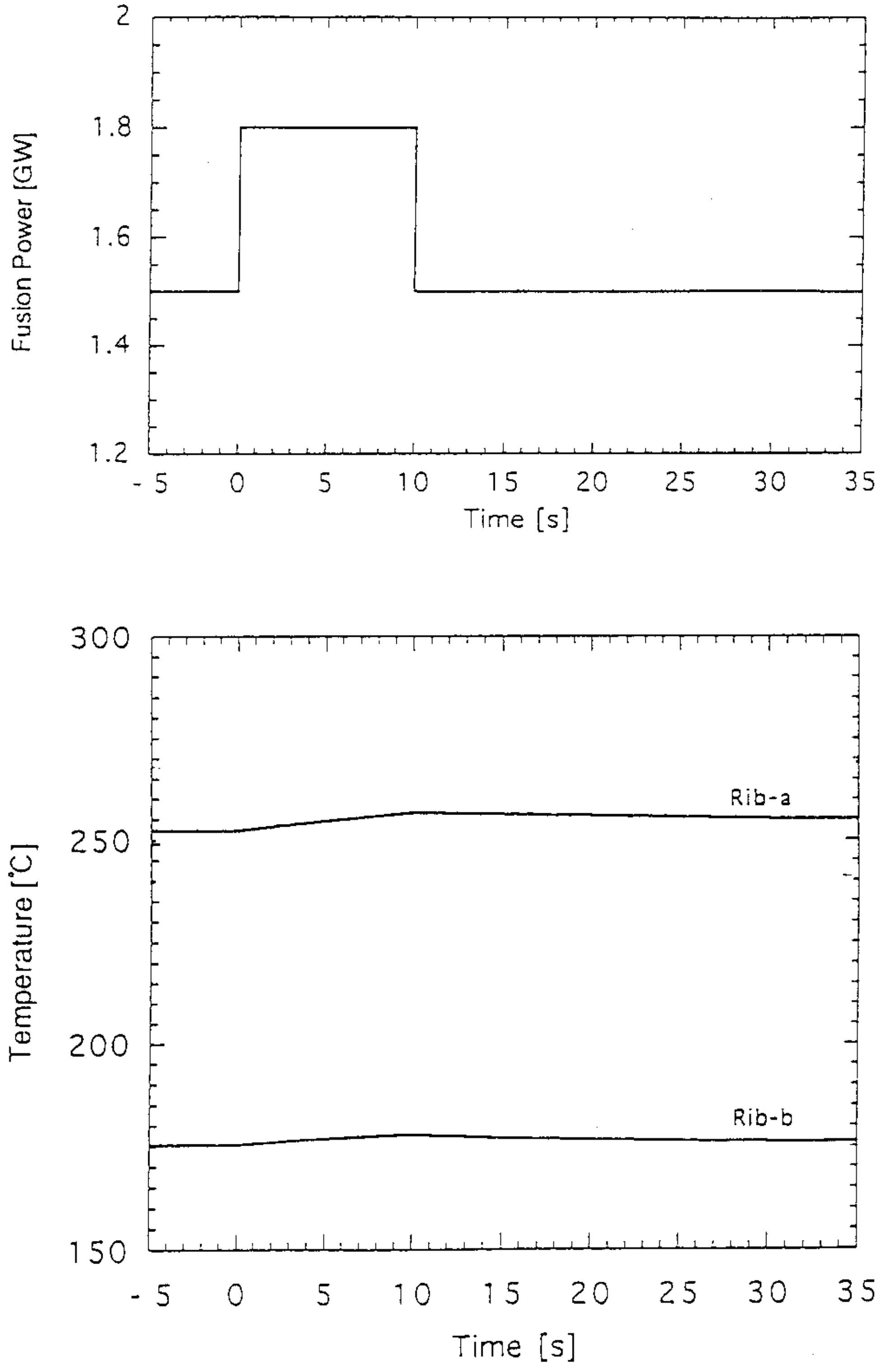


Fig. 33 Responses of Shield Temperature at PEC

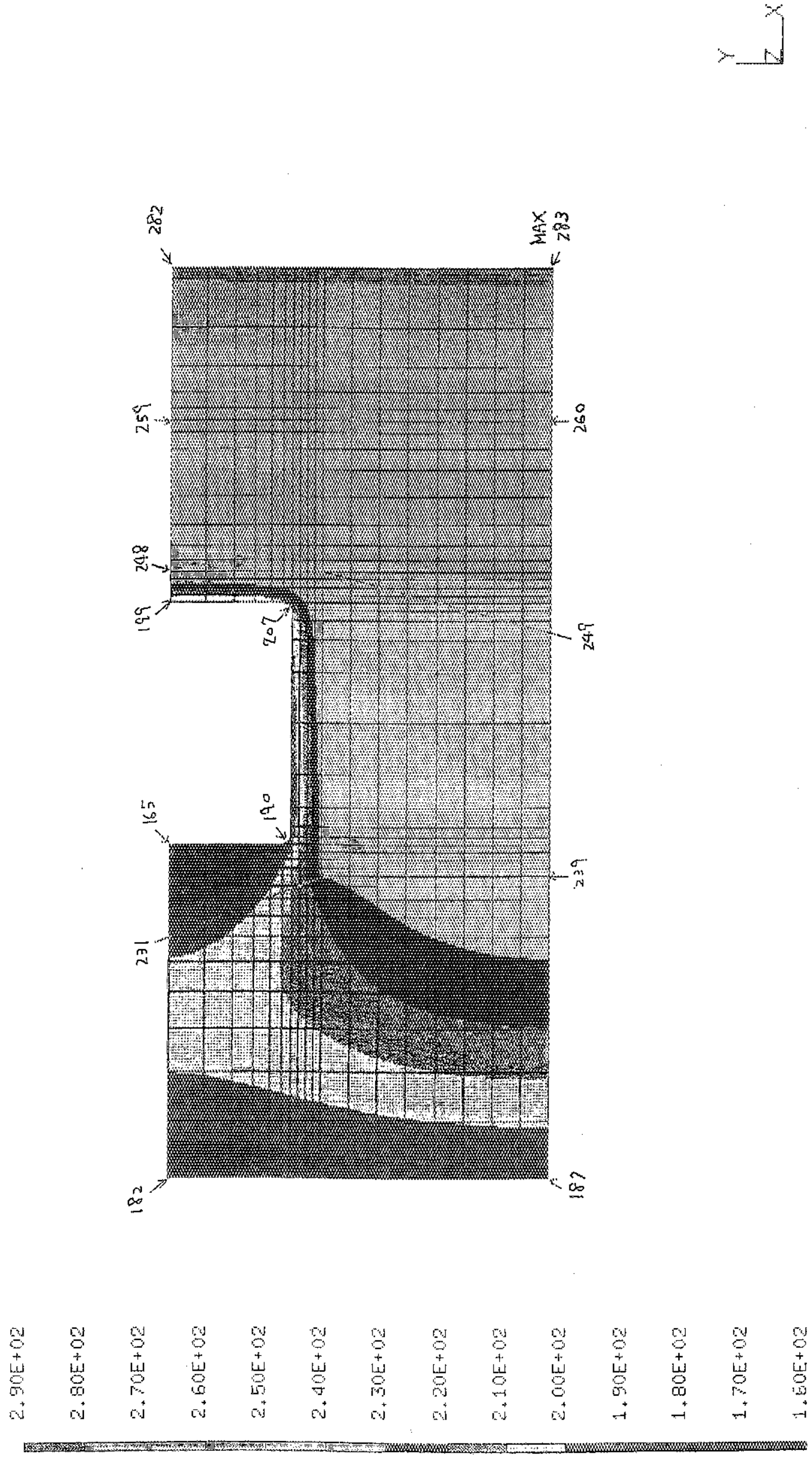


Fig. 34 Temperature Distributions in FW at PEC (after 10s)

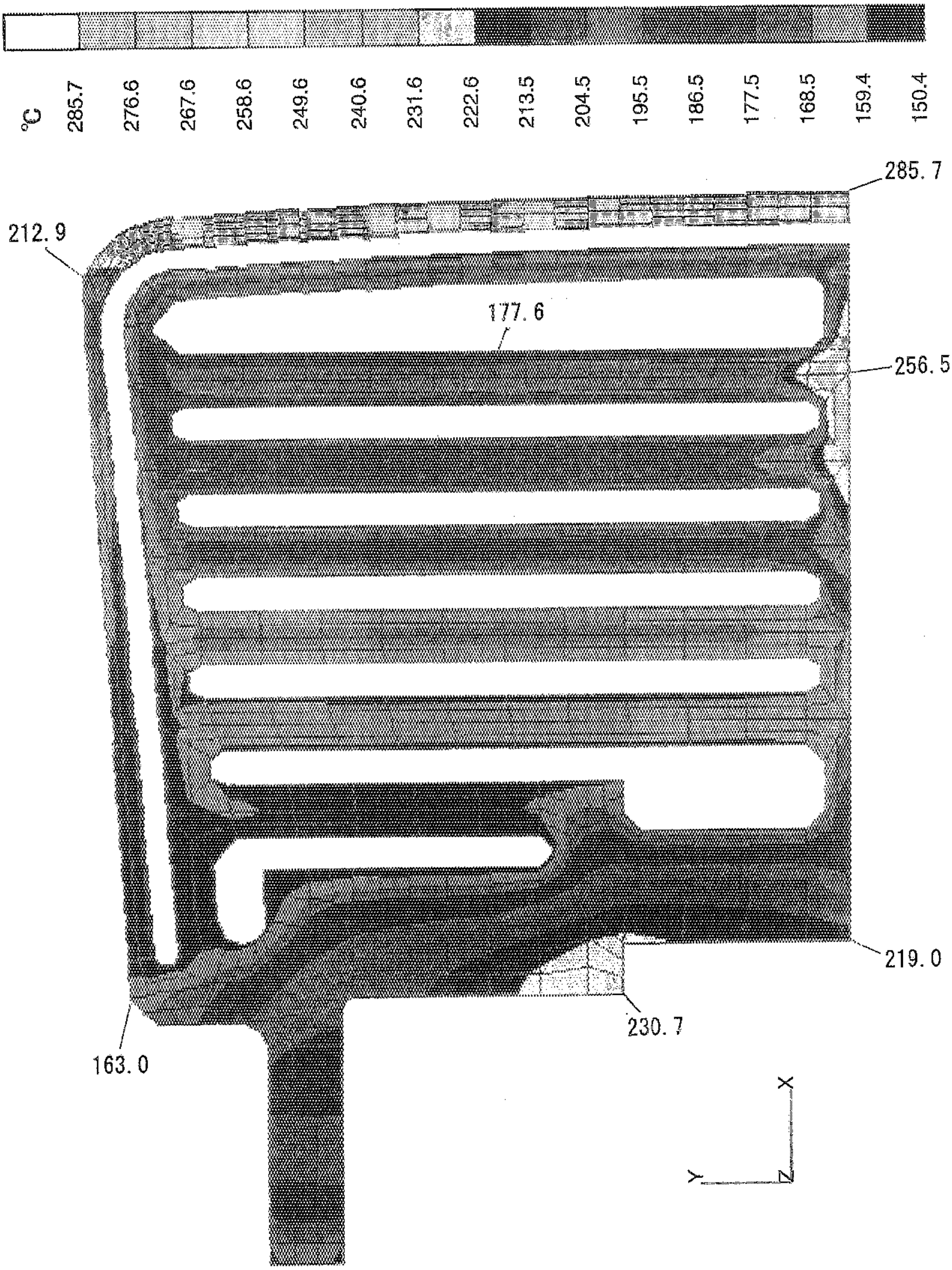


Fig. 35 Temperature Distributions in Shield at PEC (after 10s)

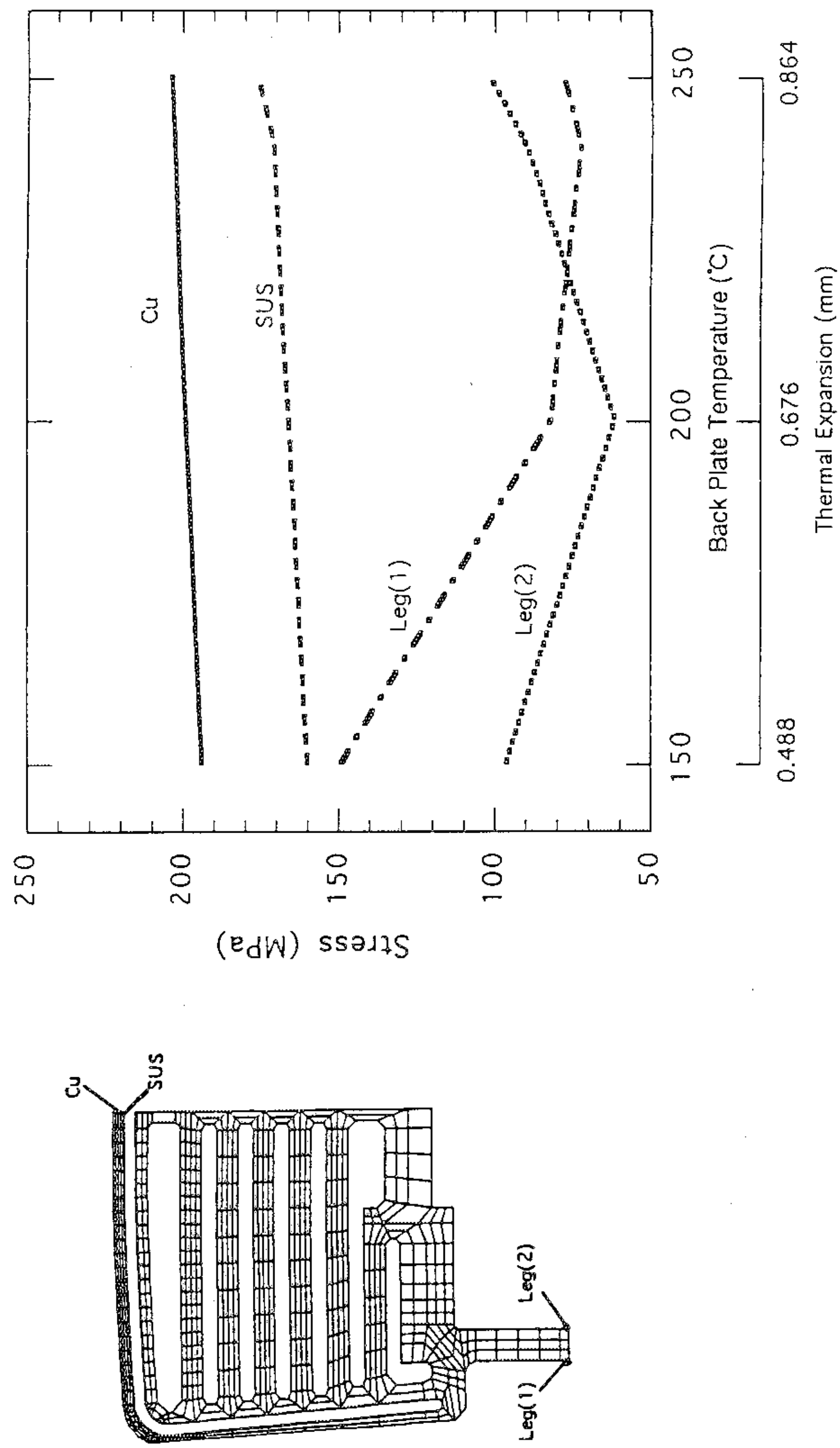


Fig. 36 Back Plate Temperature and Stress of Leg

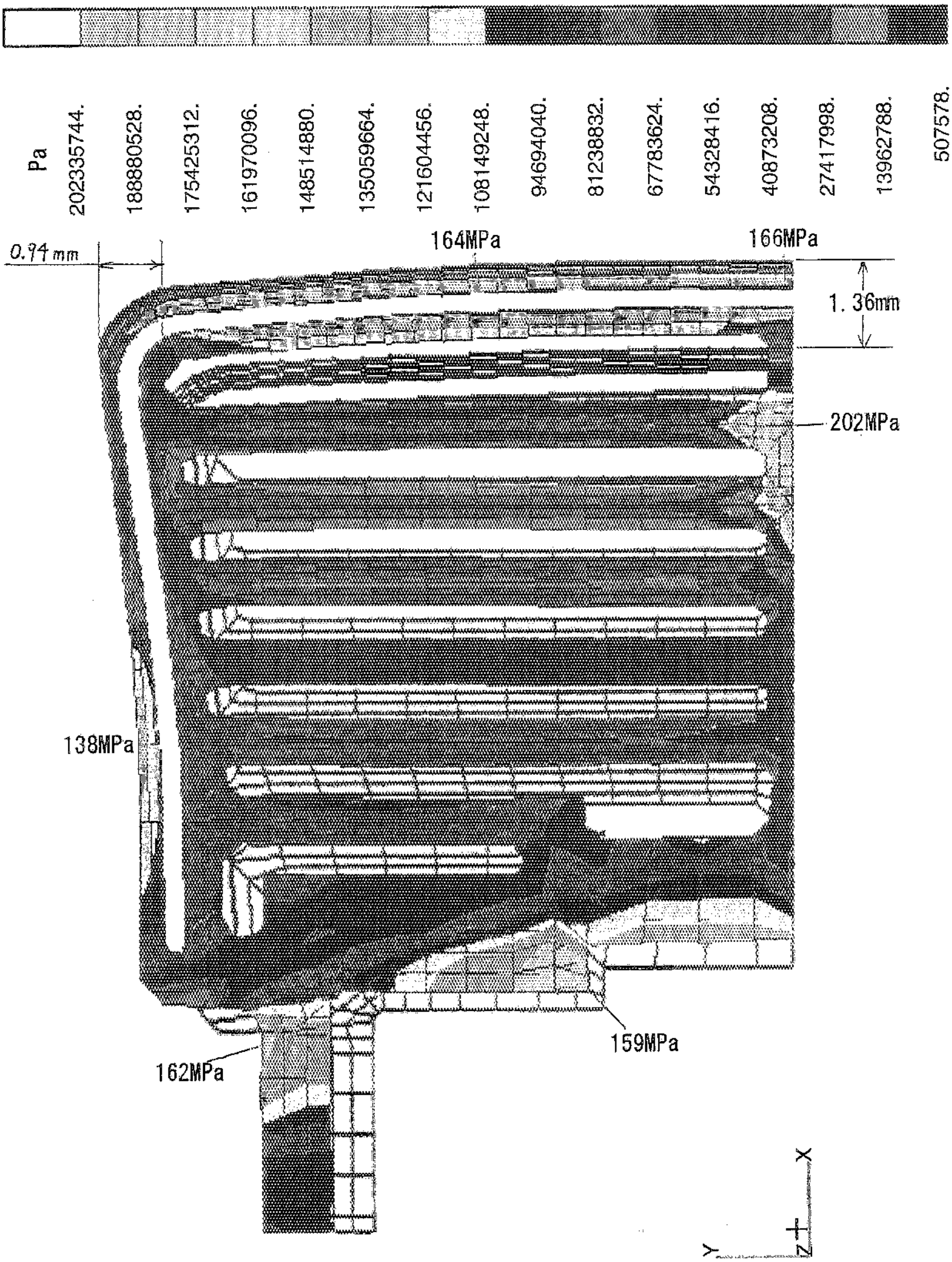


Fig. 37 Stress Distributions in Shield at Normal Operation

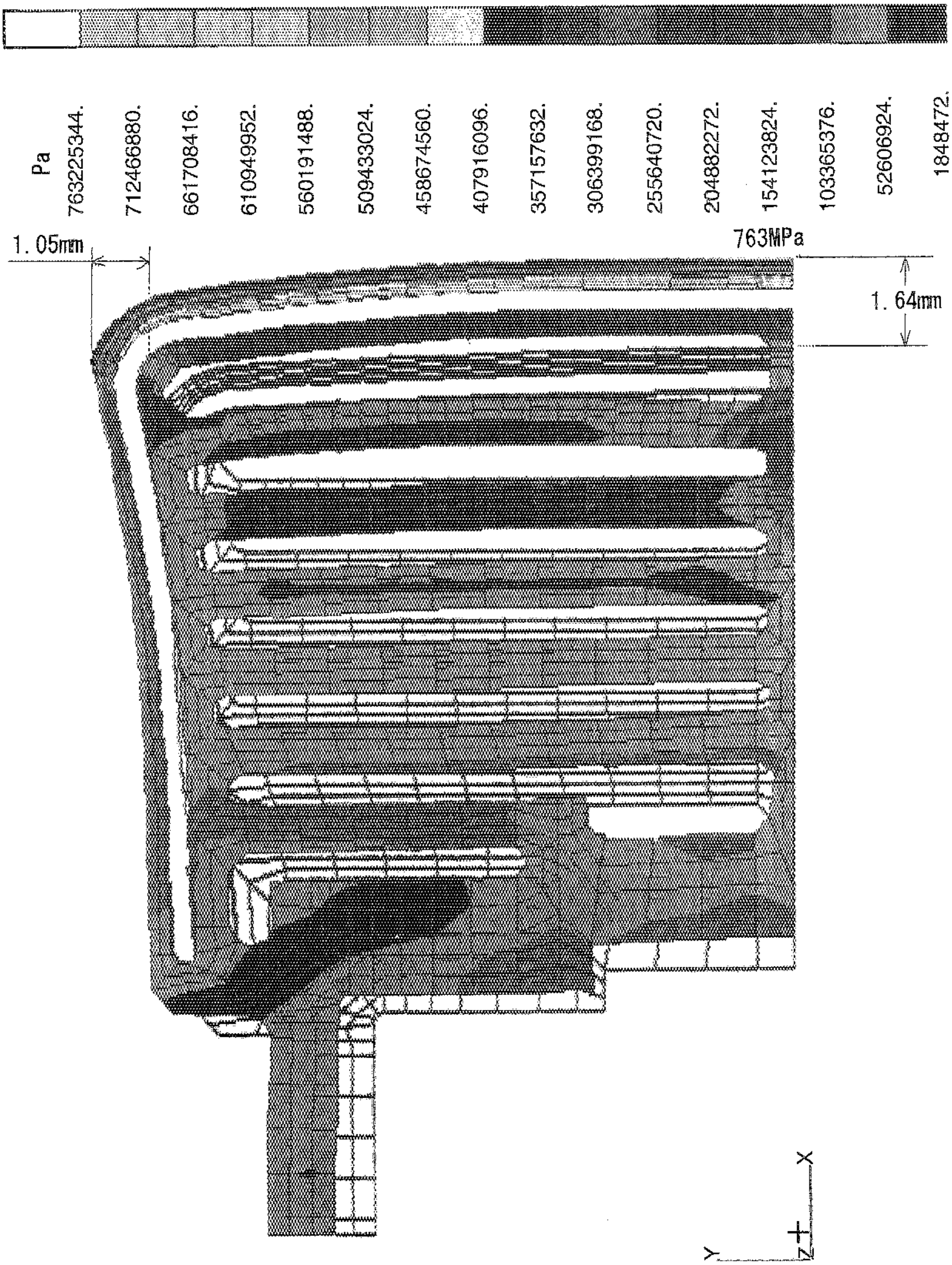


Fig. 38 Stress Distributions in Shield at FW LOFA (after 10s)

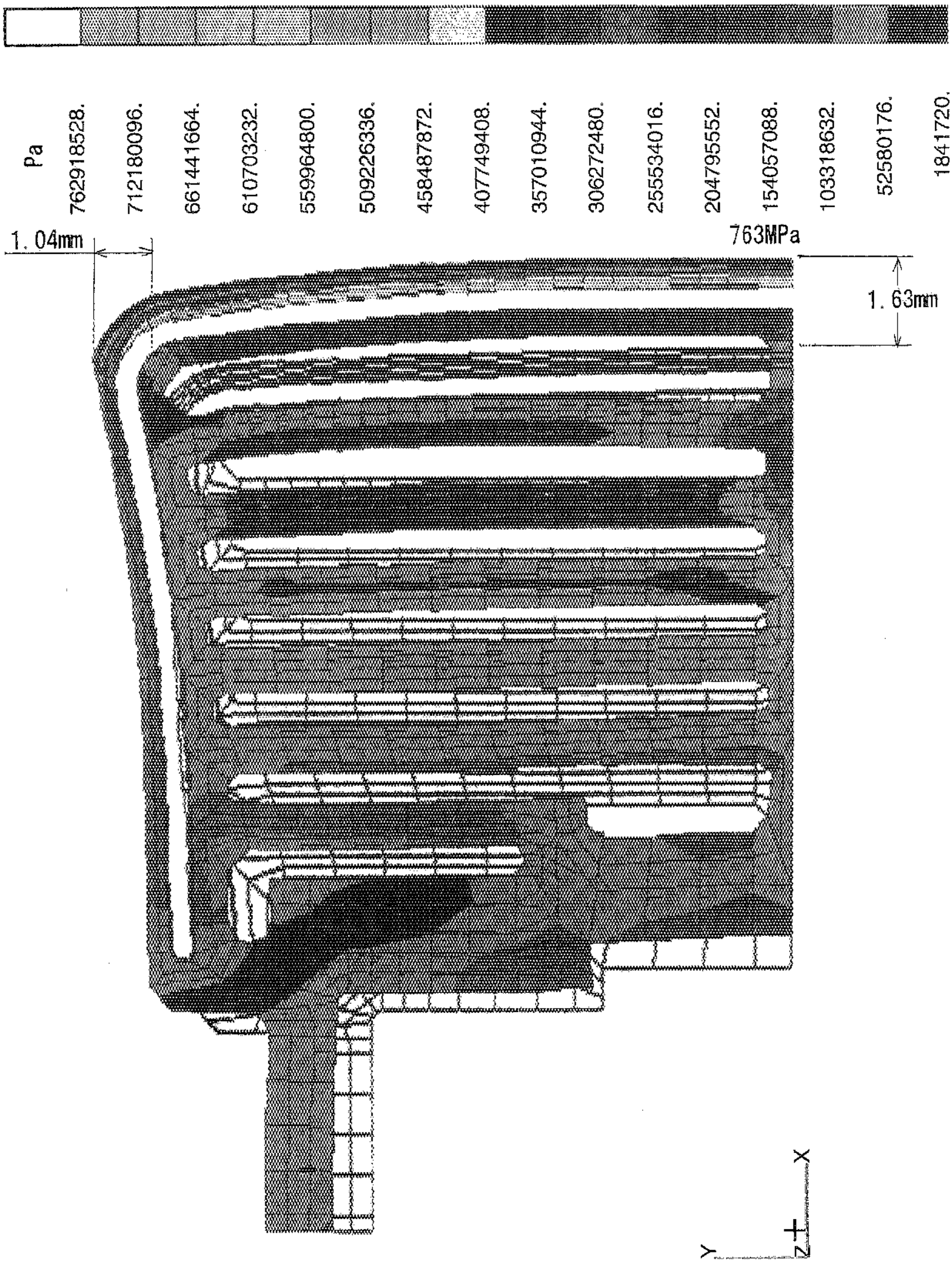


Fig. 39 Stress Distributions in Shield at FW LOCA (after 10s)

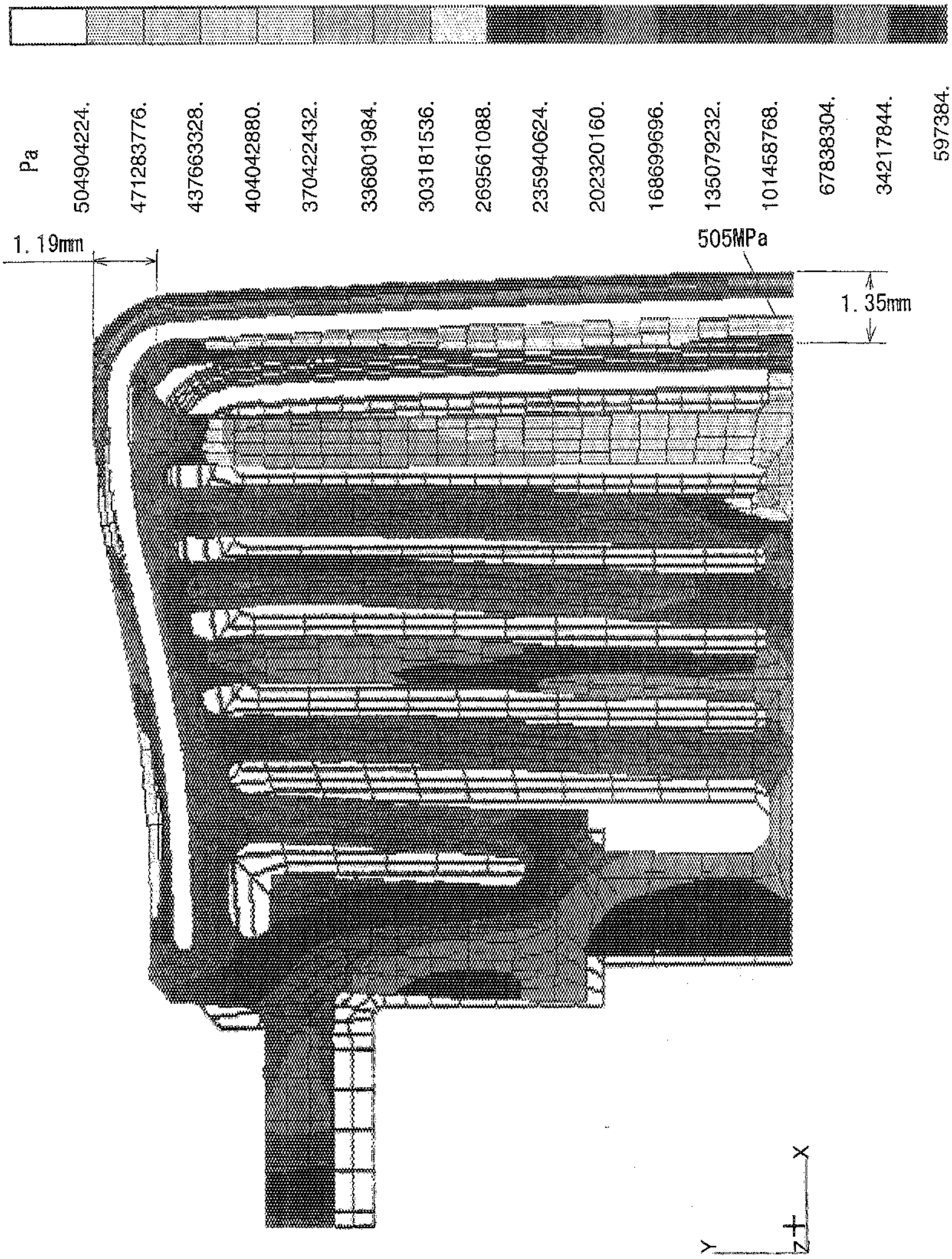


Fig. 40 Stress Distributions in Shield at Shield LOFA (after 50s)

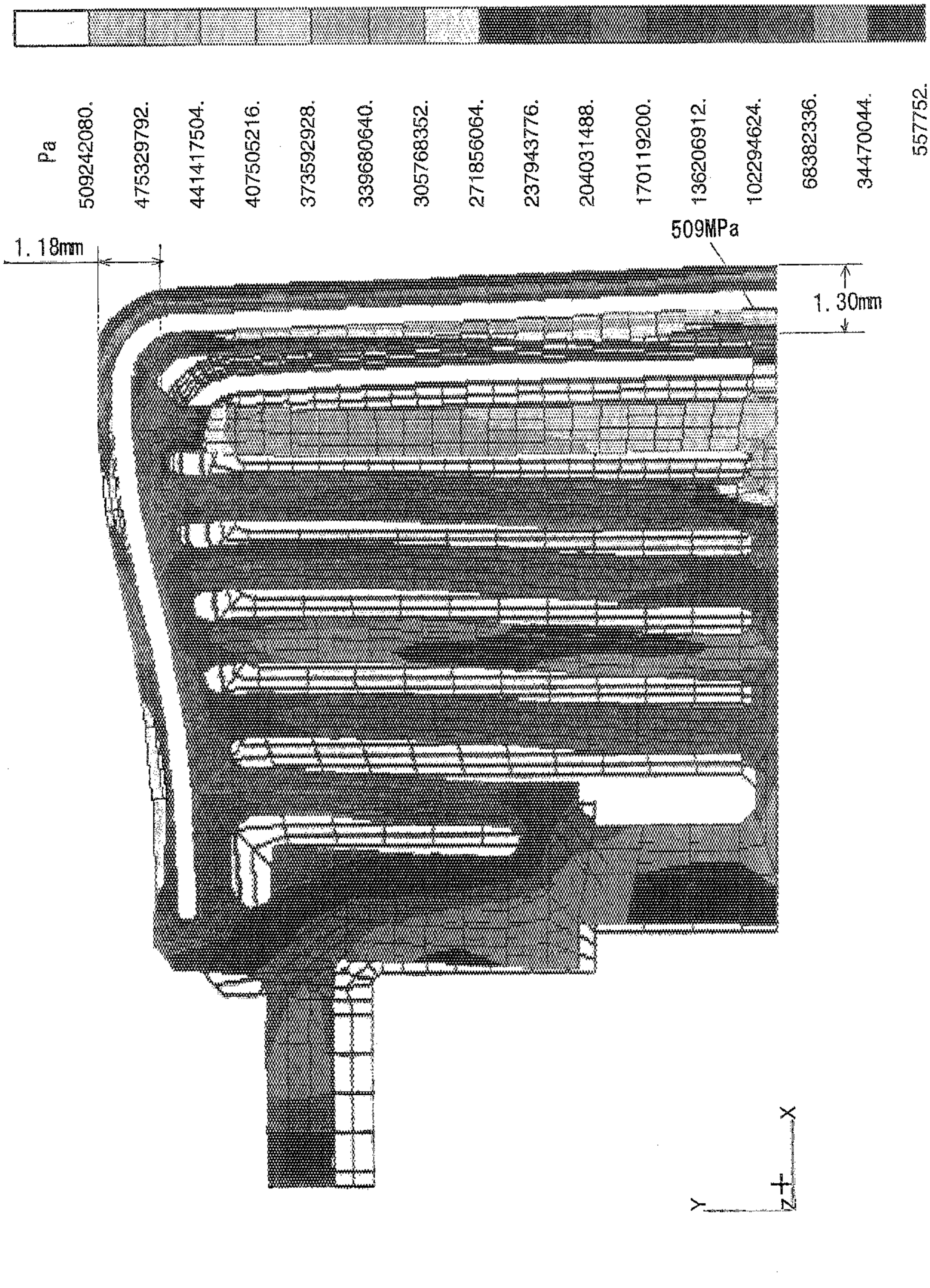


Fig. 41 Stress Distributions in Shield at Shield LOCA (after 50s)

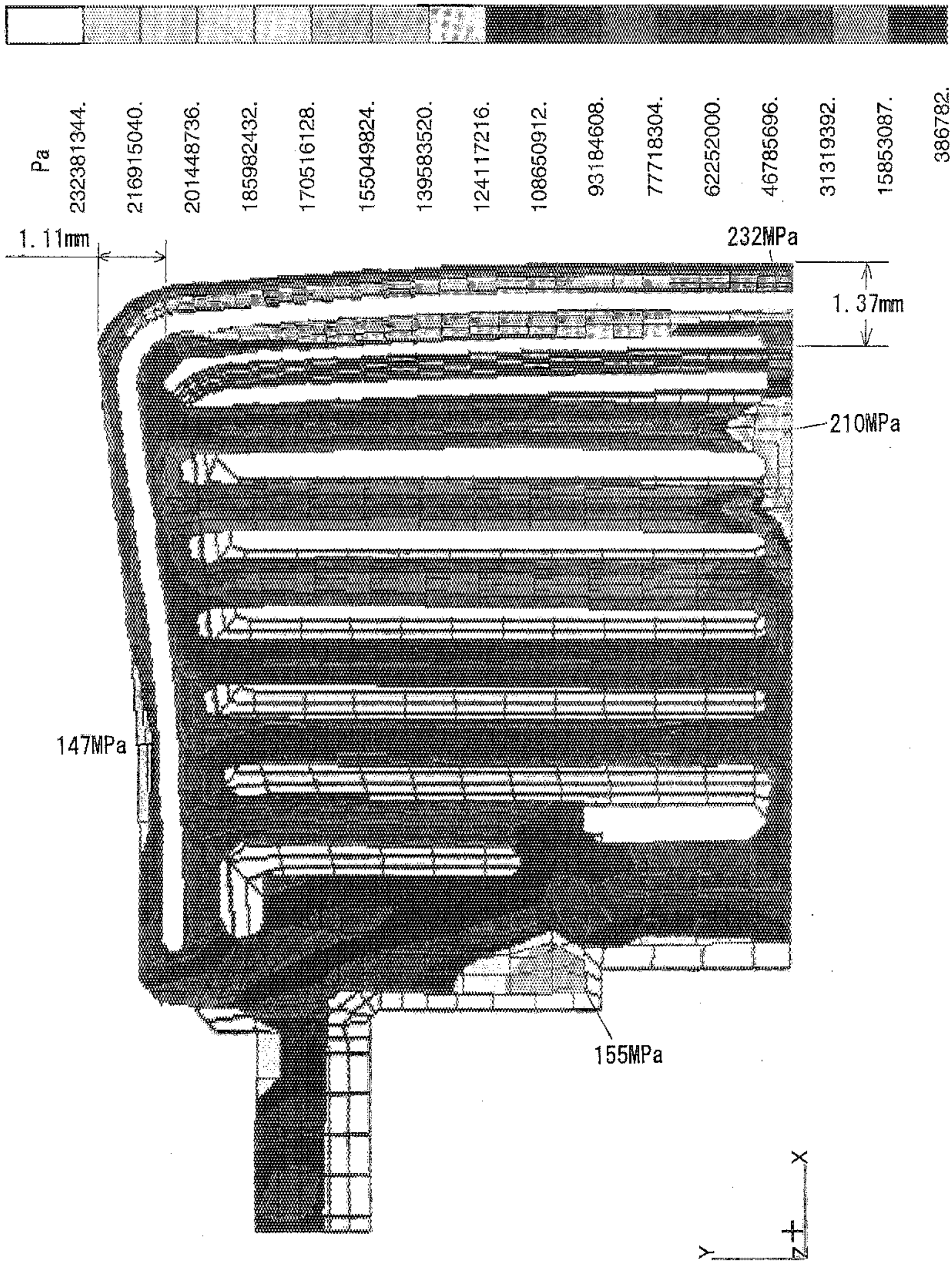


Fig. 42 Stress Distributions in Shield at PEC (after 10s)

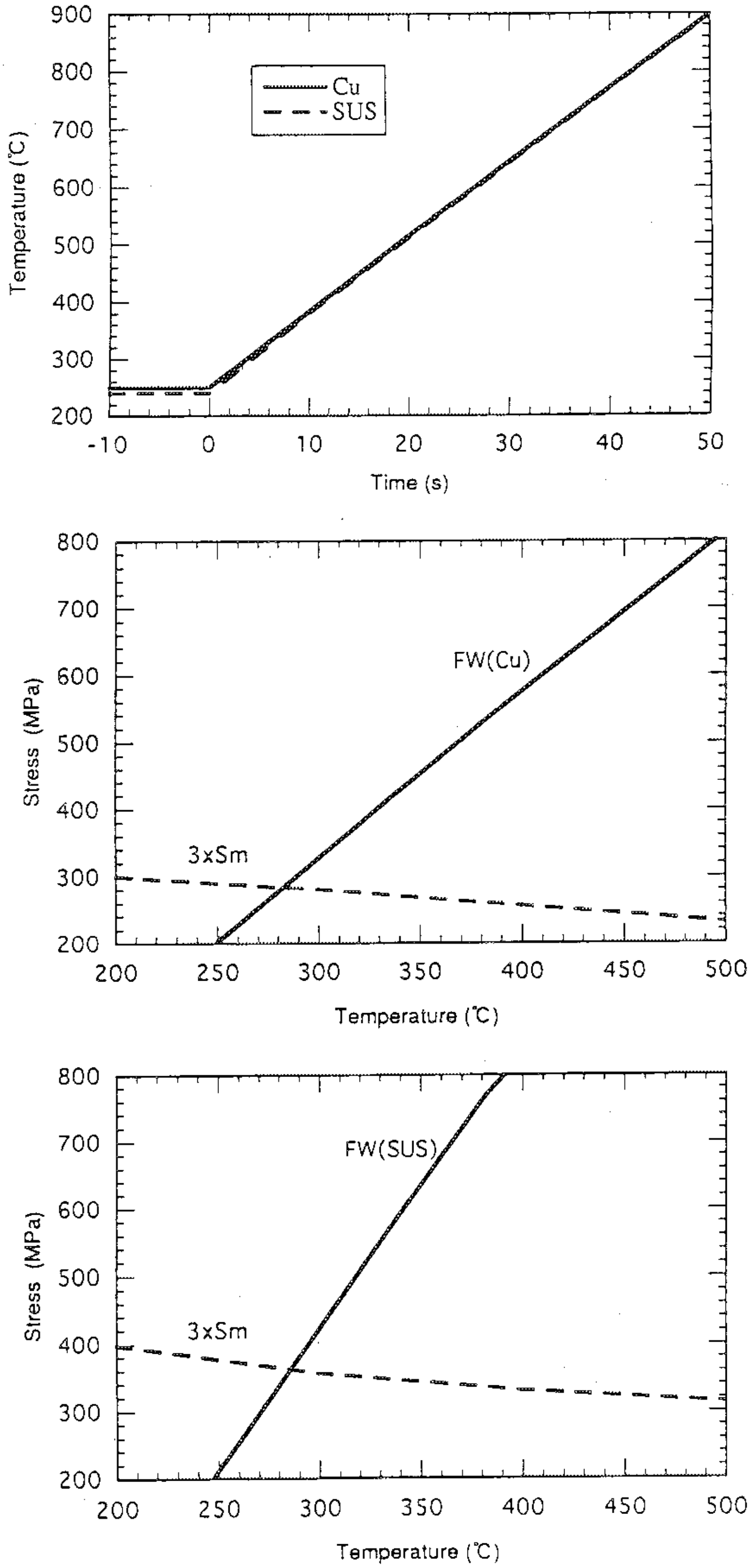
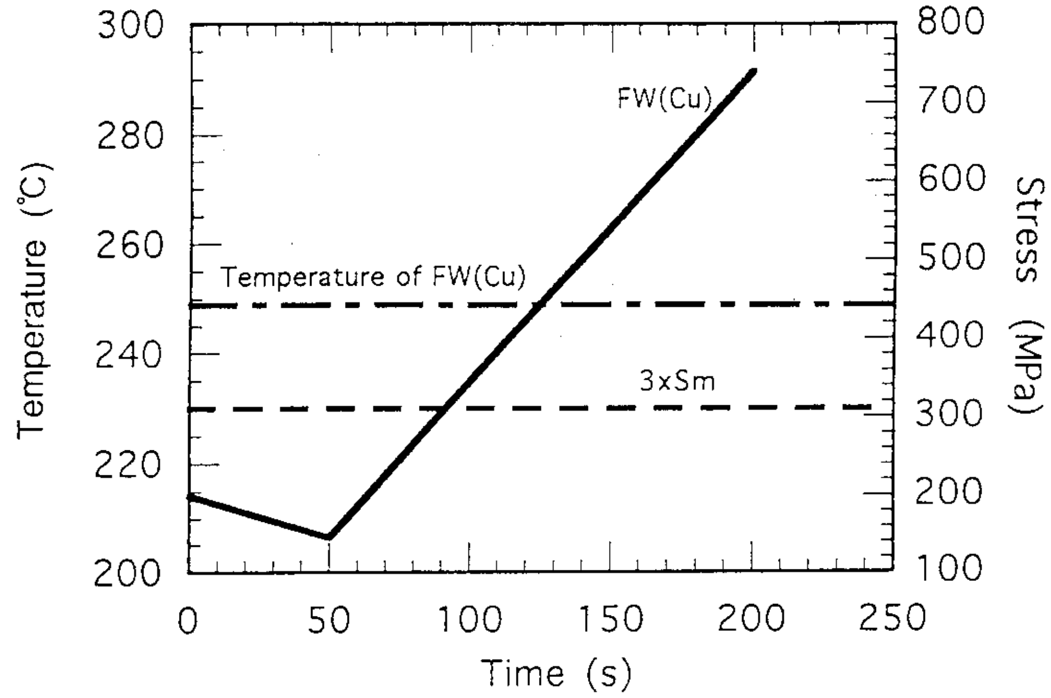


Fig. 43 Temperature and Stress Transient during FW LOFA／LOCA (MODEL-1)



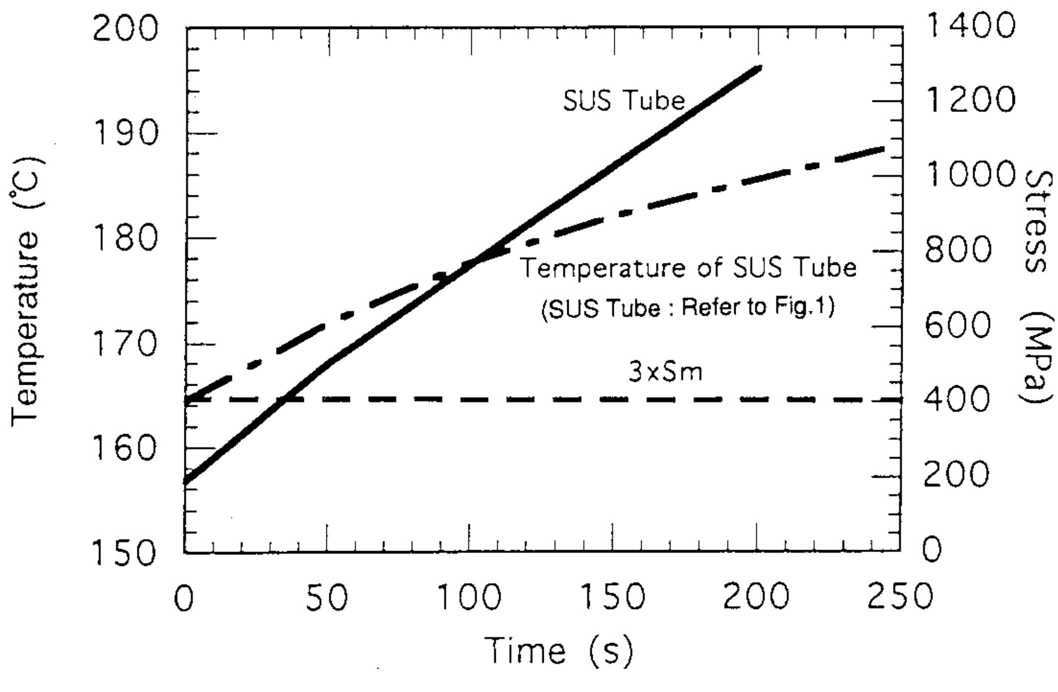


Fig. 44 Temperature and Stress Transient during Shield LOFA/LOCA (MODEL-1)