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Preliminary Design of Mercury Target - Return Flow Type -

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ABSTRACT

A preliminary design of 5MW RFT (Return Flow Type) mercury target for JAERI neutron source project has been carried out. Major design parameters and the target geometry were determined based on thermal and structural analyses. Structural and thermal-hydraulic analyses show that the RFT target design is a feasible candidate for JAERI's 5MW mercury target.

1. Introduction

In the development of 5MW mercury target for Japan Atomic Energy Research Institute (JAERI) Spallation Neutron Source project, two types of mercury target concepts, Cross Flow Type (CFT) target and Return Flow Type (RFT) target, have been investigated [1].

In CFT target concept [2], mercury flows crossing (perpendicular to) the proton beam in the beam reaction zone. On the contrary, in RFT target concept, mercury enters the beam reaction zone from both sides of the inlet channel, returning at the beam window. Proton beam bombards parallel flowing mercury in the outlet channel. The potential merits of the RFT target are summarized as follows:

(1) Smaller Target Size
For CFT target, inlet cold plenum region to produce the crossing flow and outlet hot plenum one to accept the flow will be necessary for each side respectively, therefore the CFT target size will be increased compared with the RFT target with entry flow from both sides.

(2) Simple Flow Pattern
The flow pattern of the basic RFT is very simple compared with CFT design where complex flow distribution from the inlet plenum region to the outlet plenum must be designed.

In this paper, we will describe the result of the preliminary design of the RFT mercury target, especially attention to the structural and thermal-hydraulic analyses performed to confirm the feasibility as a candidate for JAERI 's 5MW target.

2. RFT Target Design Description

2.1 Design Condition

Table 1 summarizes the system parameters of the incident proton beam on the mercury target.

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Proton beam with uniform profile and rectangular shape is assumed in this study. Assuming that the maximum acceptable current density of the proton beam at the beam window is 48 microA/cm^2, the proton beam size is determined to be 6.88cm in height and 10.0cm.

2.2 RFT Target Design Concept and Geometry

The energy deposition in the target was calculated by using a high-energy hadron transport code system LCS (LAHET code system). The total energy deposition is 744 kW/mA, which is about 50% of the beam power. This result is consistent with that of NMTC-JAERI code. Therefore we use the result of LCS in this study.

Figure 1 shows a schema of the RFT target concept. The following coolant design conditions were adopted:

Volumetric Flow Rate:	40m^3/h
Velocity:	< 1m/s
Pressure:	0.5MPa
Inlet Temperature:	70 deg.C
Outlet Temperature:	200 deg.C (mixed mean)

The mercury velocity was restricted below about 1 m/s in order to mitigate the effect of mercury erosion damage on the structural material surface.

Figure 2 shows the geometry of the RFT target design. The target consists of the followings:

The Mercury Target Shell (Inner Vessel)
The Leak Jacket (Outer Vessel)
Target Unit Main Flange
Supporting Skirt
Mercury Inlet Pipe (two)
Mercury Outlet Pipe

The target with a height of 119 mm, a width of 359 mm, and a length of 650 mm is connected with two mercury inlet pipes and one outlet pipe. The leak jacket is designed as a barrier for mercury leakage prevention to helium vessel in case of the target beam window failure. SUS316 is employed as the target structural material.

3. Structural Analysis

3.1 Structural Analysis of Target Inner Vessel

Structural analysis has been performed to determine the basic design specification of target inner vessel. The tentative design criteria for the stress and the displacement of the vessel is assumed as follows:

Stress < 1.5S_m (206MPa at 100 deg.C, 179MPa at 300 deg.C for SUS316)
, where S_m is the design stress intensity limit.
Displacement < 1mm

Parametric survey was carried out step-by-step from a simple vessel model to a reinforced model with ribs and webs. The shell model was used for the calculation. The result is summarized in Table 2.

<u>Model-A</u>

The thickness (t_1 and t_2 in Table 2) and the length (L_1 and L_2) of upper & lower walls are parameters. Among Model-A calculations, A-3, with a thickness t_1, t_2 of 10mm showed a rather good result that the maximum displacement and the maximum stress are 1.6mm and 229Mpa, respectively. However, the thickness of 10mm is too thick to realize better neutronics performance, and the result did not satisfy the design criteria, therefore the model was withdrawn.

Model-B

Ribs (with a height of h in Table 2) on the upper and lower walls and two webs between upper and lower walls were added to improve Model-A. The wall thickness is fixed as 5mm. In all cases (h=0mm, 15mm and 30mm), this model satisfied the design criteria. The ribs on the upper and lower walls are not always necessary to install, but two webs shall be essential to prevent large displacement of both walls.

Model-C

In this case only two ribs between upper and lower wall exist as reinforcement member to Model-A. The head part and bottom part thickness (t_a and t_b in Table 2) of the upper & lower walls are the parameters. When the head part thickness is 5 mm and the bottom part thickness is 15 mm (C-1), the maximum displacement is 0.69mm and the maximum stress is 168Mpa, which satisfy the stress and displacement criteria. Therefore Case C-1 is adopted for further design study.

3.2 Lifetime Estimation

Lifetime of the beam window due to the thermal cycle fatigue was estimated by using the design fatigue limit curve for SUS316. There are two types of thermal cycles to be considered:

(1) Thermal Cycle due to Normal/Off-normal Beam Shut Down Incident
(2) Thermal Cycle due to 50 Hz Pulse Operation

Figure 3 shows the relationship between the wall temperatures (the maximum temperature in the wall, Hg side temperature and D_2O side temperature) and the wall thickness obtained by 1-D thermal calculation of the beam window. The result shows that the temperature difference within the beam window is 71 degrees at the target beam window and 110 degrees at the leak jacket. The strain of the leak jacket is 0.00282 and the fatigue limit is estimated to be 1×10^5 cycles. Because the frequency of the occurrence of beam shutdowns more than 1 minute is anticipated to be 200 times a week, the 1×10^5 cycles corresponds to approximately 10 years operation.

The energy deposition rate per pulse in the target beam window and the leak jacket window is estimated to be 2.77kcal/s/mm^3. So the maximum temperature rise during one pulse is about 3 deg.C. Hence the thermal fatigue effect due to 50Hz-pulse operation on both beam windows is negligible by small.

The result of the lifetime estimation is summarized in Table 3. For more precise estimation, radiation damage of the wall material and the fatigue due to pulsed pressure wave should be considered.

4.Thermal-hydraulic Analysis

A three-dimensional thermal-hydraulic analysis has been carried out. The purpose of this analysis is to design flow configuration of the RFT target and to confirm that the RFT target can remove the generated heat effectively and, as the result, can assure its structural integrity. The following values were used as tentative judgement criteria for this thermal-hydraulic analysis:

(1) No boiling in mercury(bulk): $T_{Hg} < 358$ deg.C (at 0.1MPa)
(2) Structural material temperature limit: $T_{st} < 400$ deg.C

Criteria (2) requires that the maximum mercury temperature near the target beam window should be below 330 deg.C because 1-D thermal calculation result (Figure 3) showed that the temperature difference between the maximum temperature in the beam window and the mercury temperature is approximately 70 deg.C. However more detailed analysis should be required to confirm this value.

SALE-3D [3] computer code, which is a simplified ALE computer program originally developed by Los Alamos National Laboratory, is use. The structure surface is treated as adiabatic, therefore no heat conduction between mercury and target structure is considered. Velocity constant and pressure constant condition are used for the coolant inlet and outlet, respectively. The heat deposition profile calculated by LCS is used.

Figure 4 shows the design approach of the flow configuration of the RFT target. As described in section 1, the RFT target design has some potential advantages such as smaller target size and simple flow pattern. Here, we tried to find feasible solution for the thermal-hydraulic problem for the compact FRT target design.
The result of the analysis is summarized in Table 4.

CASE-1
This reference case has a symmetric flow configuration. Mercury enters the beam reaction zone from both sides and bottom of the inlet channel, returning at the beam window. Figure 5 shows the calculated temperature profiles on the vertical and horizontal planes where the maximum temperature occurs. Although the flow pattern of this case is very simple, that is a potential merit of RFT target, the stagnant flow region occurs near the target beam window, and therefore hot zone exceeding mercury boiling temperature occurred in the center line near the beam window.

CASE-2
In CASE-2, flow configuration was modified to give asymmetric flow to reject a stagnant flow region near the center of the beam window. As shown in Figure 6, the stagnant flow near the beam window is diminished but the re-circulating flows occurred inside the outlet channel. As the result, hot zone occurred (Tmax=380 degree C) in the outlet channel.

CASE-3
To prevent the formation of re-circulating flow in the outlet channel, side holes are installed on the outlet channel box of CASE-2. As shown in Figure 7, the re-circulating flow still remains, but the effect is rather mitigated. In this case the maximum mercury temperature is below the boiling point (358 deg.C at 0.1MPa).

CASE-4
This case is the same configuration as CASE-3, but the flow rate is increased from 40 m^3/h to 44 m^3/h (10% up). The result (Figure 8) shows that the maximum temperature of the re-circulation flow regions well decreased to marginal value.

As the result of a series of analyses, it was demonstrated that the modified RFT target, which employs asymmetric flow and side holes, could keep maximum mercury temperature below boiling point. Therefore, we concluded that the modified RFT target is also a feasible candidate for JAERI's 5MW mercury target.

5. Conclusions

As a first step of the JAERI's 5MW mercury target development, the basic structure of the Return Flow Type (RFT) target has been investigated.
The structural analysis showed that the target structure with 2 mm thickness beam window and 5 mm thickness upper and lower walls is feasible by incorporating two webs between upper and lower walls of the target.

Thermal-hydraulic analysis showed that hot zone exceeding mercury boiling temperature occurred in the centerline near the beam window of reference RFT target. The modified RFT target, which employs asymmetric flows and side holes, can keep maximum mercury temperature below boiling point. Therefore, we concluded that the modified RFT target is also a feasible candidate for JAERI's 5MW mercury target.

REFERENCES

[1] R.Hino et al, "Spallation Target Development at JAERI", ICANS-XIV, 1998

[2] M.Kaminaga et al., "Thermal and Hydraulic Design of Mercury Target - Cross Flow Type-", ICANS-XIV, 1998

[3] A.A.Amsden and H.M.Ruppel, "SALE-3D: A Simplified ALE Computer Program for Calculating Three-Dimensional Fluid Flow", NUREG/CR-2185 LA-8905, 1981

Table 1 Proton Beam Parameters

Proton beam	Energy (GeV)	1.5
	Profile	uniform rectangular
	Size	$6.88cm^H \times 10.0cm^W$
	Current	3.33 mA

Table2 Result of Structural Analysis

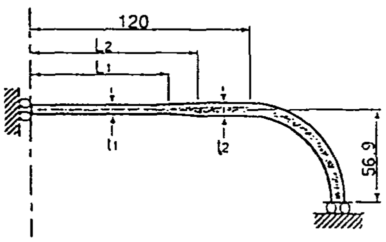
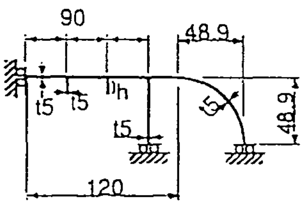
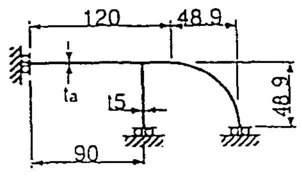
<table>
<tr><td rowspan="4"> </td><td>Case</td><td>t_1 [mm]</td><td>t_2 [mm]</td><td>L_1 [mm]</td><td>L_2 [mm]</td><td>Max. Disp. [mm]</td><td>Max. Stress [MPa]</td></tr>
<tr><td>A-1</td><td>5</td><td>5</td><td>—</td><td>—</td><td>10.7</td><td>687</td></tr>
<tr><td>A-2</td><td>3</td><td>10</td><td>70</td><td>110</td><td>5.0</td><td>475</td></tr>
<tr><td>A-3</td><td>10</td><td>10</td><td>—</td><td>—</td><td>1.6</td><td>229</td></tr>
<tr><td rowspan="4"> </td><td>Case</td><td colspan="4">Rib Height h [mm]</td><td>Max. Disp. [mm]</td><td>Max. Stress [MPa]</td></tr>
<tr><td>B-1</td><td colspan="4">0</td><td>0.25</td><td>86.7</td></tr>
<tr><td>B-2</td><td colspan="4">15</td><td>0.15</td><td>86.0</td></tr>
<tr><td>B-3</td><td colspan="4">30</td><td>0.11</td><td>64.7</td></tr>
<tr><td rowspan="4"> </td><td>Case</td><td colspan="2">Head t_a[mm]</td><td colspan="2">Bottom t_b[mm]</td><td>Max. Disp. [mm]</td><td>Max. Stress [MPa]</td></tr>
<tr><td>C-1</td><td colspan="2">5</td><td colspan="2">15</td><td>0.69</td><td>168</td></tr>
<tr><td>C-2</td><td colspan="2">3</td><td colspan="2">15</td><td>2.62</td><td>497</td></tr>
<tr><td>C-3</td><td colspan="2">5</td><td colspan="2">5</td><td>1.10</td><td>236</td></tr>
</table>

Table 3 Estimated Lifetime

	ΔT[°C]	T_{max}[°C]	Strain ε	Life Time
Target Beam Window	71	210	0.00178	$>1\times10^6$
Leak Jacket Window	110	260	0.00282	$>1\times10^5$

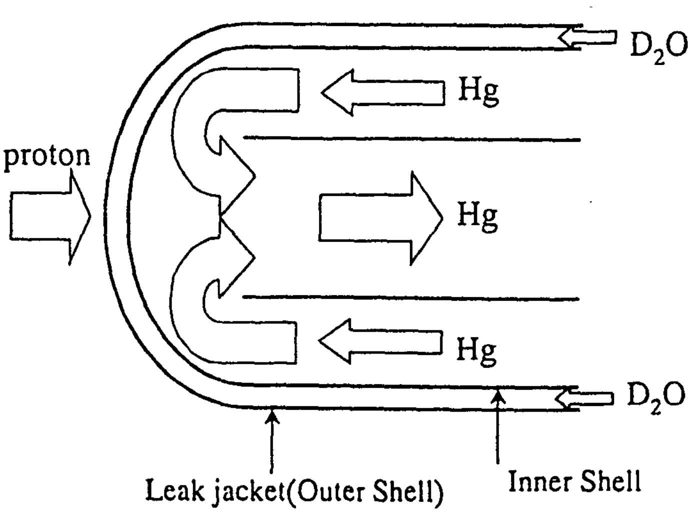
$$\varepsilon = \frac{\alpha \Delta T(1+\nu)}{2(1-\nu)} q$$

α: thermal expansion coefficient μ: Poisson ratio q=1.5

Table4 Result of Thermal Hydraulic Analysis

Model		Flow Rate $[m^3/h]$	Maximum Mercury Temperature[°C]		Remarks
			Whole Region	Near Beam Window	
Case 1	Reference	40	474	474	×
Case 2	Asymmetric Flow without side holes	40	380	260	×
Case 3	Asymmetric Flow with side holes	40	356	283	○
Case 4	Up Flow Rate of Case 3	44	343	228	○

○ acceptable × not acceptable



- Mercury(Hg) flows along the proton beam direction and returns at the beam window
- Mercury Coolant
  - Flow rate: $40m^3/h$
  - Velocity < 1m/s
  - Pressure : 0.5MPa
  - Inlet temperature : 70 °C
  - Outlet temperature: 200 °C
- Target cross section: $119mm^H$ $359mm^W$
- Leak jacket : Mercury leakage prevention to helium vessel in case of mercury beam windows failure
  - Inlet temperature: 45 °C
  - Outlet temperature: 56 °C
- Structural material : SUS316

Figure 1 RFT Target Concept

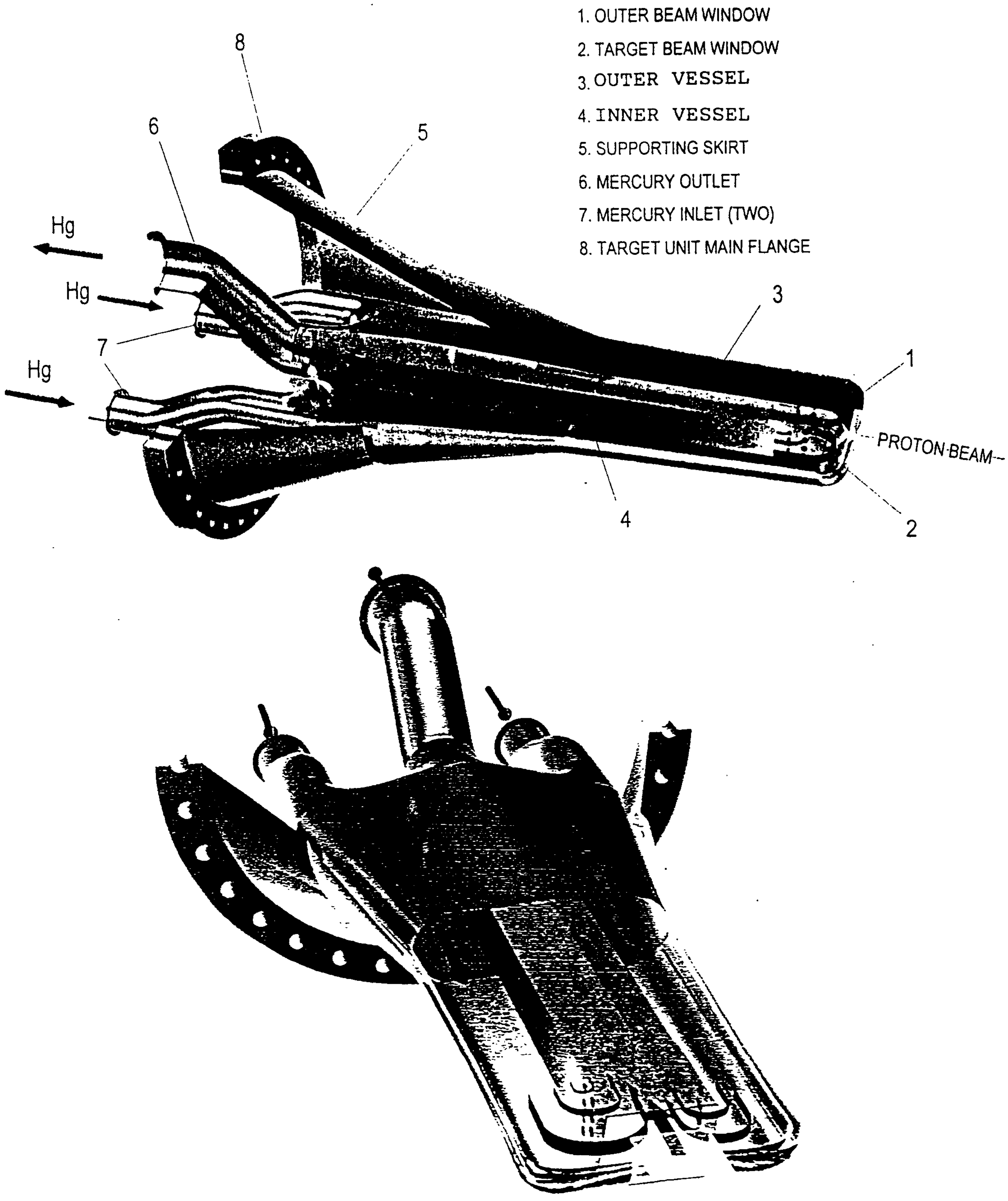
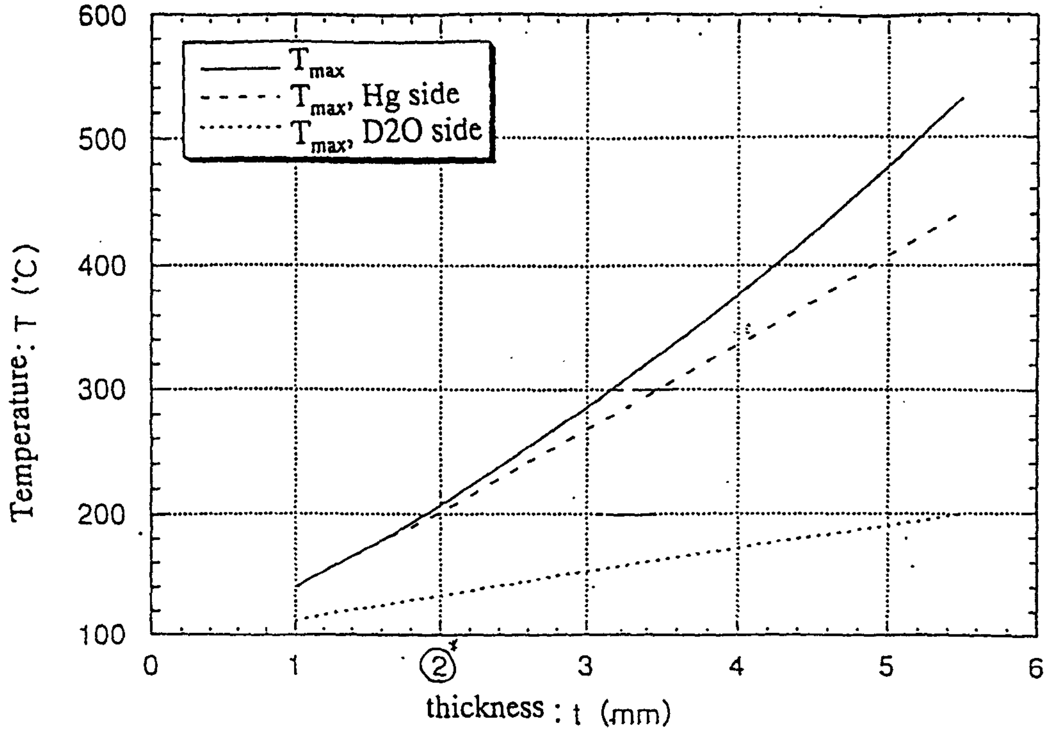


Figure2 View of Return Flow Type Target

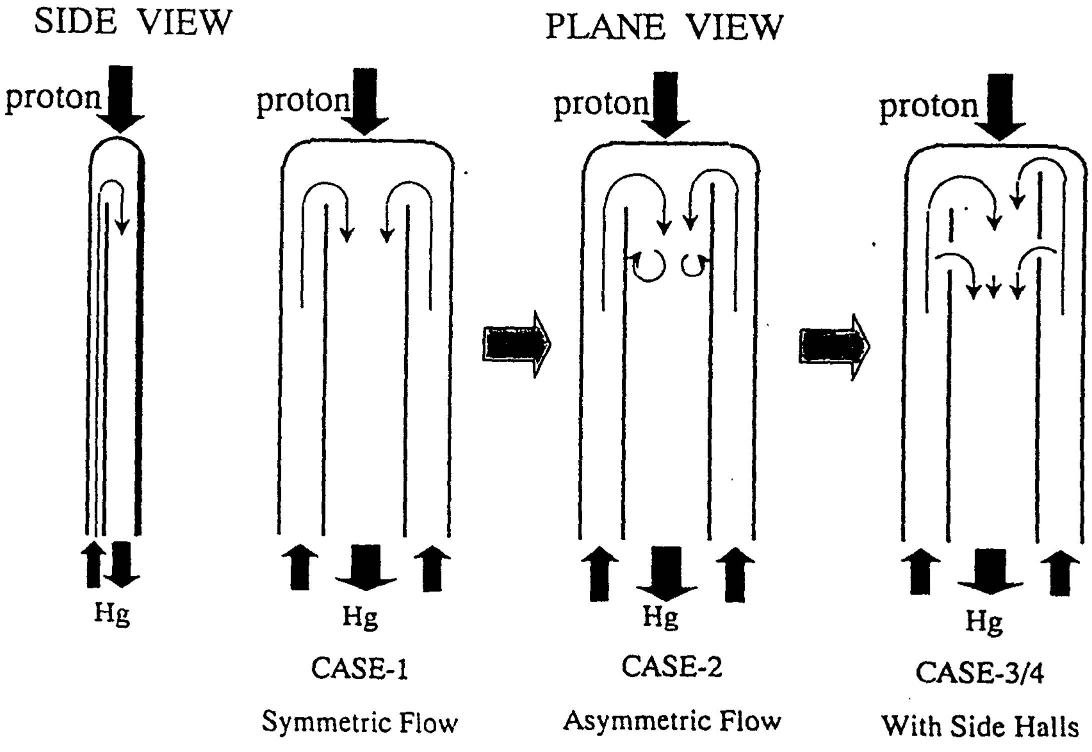


T_{Hg}=135 ℃, α_{Hg}=5000kcal/m2·hr·℃ (mercury cooling)

T_w=80 ℃, α_w=25000kcal/m2·hr·℃ (D_2O cooling)

1.2kW/mm/mA (energy deposition at beam window)

Figure 3 Beam Window Temperature vs. Its Thickness



CASE-1 Symmetric Flow

CASE-2 Asymmetric Flow

CASE-3/4 With Side Halls

Figure 4 Design Approach of RFT Target Flow Configuration

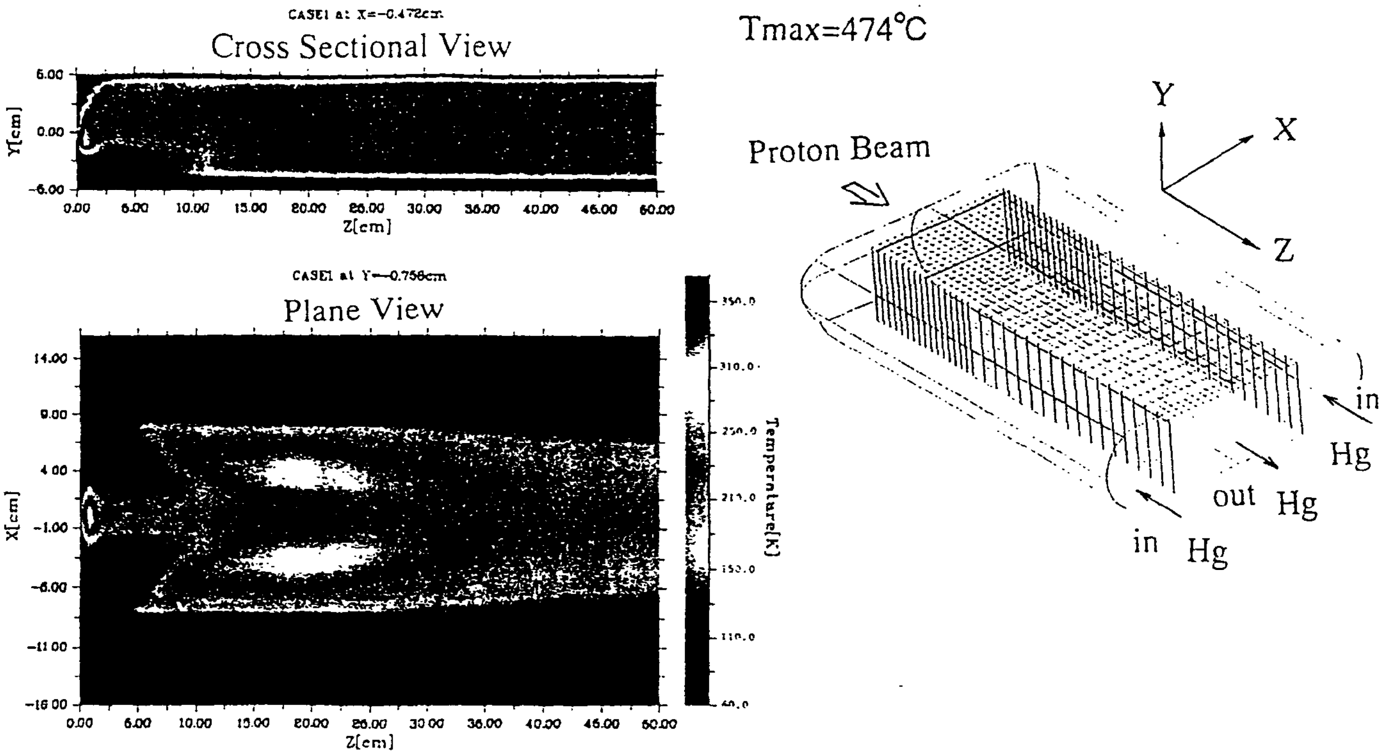


Figure 5 Temperature Profile of CASE-1

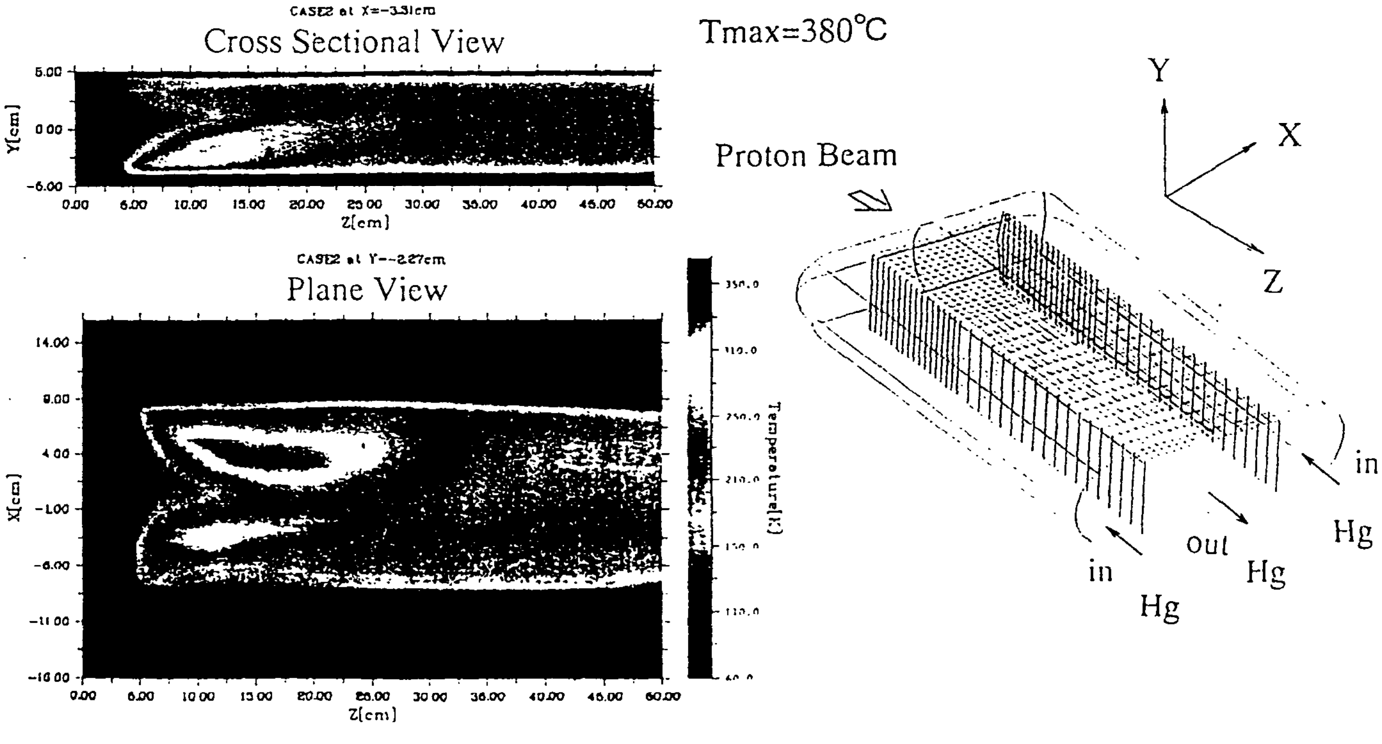


Figure 6 Temperature Profile of CASE-2

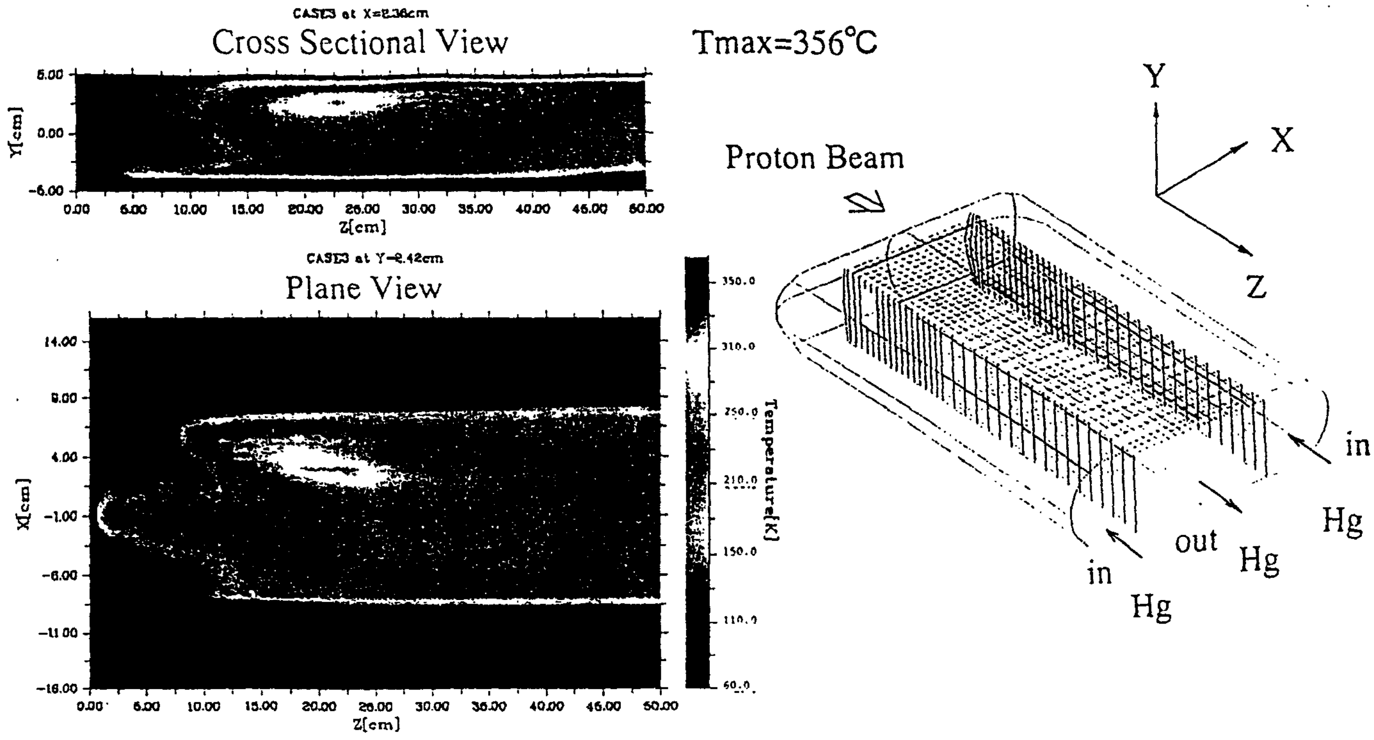


Figure 7 Temperature Profile of CASE-3

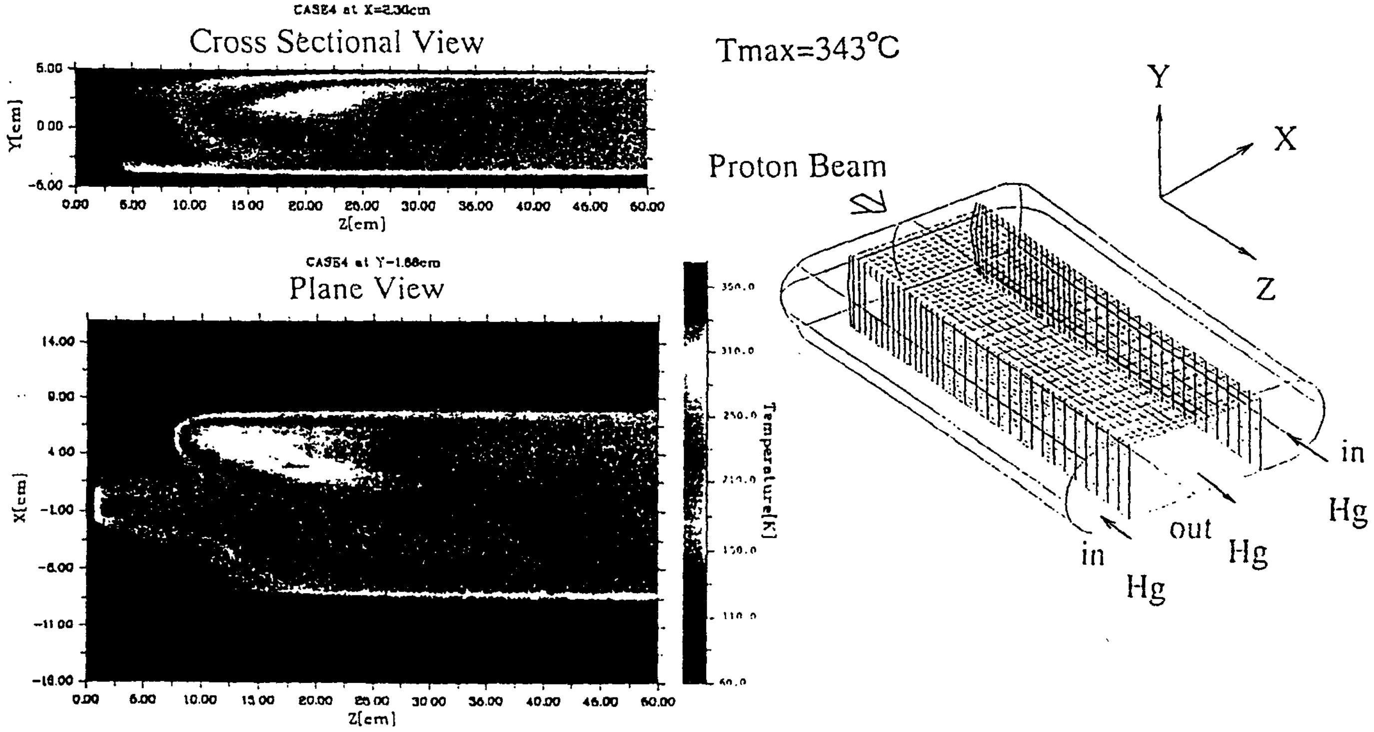


Figure 8 Temperature Profile of CASE-4