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Spallation Target Development at JAERI

- R&Ds on thermo-mechanical design -

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ABSTRACT

Rib-roughened plates for a solid target, a cross-flow and a return-flow type containers for a mercury target are proposed as design concepts through a preliminary conceptual design. To realize these concepts, analysis and experimental works are being carried out. This paper describes an outline of the present status of R&D for the target at JAERI such as heat transfer augmentation experiments for the solid target, mercury flow tests with a loop of maximum flow rate of 15 L/min, flow pattern measurements for a cold source moderator etc., as well as preliminary conceptual design works.

1. INTRODUCTION

The Japan Atomic Energy Research Institute (JAERI) has started the Neutron Science Project for utilizing high intensity neutrons relating to fundamental science and nuclear engineering by using a proton accelerator generating a high energy proton beam of 1.5 GeV with a high current of 3.3 mA to produce 5 MW. In the project, a neutron scattering facility is planed to be constructed first, where high intensity neutrons are generated at a target by spallation reaction between target materials and the proton beam. Since technology of a MW-scale target has not been established yet, development of a 5 MW spallation neutron source is one of the most difficult technical challenges in this project.

In the world, the European Spallation Source (ESS) Project in Europe [1] and the

Spallation Neutron Source (SNS) Project in the USA [2] are progressing with the construction of MW-scale target neutron scattering facilities, which are focused on mercury as the target material. Target concepts would be limited to those two types: a solid metal target like the ISIS at the Rutherford Appleton Laboratory in the UK, and the mercury target under conceptual design in the ESS and the SNS projects. While technology of the solid target, especially of KW-scale, has been established and could extend to MW-scale with minimum efforts, there is almost no technology base on the mercury target.

JAERI is going to develop two types of target, the mercury target as the main and the solid target as the backup. In the first step, targets will be operated under 1.5 MW proton beam power to adjust the accelerator system including the proton beam lines. In the 1.5 MW operation, the solid and the mercury targets will be installed in order to establish 5 MW-target technology and to accumulate technical data to improve their structures and performances. In the 5 MW operation following the 1.5 MW operation, the improved targets will be installed in the system. This two-step plan of target R&D was started in April 1997, when the Spallation Target Laboratory was organized at JAERI. This paper presents an outline of one-year activities on target R&D.

2. FRAMEWORK OF TARGET DEVELOPMENT

Figure 1 shows a concept of a mercury target system except moderators and reflectors. The proton beam is led into the target horizontally. The mercury target system consists of circulation pumps, heat exchangers, a surge tank, drain tanks and connecting pipes. Whole components are fixed on a trolley, and are covered by stainless steel plates in order to avoid the leakage of mercury to the environment surrounding the trolley. The trolley can be moved into a maintenance area during a maintenance period, and all components can be handled with remote handling devices.

To construct the target system, a framework as shown in Fig.2 was determined from an engineering viewpoint. The preliminary conceptual design prior to the conceptual design has been carried out with a close connection with both numerical analyses and experiments. After completion of the detailed engineering design based on the conceptual design results, demonstration tests using full-scale mock-up models, including remote handling devices, will be conducted to ensure the structural integrity and the safety aspects of the target system.

To promote conceptual design and analytical works effectively, a basic system of CAE - the computer aided engineering system- has been introduced. Hardware of CAE consists of three groups, analysis servers, personal computers and data servers. Drawings made by using Auto-CAD with the data server are entered into thermal-hydraulic and structural-strength analysis codes installed in the analysis server to analyze target performances. Using the CAE system, a preliminary conceptual design was carried out to define the specifications of the 1.5 MW / 5 MW target system with more than 30 neutron-beam ports. As a result, the system layout and solid/mercury target concepts were made clear. In the following chapter, an outline of the solid/mercury target concepts as well as R&D activities will be introduced.

3. SOLID TARGET

Figure 3 shows the solid target structure which is being designed on the basis of the existing target structure such as the ISIS. The solid target consists of heavy metal plates made of tungsten or tantalum, whose dimension is 140 x 100 mm, and these plates are cooled by heavy water. Cooling channels between plates are very narrow so as to decrease water volume ratio affecting the neutron yield. In the solid target design, channel height (water gap) is only 1.2 mm, and the water volume ratio to the target metal volume is kept less than 20%.

Figure 4 shows a heat density distribution generated in the tungsten target under 1.5 MW operation, which was calculated with a neutronic code systems NMTC/JAERI [3]. In the thermal-hydraulic and structural design, 20% higher values than the calculated results are used for keeping a wide margin on heat removal; it is necessary to verify this margin by estimating measurement and analytical evaluation errors. Figure 5 illustrates a relationship between plate thickness and heat flux estimated by the heat density distribution shown in Fig.4. Thickness of the target plate increases from 6 mm to 75 mm with an axial length. Then maximum heat flux is 2.9 MW/m^2, which is around 1/8 of the critical heat flux calculated with the Sudo correlation[4].

Using these results, plate temperatures were estimated under 10 m/s of water velocity. Then, heat transfer rates were calculated with the Dittus-Boelter correlation[5] which is available for smooth channels. As seen in Fig.6, surface temperature can be kept below 120℃, which is much lower than the saturation temperature of 1MPa, 180℃; the inlet pressure of the cooling channel is 2MPa and the pressure loss is estimated to 1MPa at maximum. From this result, it can be deducted that the target plates would be cooled down without the flow boiling. But, 10 m/s of water velocity is very high from an engineering viewpoint on flow induced vibration, erosion and flow distribution.

The heat transfer enhancement technique with micro ribs was focused on to decrease water velocity while keeping high heat transfer rates. This is because there is almost no heat transfer data and correlations available for the narrow channel like the target cooling channel. In order to deduce correlations for the target design, a simulated target cooling channel with micro ribs was fabricated as shown in Photo 1. Micro ribs of 0.2 mm in height (k) and width were formed on the surface in pitch (p) of

2 or 4 mm by using a NC machine tool. Water is able to flow in the test section at a maximum velocity of 20 m/s.

Figure 7 shows the relationship between the Nusselt number - dimensionless heat transfer rate - and the Reynolds number - dimensionless velocity - in the channel height of 1.2 mm. The Nusselt number of rib-roughened channel of p/k=10 is more than two times higher than that of the smooth channel when the Reynolds number is less than 20,000 which assumes the operational Reynolds number of the solid target. From this result, it can be expected to decrease water velocity down to 5 m/s while keeping the same plate temperatures as those in the smooth channel under 10 m/s of water velocity.

4. MERCURY TARGET

Figure 8 shows one of JAERI's concepts of the mercury target : a cross-flow type target using baffle plates. Mercury flows across the proton beam through baffle plates so as not to generate a recirculation flow which would make the mercury temperature rise excessively under high heat generation density. The target container will be made of SUS316 and its size presently under design is 590 mm in width, 120 mm in height and 1000 mm in length. Figure 9 shows thermal-hydraulic analysis results of the cross-flow type target using the baffle plates under a 5 MW (1.5 GeV, 3.3 mA) operation. A heat generation density distribution in the mercury target was calculated with the NMTC/JAERI code system[3] as well as the solid target. An inlet temperature of 323 K and a mercury flow rate of 50 m^3/h were assumed in the analysis. As shown in Fig.9, the recirculation flow was hardly observed as we expected. A maximum mercury velocity of 1.5 m/s and a maximum mercury temperature of 494 K were obtained in this case. Further analysis will be carried out to optimize flow patterns in the target vessel by changing configurations of baffle plates or other configuration such as bladed-frames to reduce the maximum temperature of mercury. .

In JAERI, the other type of target concept called "return-flow type", just like ESS or SNS, has also been proposed in the preliminary conceptual design as shown in Fig.10. The target container will be made of SUS316 and its size presently under design is 360 mm in width, 120 mm in height, 650 mm in target region length and 1550 mm in total length. The mercury flow rate of the return-flow type target should be smaller than that of the cross-flow type target to reduce the maximum velocity of mercury in the target. This is because, the cross-sectional area of the return-type target is less than that of the cross-flow type target. But it can not be reduced too much, because of the mercury temperature rise. As a results, 40 m^3/h was selected as the design flow rate for the return-flow type target.

All of the above target containers have an inner and an outer vessel. Almost all heat generated in the beam windows are expected to be removed by heavy water flowing through a narrow channel between the inner and the outer vessels. Table 1 summarized the merits and demerits of both cross-flow type and return-flow type target concepts. The cross-flow type target container has an advantage from the viewpoint of temperature and velocity. On the other hand, the return-flow type has an advantage from the viewpoint of container size and flow distribution. During the conceptual design period, both types of target containers will be investigated together in relation with the neutron yield and then will be integrated into one concept making use of each advantages.

A pressure wave which is one of the most critical issues for the mercury target design has also been analyzed during the preliminary conceptual design period. Figure 11 shows one of two dimensional analysis results using a simple cylindrical container under 5 MW operation. A rectangular beam profile with uniform power distribution was assumed in the analysis. The target consists of a dome-shaped window and a cylinder of 200 mm in diameter, 1100 mm in length and 2.5 mm in wall thickness. SUS316 was used as a container material. Figure 13 shows pressure distribution in the target 26μs after a proton beam injection. At 26μs , the highest pressure of 93 MPa can be seen near the beam window. In the analysis, a maximum pressure of 97 MPa was generated at the beam window 10μs after the proton beam injection.

To effectively realize the above target concepts, as a first step, pressure loss and erosion characteristics will be measured using a mercury test loop. Figure 12 shows the flow sheet and an outer view of the mercury test loop. The maximum design flow rate of the mercury is 15 L/min. A test section of annular channel, 25 mm of an outer tube diameter, and 20 mm of an inner tube diameter, is used so as to measure the pressure loss and erosion rate under the velocity up to 1.5 m/s. Mercury is circulated by an electromagnetic pump (EMP), and flow-rate is measured with an electromagnetic flow meter (EMF). These components were fabricated on the basis of existing techniques developed for a fast breeder reactor cooled by liquid sodium. The loop was installed in a movable box enclosed tightly with acrylic plates and a steal tray. 20 liters of mercury were poured into the loop this April, and preliminary tests were carried out to check whether all the components were working properly. Figure 13 shows typical trend graphs of the loop operation and preliminary pressure loss measurement results. Flow rate oscillation shown in Fig.14(a) was caused by argon bubbles flowing through the loop. At this moment, EMF has not been calibrated yet. Therefore, the flow rates shown in Fig.14(a) and (b) are not correct. But as shown in Fig.14(b), pressure loss characteristics of the test section are consistent with those calculated by the Blasius' resistance formula. EMF will be calibrated soon by using an ultra sonic flow meter. This loop will be used efficiently for thermal-hydraulic and erosion experiments, safety experiments simulating transients and accident conditions, component development tests such as pumps, flow-meters, compact heat exchangers and so on.

5. COLD SOURCE MODERATOR AND TARGET MATERIAL

An other important component consisting included in the target system is a cold source moderator using supercritical hydrogen (1.5 MPa, 20 K). One of the major technical issues in the design is to keep structural strength of a moderator vessel made of aluminum alloy under 1.5 MPa and to prevent temperature rises more than 3 K for keeping a high neutron yield. Figure 14 shows a concept of JAERI's cold source moderator vessel - a supercritical hydrogen container. The vessel is a thin-walled structure supported with thin frames and inner plates. A twisted tape is installed inside the inlet pipe to obtain better heat removal performance on the bottom surface of the vessel. Most of supercritical liquid hydrogen flows through the inlet pipe towards the bottom of the vessel, but small amounts of flow bypass through small holes located at the bottom half of the inlet pipe to suppress recirculation flow in the vessel. To obtain optimum performance of the cold source moderator vessel, structural strength analyses coupled with neutronic analyses will be carried out soon to determine wall thicknesses in cases using forging aluminum alloy, such as A2014. Thermal-hydraulic analysis to determine flow patterns in the vessel will also be performed. While designing the moderator vessel with CAE, a test apparatus was fabricated to visualize flow patterns under water flow conditions in order to obtain design information on the occurrence of the recirculation flow affecting temperature rise. Figure 15 shows a flow diagram and an outer view of the test apparatus. The moderator is simulated with acrylic cylinders in order to visualize the recirculation flow behaviors generated by the jet flow from the inlet pipe using a laser imaging method (PIV system).

On the other hand, thermal shock caused by the pulsed proton beam has the potential to damage the structural integrity of the target and the moderator. Since there is almost no data to verify analysis codes, a pulsed heating apparatus was fabricated to obtain verification data as well as to clarify the thermal shock behavior. Figure 16 shows the pulsed heating apparatus for the target material test. Thermal shock is generated in a disk specimen of 30 mm in diameter and of 1 to 5 mm in thickness which are made of tungsten, SUS316 etc. by using a 0.1 μs-pulsed ruby laser beam. The thermal shock tests will be carried out soon.

6. CONCLUDING REMARKS

In this paper, solid/mercury target concepts and several topics on target R&D were introduced. The solid target consisting of rib-roughened tungsten or tantalum plates could be adopted to a 1.5 MW proton beam by heavy water cooling. A cross-flow type and a return-flow type containers proposed for the mercury target are identified their advantages and disadvantages, and will be improved through experimental works using a mercury test loop, pulsed heating tests etc. as well as structural and thermal-hydraulic analyses. On the other hand, a cold source moderator vessel of a thin-walled structure with a twisted tape is needed to optimize its design through further R&Ds on mechanical structure, thermal-hydraulics and neutronics.

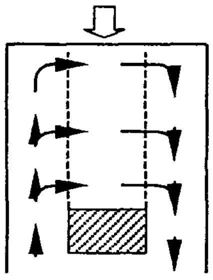
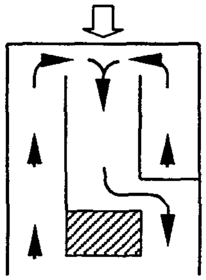
Acknowledgement

We are grateful to G. Bauer (PSI), Y. Takeda (PSI) , T. A. Broome (ISIS) and all the member of JAERI Neutron Science Project for helpful discussions of the target development.

References

[1] The European Spallation Source Study – Volume III. The ESS Technical Study, ESS-96-53-M(1996).
[2] National Spallation Neutron Source Conceptual Design Report, Volume I. The NSNS Collaboration, NSNS/CDR-2/V1(1997).
[3] Y. Nakahara and T. Tsutsui, JAERI-M 82-198(1982) (in Japanese).
[4] Y. Sudo, Trans. Japan Soc. Mech. Engrs., Ser.B63(608), 1305-1311(1997).
[5] Handbook of Heat Transfer, edited by W.M. Rohsenow and J.P. Hartnett, McGraw Hill, 7-32(1973).

Table 1 Comparison of mercury target between cross flow type and return flow type

Flow Type	Cross Flow Type Proton Beam 	Return Flow Type Proton Beam 
Max. Temperature	Low ○	High
Mercury Velocity	Low ○	High
Container Size	Large	Small ○
Flow Distribution	Complicated	Simple ○

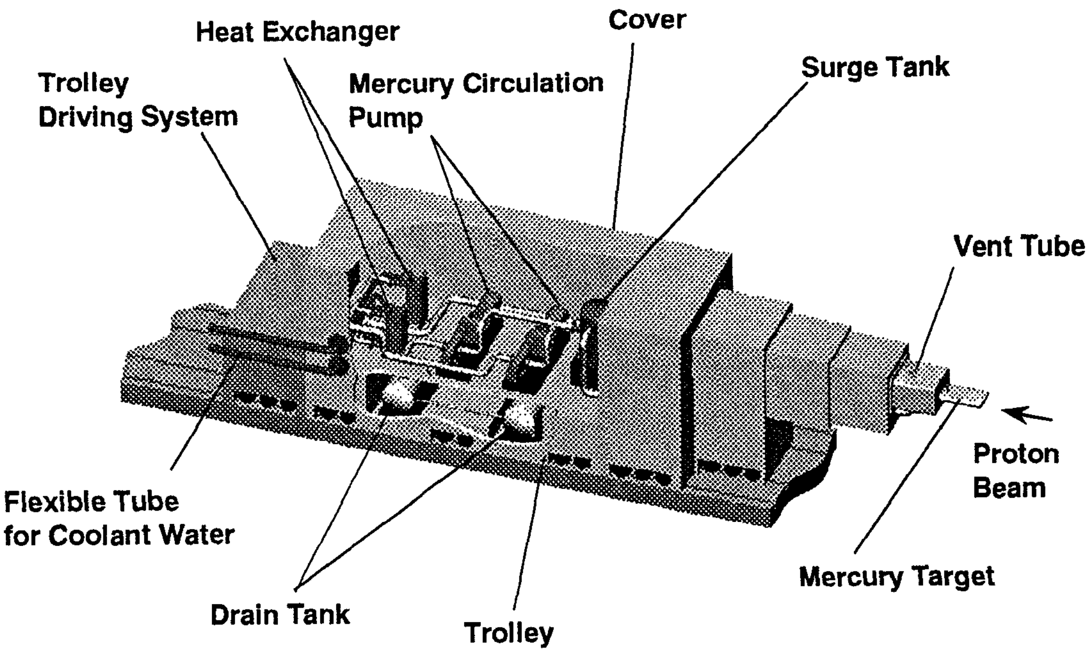


Fig.1 Conceptual design of spallation target system - Mercury target trolley -

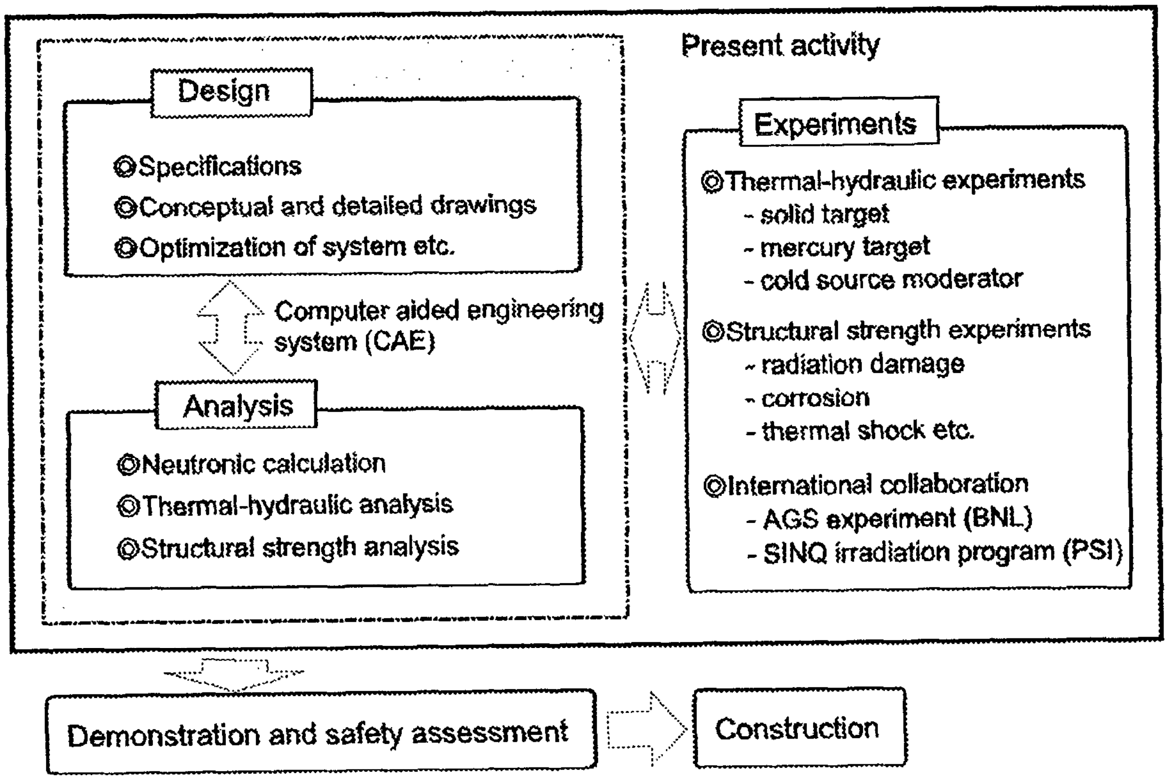


Fig.2 Framework of target development

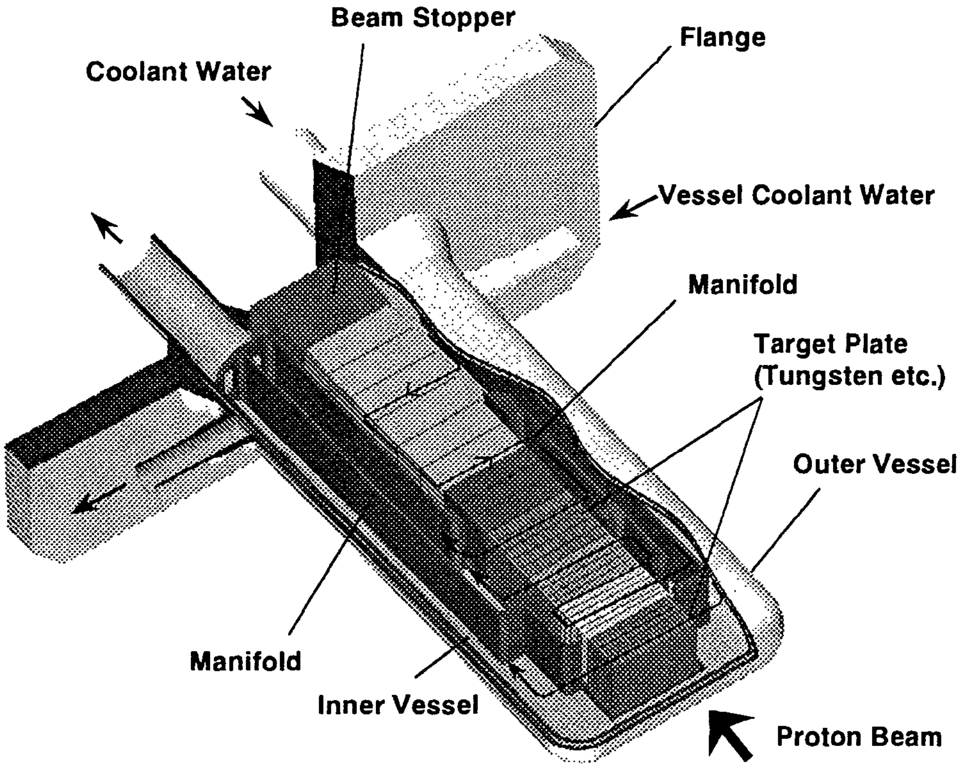
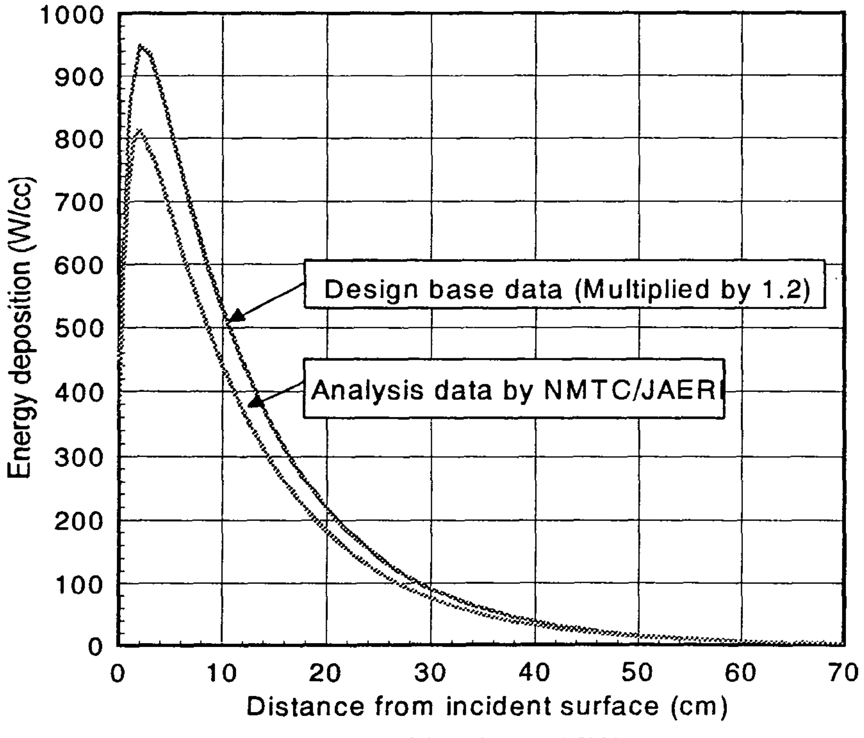
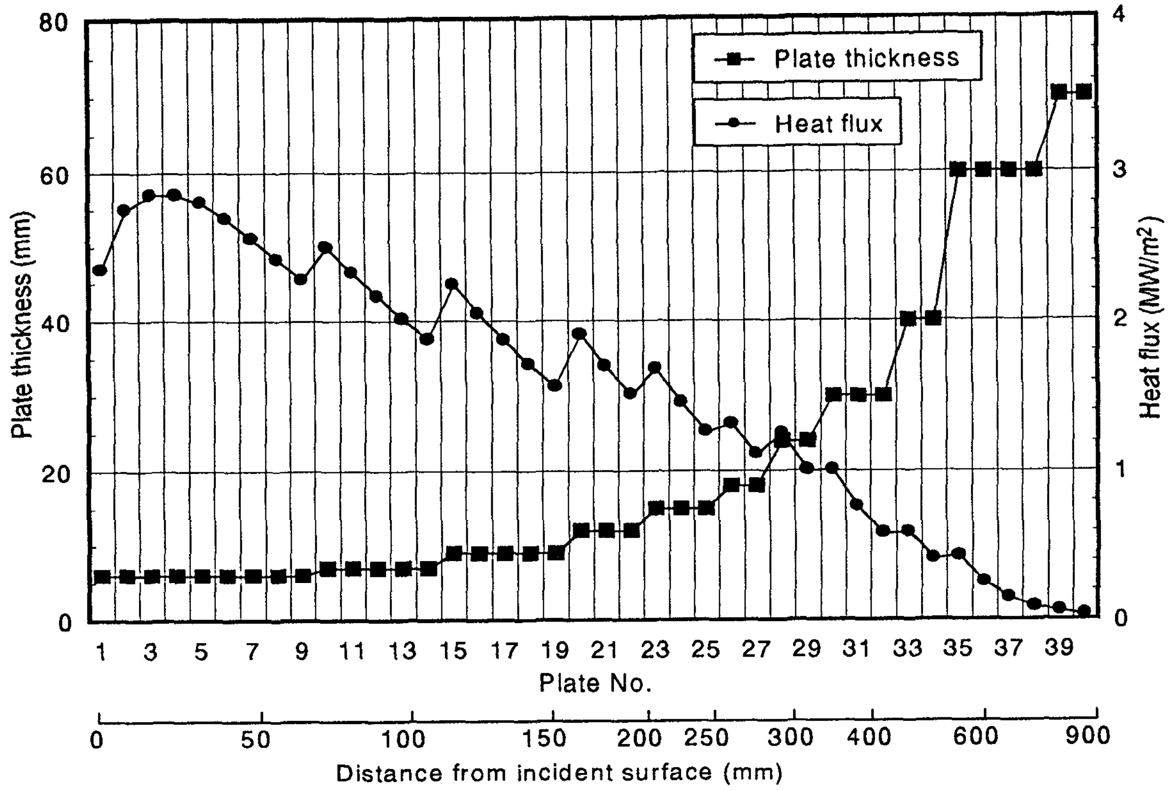


Fig.3 Cutaway view of solid target



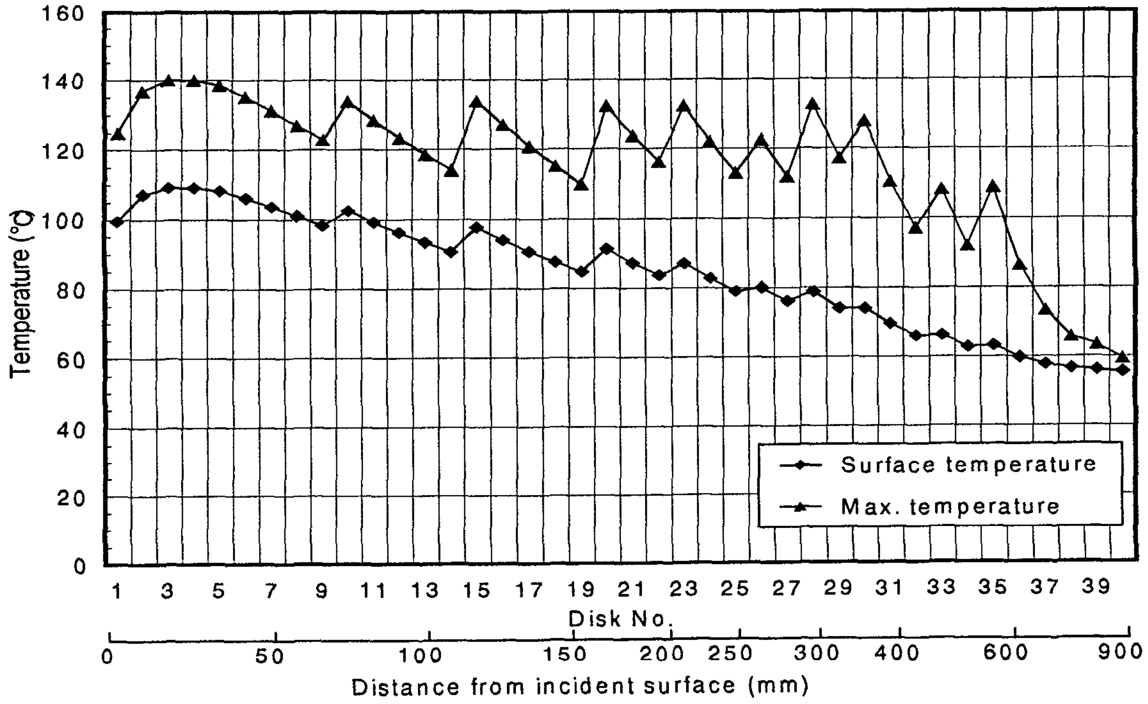
Axial energy deposition in 1.5MW tungsten target

Fig.4 Axial energy deposition in tungsten target under 1.5 MW proton beam incidence



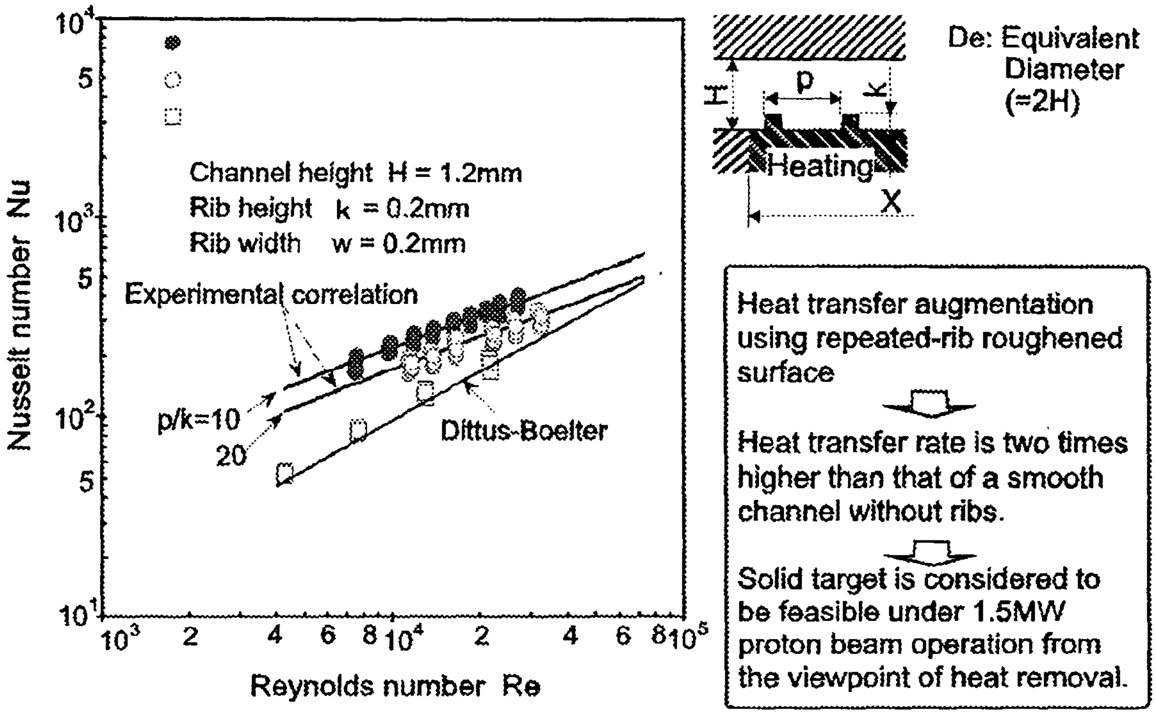
Relation between plate thickness and heat flux
(Tungsten , fromt plate thickness:6mm, coolant gap:1.2mm)

Fig.5 Relationship between plate thickness and heat flux (Tungsten target)



Surface and maximum temperatures of target disk
(tungsten , fromt disk thickness:6mm , coolant gap : 1.2mm)

Fig.6 Surface and maximum temperatures of target plates (Tungsten target)



Heat transfer augmentation using repeated-rib roughened surface

⇩

Heat transfer rate is two times higher than that of a smooth channel without ribs.

⇩

Solid target is considered to be feasible under 1.5MW proton beam operation from the viewpoint of heat removal.

Fig.7 Relationship between Nusselt number and Reynolds number - Experimental results of heat transfer augmentation with micro ribs-

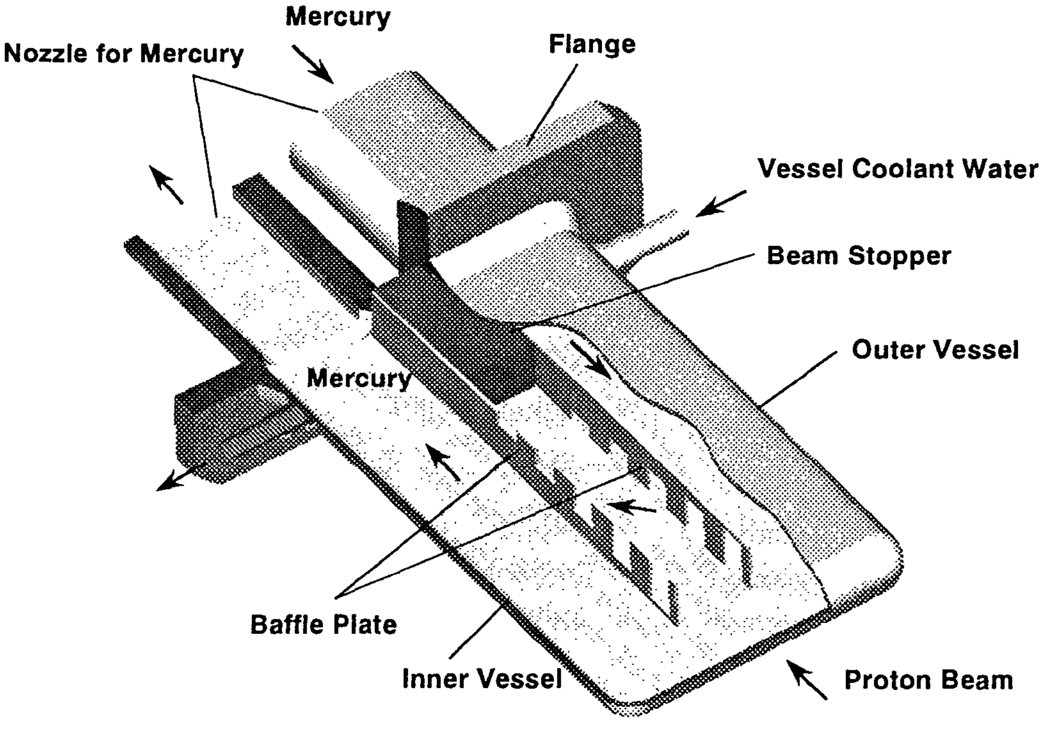
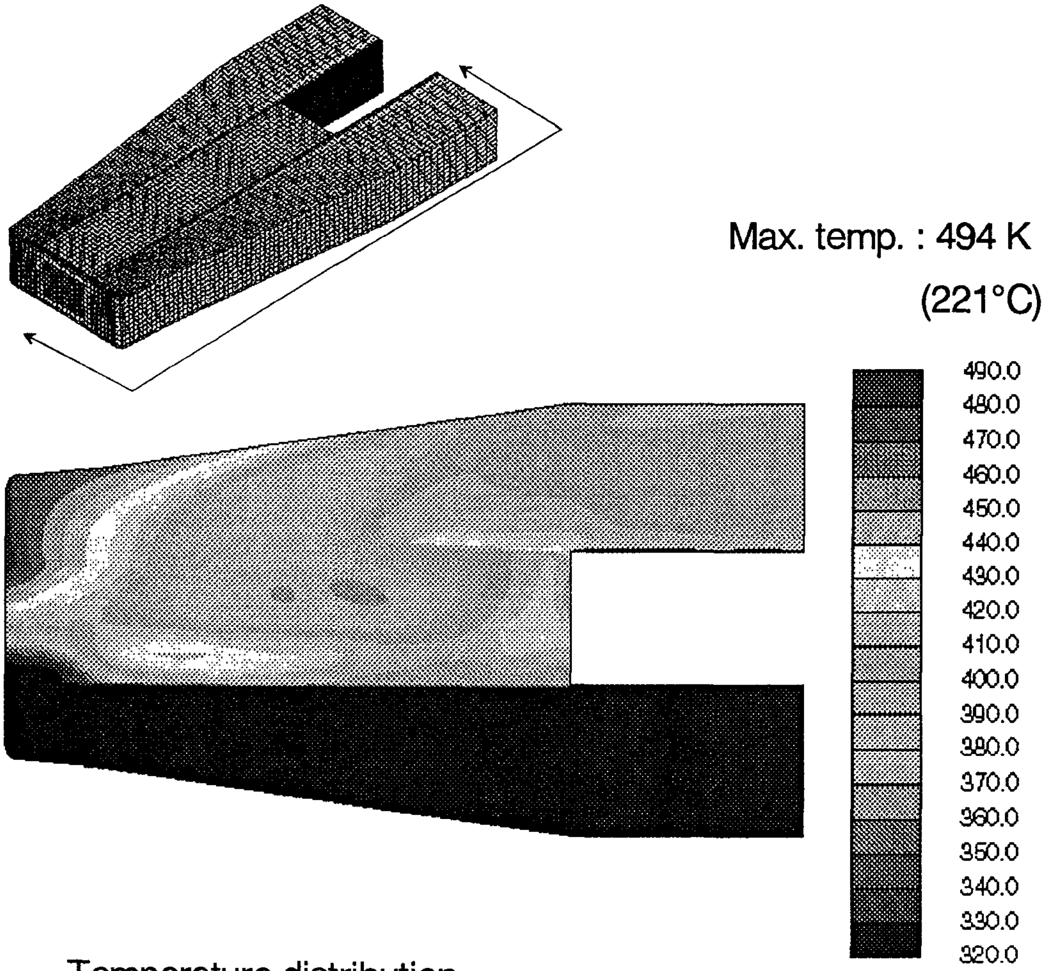
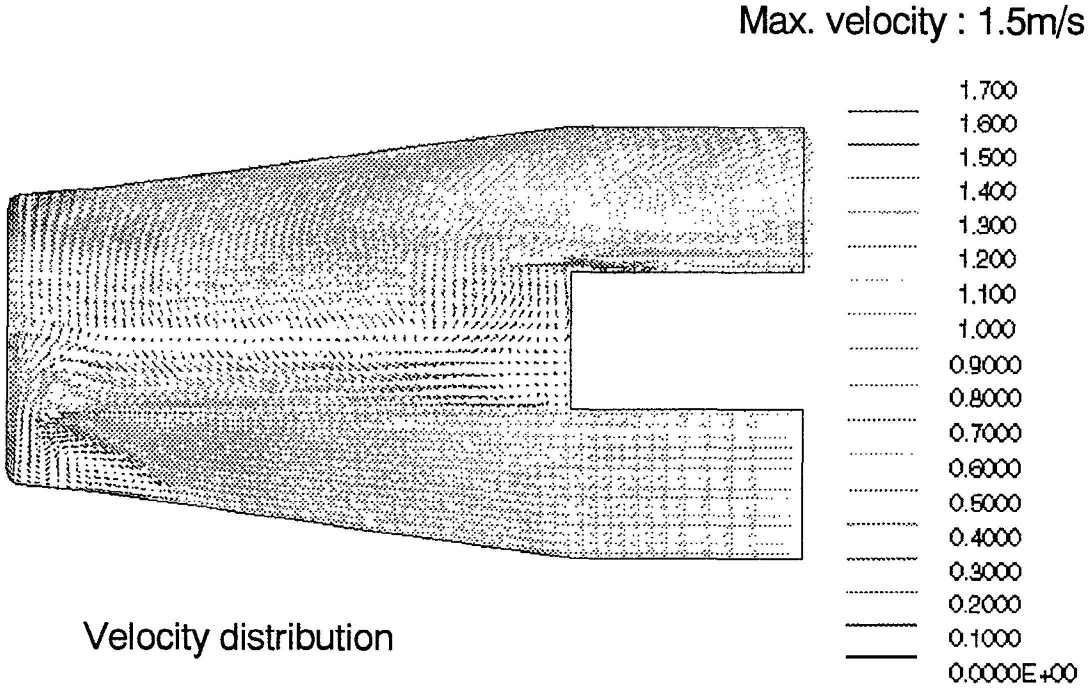


Fig.8 Cutaway view of mercury target -Cross flow type using baffle plates -



Temperature distribution



Velocity distribution

Fig.9 Thermal-hydraulic analysis results of cross flow type mercury target

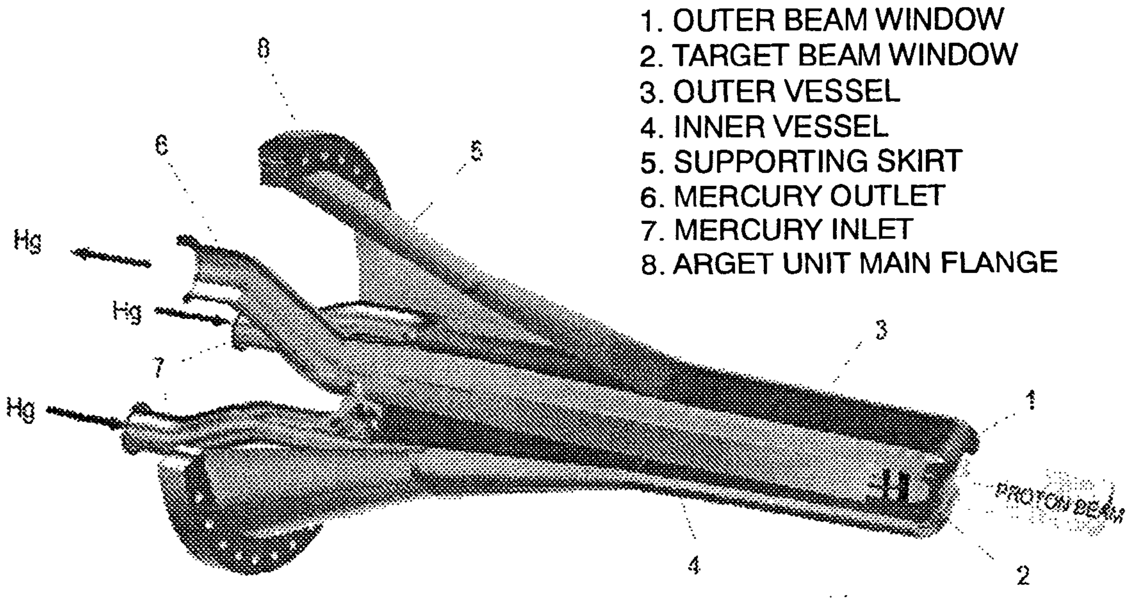


Fig.10 Cutaway view of mercury target - Return flow type

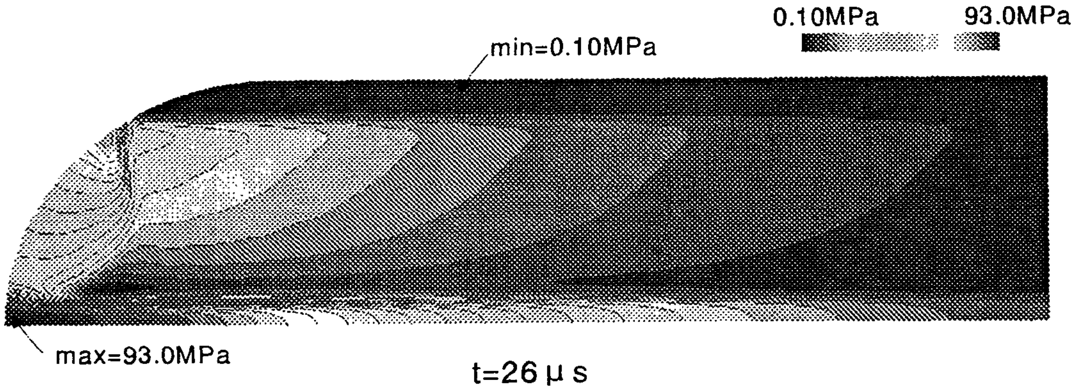
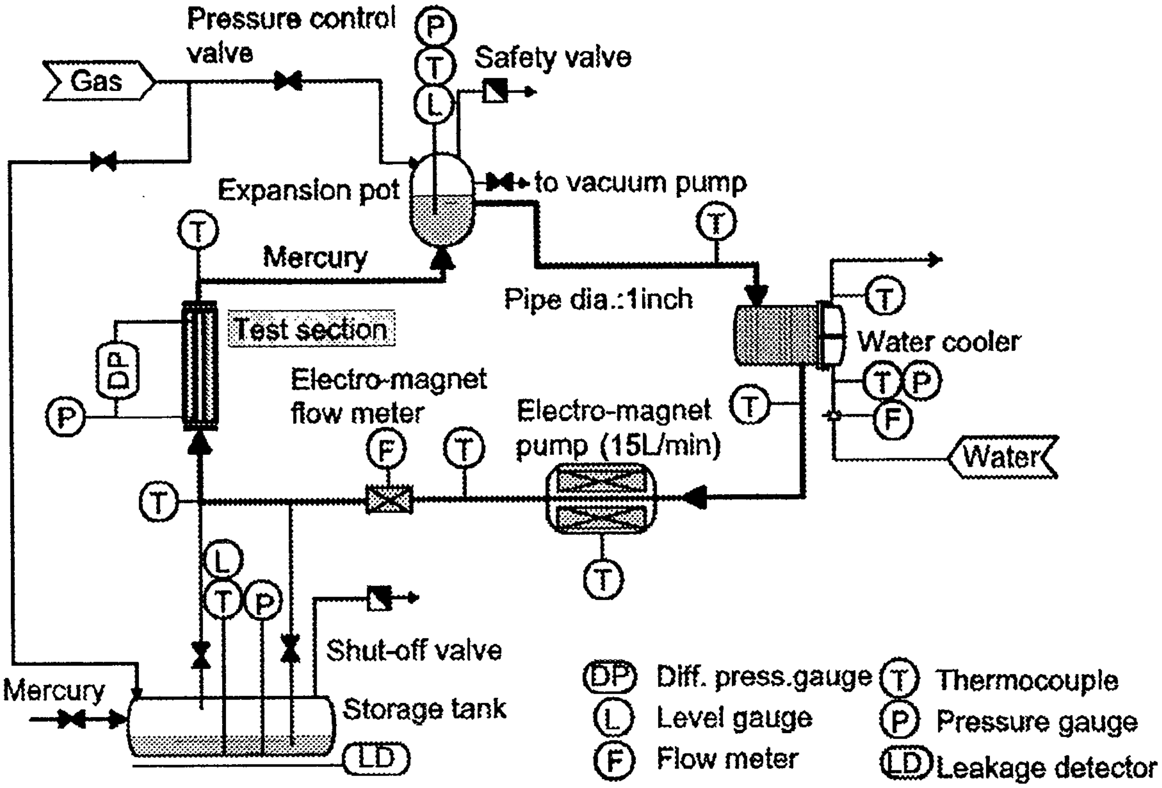
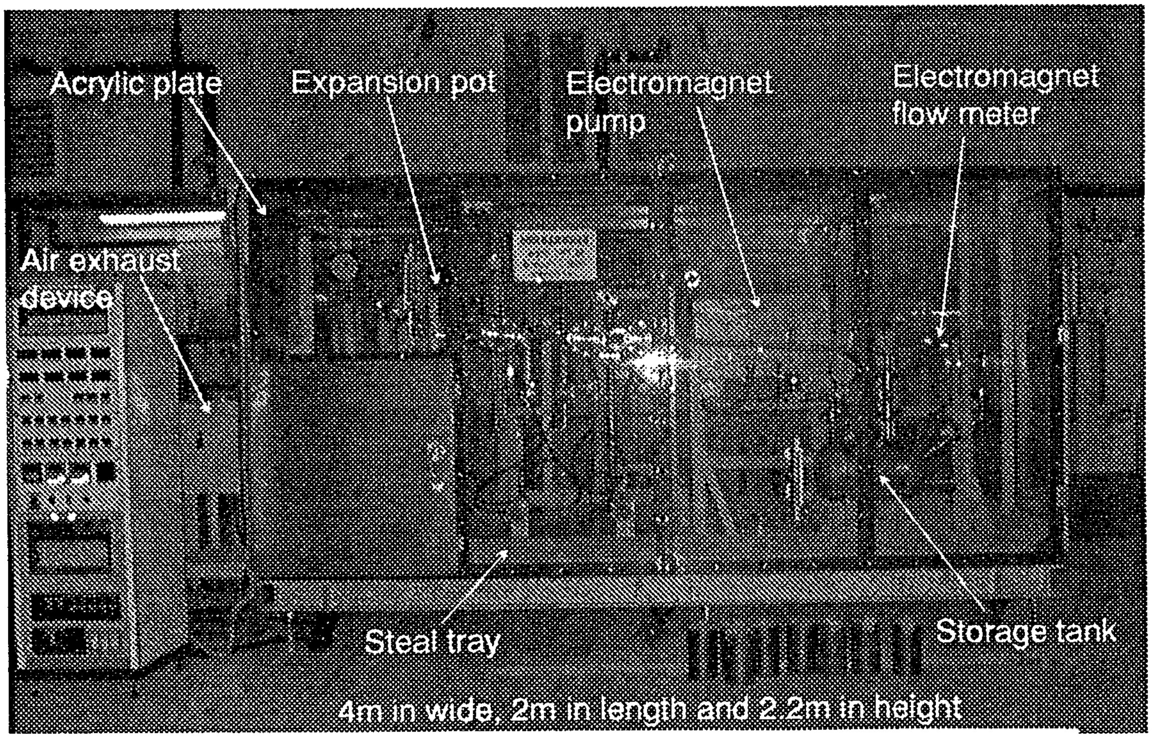


Fig.11 Pressure distribution in the 5MW mercury target
- Pressure contour after 26 μs from proton beam incident -

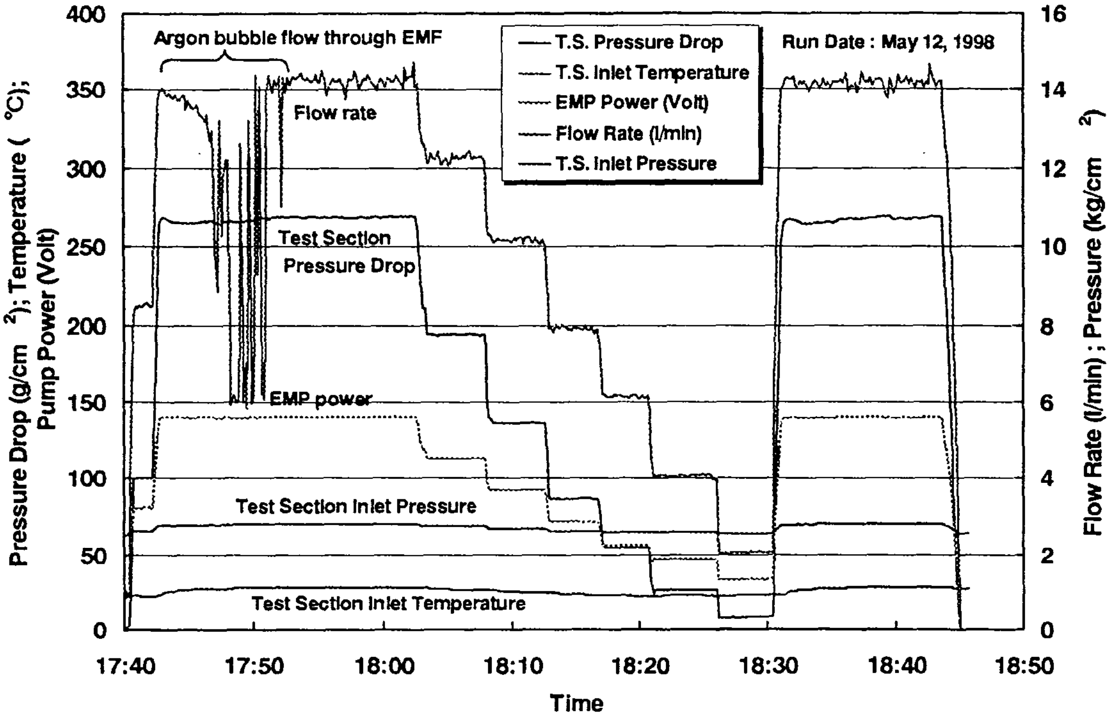


(a) Schematic flow diagram of mercury test loop

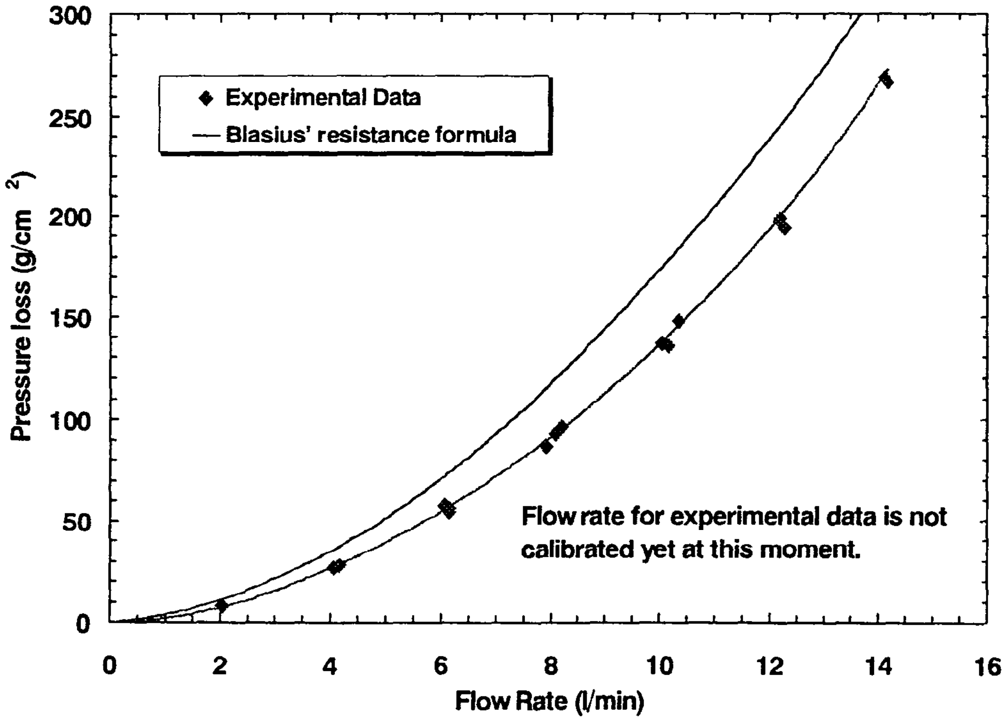


(b) Outer view

Fig.12 Schematic flow diagram and outer view of mercury test loop
Maximum flow rate: 15L/min , Maximum inventory : 400kg



(a) Typical trend graph during loop operation



(b) Pressure loss characteristics of a test section

Fig.13 Test results obtained by using a compact-sized mercury loop

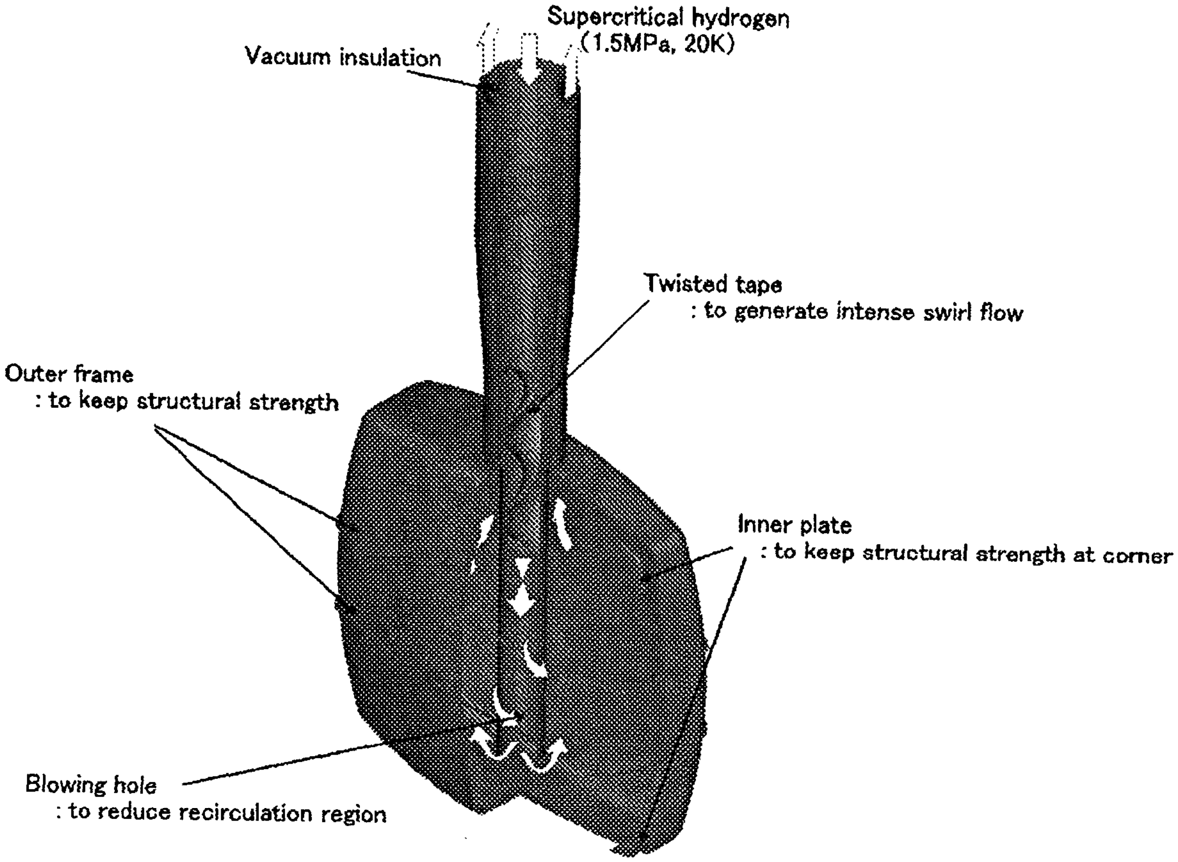


Fig.14 Concept of cold source moderator vessel

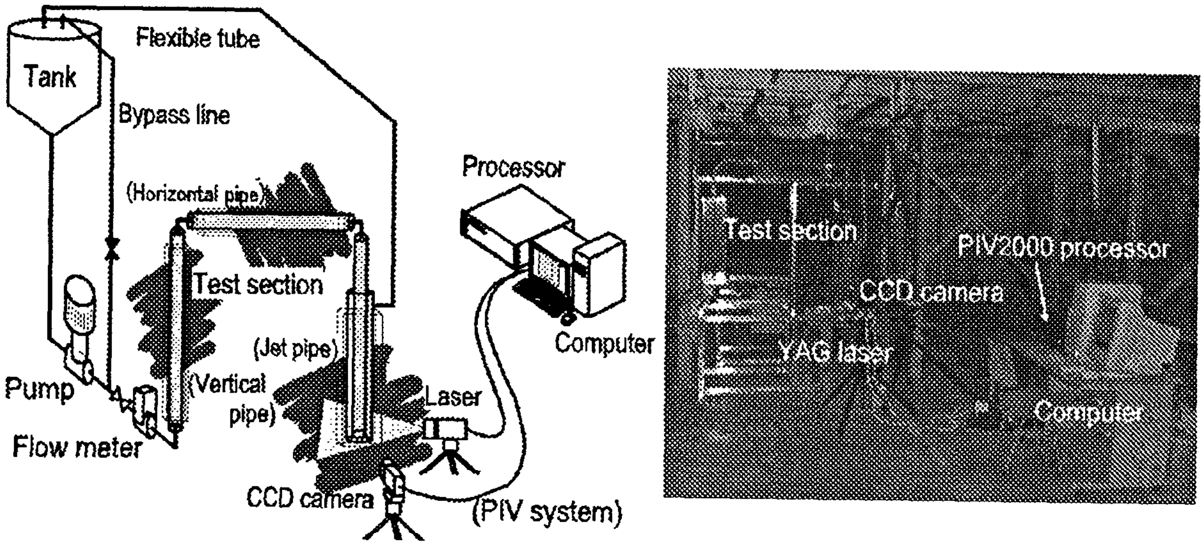


Fig.15 Experimental apparatus for flow pattern measurement

Main objectives

- Verification of analysis codes using experimental data of stress wave obtained by pulsed heating.
- Verification of countermeasures to mitigate amplitudes of stress wave.

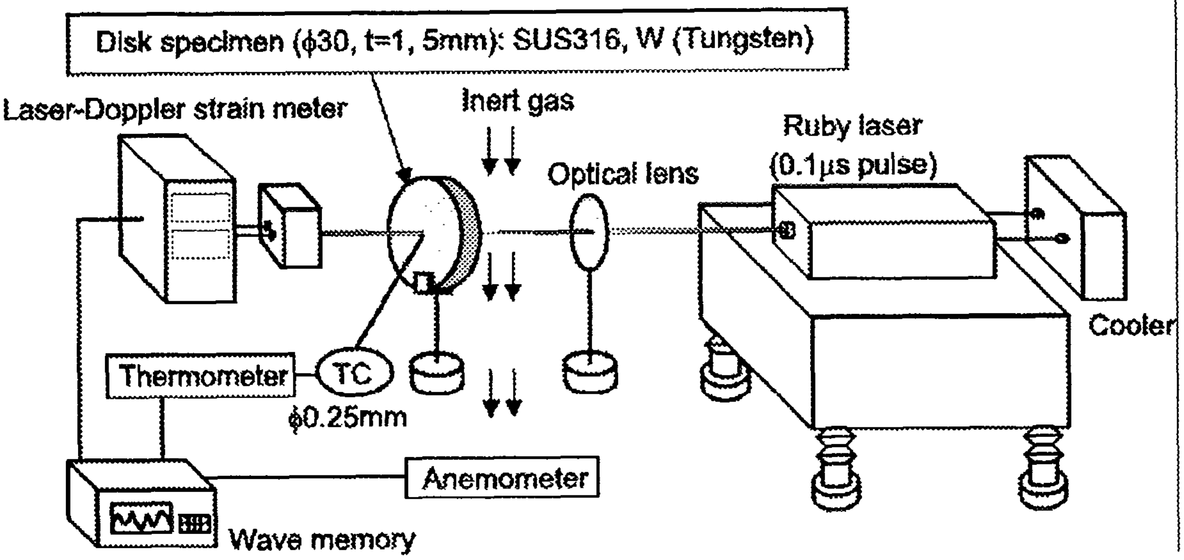


Fig.16 Pulsed heating test apparatus for target materials

Rectangular channel:
Channel height / width : 1.2 - 3.2mm / 20mm
Flow length : 250mm
heating length : 200mm
micro-rib : 0.2 x 0.2mm - 2, 4mm in pitch

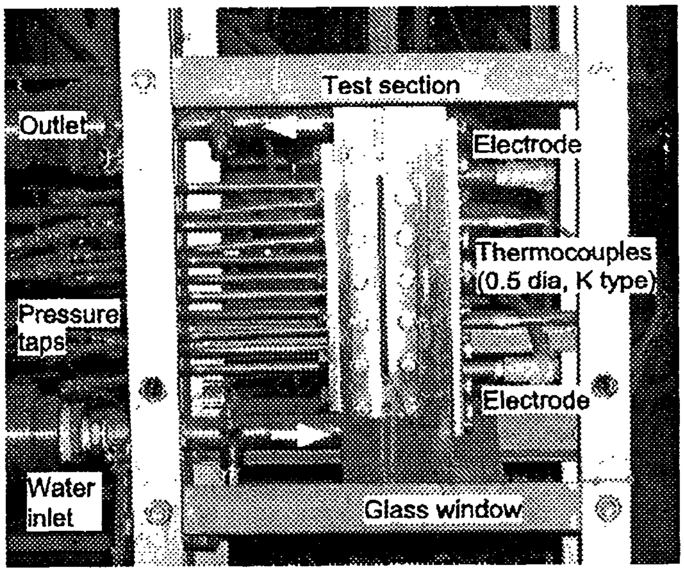


Photo 1 Test section for high heat flux removal transfer
- Simulated solid target cooling channel -