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# 23.5 Thermal-Hydraulic Design of Cross-Flow Type Mercury Target for JAERI/KEK Joint Project

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## Abstract

The Japan Atomic Energy Research Institute (JAERI) and the High Energy Accelerator Research Organization (KEK) are promoting a plan to construct a neutron scattering facility. In the facility, 1 MW pulsed proton beam from a high-intensity proton accelerator will be injected into a mercury target in order to produce high-intensity neutrons for use in the fields of life and material sciences. In the spallation mercury target system design, an integrated structure of target vessel with a safety hull was proposed to ensure the safety and to collect mercury in case of mercury leakage caused by the target beam window failure. The inner structure arrangement of the mercury target vessel was determined based on the thermal hydraulic analytical results of 3GeV, 1MW proton beam injection. The safety hull consists of vessels for helium and heavy water. The vessels for mercury target, helium and heavy water will be connected each other by reinforcement ribs mounted on the surface of each vessel. From the structural analyses, the structural integrity of the safety hull would be maintained under the static pressure of 0.5MPa.

## 1. Introduction

The Japan Atomic Energy Research Institute (JAERI) and the High Energy Accelerator Research Organization (KEK) are promoting a plan to construct a neutron scattering facility at Tokai Research Establishment, JAERI. In the facility, 1MW pulsed proton beam from a high-intensity proton accelerator will be injected into a mercury target in order to produce high-intensity neutrons for use in the fields of life and material sciences[1]. In the spallation mercury target system design, an integrated structure of target vessel with a safety hull was proposed to ensure the safety and to collect mercury in case of mercury leakage caused by the target beam window failure.

The inner structure arrangement of the mercury target vessel was determined based on the thermal hydraulic analytical results of 3GeV, 1MW proton beam injection. The mercury target currently under conceptual design adopted a cross-flow type (CFT) target vessel[2]. In the CFT target vessel, mercury crosses the main part of the target in order to remove heat generated by spallation reaction. The CFT target vessel has definite advantages with regards to the flow distribution, issues of erosion and structure strength. This is because the mercury flow in the main part of the CFT target vessel can be distributed according to heat generation distribution along the target length, the mercury velocity in main part of the CFT target vessel would be smaller than that in the SNS/ESS type target under the same mercury flow rate, blade flow distributors which form flow paths in the CFT target vessel could be used as the supports to increase vessel strength.

The safety hull consists of vessels for helium and heavy water. The vessels for mercury target, helium and heavy water will be connected each other by reinforcement ribs mounted on the surface of each vessel.

This paper presents a current status of the CFT target thermal hydraulic design using the blade flow distributors, CFD analytical results of the CFT target, an integrated structure of target vessel with a safety hull.

## 2. Thermal-Hydraulic Design of CFT Mercury Target

Table 1 shows the heat load on the mercury target currently under conceptual design for JAERI/KEK joint project. Thermal-hydraulic design criteria of the CFT mercury target for JAERI/KEK joint project are as follows.

(a) Maximum mercury temperature in the target shall be less than 300 °C.
(b) Maximum target vessel temperature shall be less than 200 °C.

In the thermal-hydraulic design of the CFT mercury target, the blade flow distributors were arranged in order to obtain appropriate mercury flow distribution by CFD analysis[2]. The flow distribution in the axial center of the CFT mercury target was adjusted to be the same as the volumetric heat generation along the axial length of the CFT mercury target while suppressing recirculation or stagnant flows in order to avoid generating hot spots. Figure 1 shows cutaway view of CFT mercury target with a safety hull. The CFT target vessel will consist of a single vessel for less than 2MW operation and will consists of double vessels for up to 5 MW operation. Mercury enters into the target from the furthest side from the beam window, and flows along the blade flow distributor in the inlet plenum toward each end of the blade, and then crosses over the proton beam and returns back through the outlet plenum along the blades. Heat generated in the beam window will be removed by bulk mercury flow for 1MW operation. The target vessel will be made of 316-stainless steel and its size presently under design is 260 mm in width, 80 mm in height at the front of the target and 800 mm in effective length. The effective volume of the CFT target will be about 23 L.

Table 1 Heat loads on CFT mercury target for JAERI/KEK joint project

| | | 1st stage | 2nd stage |
|---|---|---|---|
| Proton Energy | (GeV) | 3.0 | 3.0 |
| Proton Current | (mA) | 0.333 | 1.67 |
| Pulse Frequency | (Hz) | 25 | 50 |
| Pulse Duration | ($\mu$s) | 1.0 | 1.0 |
| Heat Deposited in Target | (%) | 54.7 | 54.7 |
| **Average Heat Load** | | | |
| Total Beam Power | (MW) | 1.0 | 5.0 |
| Total Power in Target | (MW) | 0.55 | 2.74 |
| Maximum Volumetric Heat Generation Rate in Mercury (Power Density) | ($MW/m^3$) | 372 | 1861 |
| **Loads During a Single Pulse** | | | |
| Energy Deposited in Target per Pulse | (kJ) | 21.9 | 54.7 |
| Maximum Energy Density in Mercury | ($MJ/m^3$) | 14.9 | 37.2 |
| Maximum Pulse Temperature Rise | (°C) | 8.0 | 20.0 |
| Maximum Instantaneous Volumetric Heat Generation Rate in Mercury (Power Density) | ($GW/m^3$) | 14,880 | 37,220 |
| Max. Instantaneous Rate of Temp. Rise | (°C/sec) | $8.0 \times 10^6$ | $20.0 \times 10^6$ |

Figure 2 shows the volumetric heat generation rate in the target along the target axial length used in the CFD analysis for thermal-hydraulic design of CFT mercury target. These volumetric heat generation rates were calculated for the proton beam energy at 3.0 GeV by a neutronic code system NMTC/JAERI and NCMP-4A[3]. 30% of margin was already included in these heat generation rates. The proton beam profile currently assumed in the design is a rectangular shape of 13 cm x 5 cm with a uniform current of $5.1\mu A/cm^2$. The peak value is around $0.37\ kW/cm^3$ for 1MW operation.

Figure 3 shows three-dimensional CFD analytical results of the velocity and temperature distribution in the CFT mercury target. Mercury inlet temperature of 50 °C, which is the maximum temperature of the mercury target, mercury flow rate of 40 $m^3/h$ and an average inlet velocity of 1m/s were used in the analysis for 1MW operation. CFD analyses were carried out by STAR-CD code. In the analyses, the standard k-$\varepsilon$ turbulence model was used. As for the turbulent Prandtl number 1.5 was assumed. In the analysis, the vessel outside boundary condition was assumed to be thermally isolated.

A maximum velocity of 2.5 m/s was observed near the front end of the oultet plenum. On the other hand, a maximum temperature of 130.1 ℃ was observed in the center of the target where the volumetric heat generation rate was relatively small. This is because due to the recirculation flow in this region.. The maximum temperature of 130.1 ℃ is far below the mercury saturation temperature of 356 ℃ under atmospheric pressure. This result satisfied the thermal-hydraulic design criteria of "Maximum mercury temperature in the target shall be less than 300 °C".

Figure 4 shows inner and outer surface temperatures of the mercury target vessel analyzed by STAR-CD code. Vessel thickness at the proton beam window will be 2.5 mm in order to decrease thermal stress caused by temperature difference between inner and outer surfaces, while keeping sufficient structural strength against the stress caused by inner pressure , pressure wave etc. Maximum outer surface temperature was obtained at the beam window and was calculated to be 190.1 °C. On the other hand, maximum inner surface temperature was calculated to be 149.4 °C as shown in Fig.4. This result satisfied the thermal-hydraulic design criteria of "Maximum target vessel temperature shall be less than 200 °C".

## 3. Structural Strength Analysis of Integrated CFT Target with Safety Hull

In the spallation mercury target system design, safety is a first priority of the system. In order to ensure the safety of the target system, an integrated structure of target vessel with a safety hull was proposed for collecting mercury in case of mercury leakage caused by the target vessel beam window failure as shown in Fig.5. The safety hull consists of vessels for helium and heavy water as describes above. The vessels for mercury target, helium and heavy water will be connected each other by reinforcement ribs mounted on the surface of each vessel by welding. During the structural strength analyses, arrangement of reinforcement ribs were changed in order to decrease the stress and displacement of each vessel[4].

Feasibility study of the integrated mercury target vessel with the safety hull was carrid out preliminary in order to clarify structural integrity of the vessels. Structural strength of the integrated mercury target vessel under static pressure condition of 0.5 MPa, which is the maximum design operating pressure of the mercury target system, was analyzed by using ABAQUS code. In the analysis, allowable stress of 316-stainless steel 142.5 MPa at 300 °C was compared with static-stress analytical results. Maximum allowable displacement of 1mm was used as one of the design criteria for the CFT target vessel.

Figure 6 shows stress and displacement analytical results of the mercury target vessel under the static pressure condition of 0.5 MPa. Maximum stress is appeared on the center line of the vessel and is calculated to be 53.6 MPa. On the other hand, the maximum displacement of the vessel is appeared near the front of the vessel and is calculated to be only 0.17 mm.

Figure 7 shows stress and displacement analytical results of the helium vessel which is an inner vessel of the safety hull under the static pressure condition of 0.5 MPa. Maximum stress is appeared in the front part of the center region of the vessel and is calculated to be 125 MPa. On the other hand, the maximum displacement of the vessel is appeared near in the center region of the vessel and is calculated to be 0.32mm.

Figure 8 shows stress and displacement analytical results of the heavy water vessel which is an outer vessel of the safety hull under the static pressure condition of 0.5 MPa. Maximum stress is appeared in the front part of the center region of the vessel and is calculated to be 111.7 MPa. The maximum displacement of the vessel is appeared near the region where the maximum stress was obtained and is calculated to be 0.2 mm.

From the above results, stress and displacement analytical results meet the our design criteria of the integrated mercury target vessel with the safety hull. At present, integrated stress analyses including stress caused by pressure wave, static and dynamic thermal stress etc. have not been performed yet. These analyses will be carried out soon in order to feasible the integrated mercury target vessel.

## 4. Concluding Remarks

In the spallation mercury target system design, an integrated structure of target vessel with a safety hull was proposed to ensure the safety and to collect mercury in a case of mercury leakage caused by the target beam window failure. The inner structure arrangement of the mercury target vessel was determined based on the thermal hydraulic analytical results of 3 GeV, 1 MW proton beam injection. The safety hull consists of vessels for helium and heavy water. The vessels for mercury target, helium and heavy water will be connected each other by reinforcement ribs mounted on the surface of each vessel. As for the feasibility of the integrated mercury target vessel with the safety hull, the static structure strength analyses were carried out under the condition of an internal pressure of 0.5 MPa, which was the maximum operation pressure of the target system, in order to clarify its structural strength. As a result, it was made clear that the maximum static stress appeared on the each vessel by the internal pressure could be suppressed less than the allowable stress of SUS316L at 300 °C, 142.5 MPa, by adding reinforcement ribs on the surface of each vessel.

## References


[1] The Joint Project for High-Intensity Proton Accelerators, JAERI-Tech 2000-003, (2000).

[2] M. Kaminaga, A. Terada, S. Ishikura, M.Teshigawara, Y. Sudo and R. Hino, "Mercury Traget Development for JAERI Spallation Neutron Source", Proc. of the 7th Int. Conf. on Nucl. Eng. (ICONE-7), Tokyo, Japan, Paper No. 7123, JSME No.99-201, (1999).

[3] M. Teshigawara, Private Communication (1999).

[4] M. Kaminaga, A. Terada, K. Haga, H. Kinoshita, S. Ishikura and R. Hino, "Study of Intergated Structure of Mercury Target Containar with Safety Hull", JAERI-Tech (To be published), (2000).

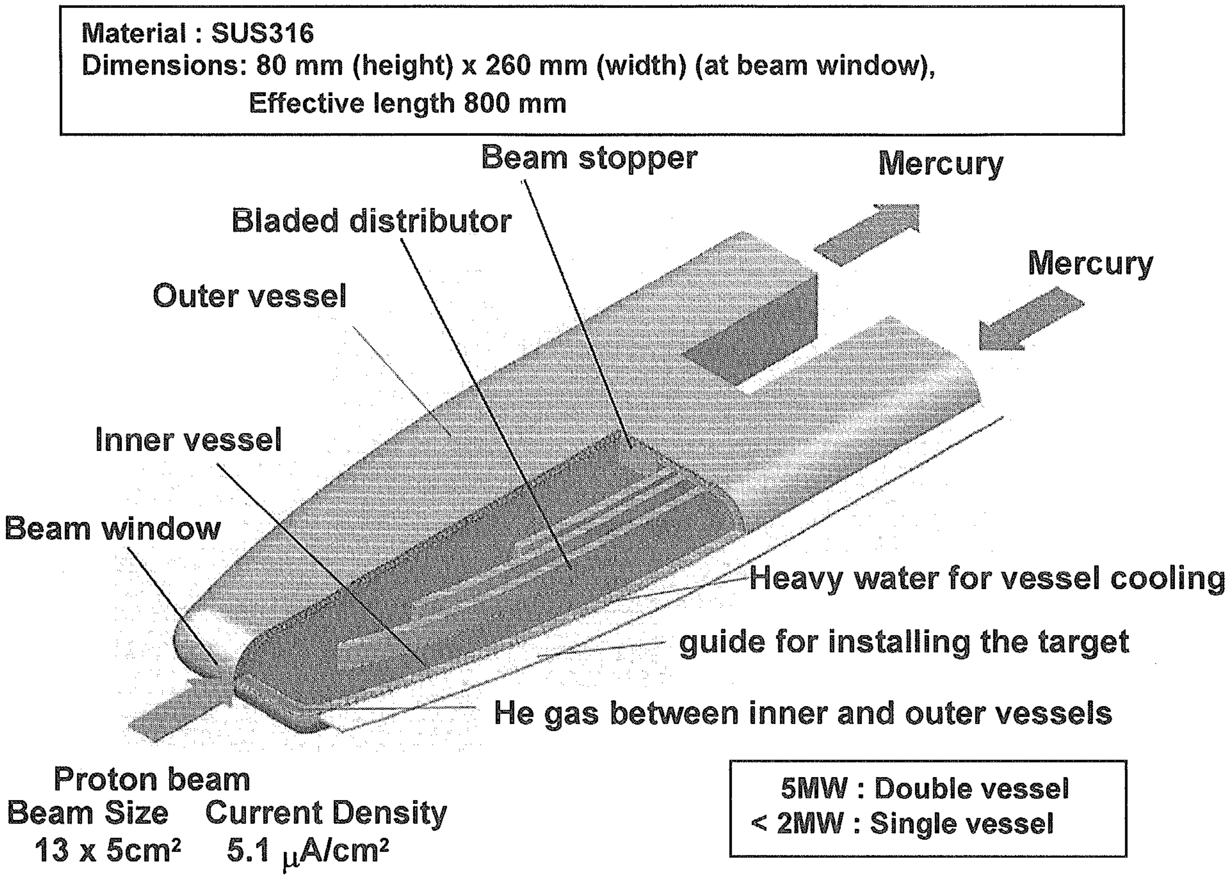
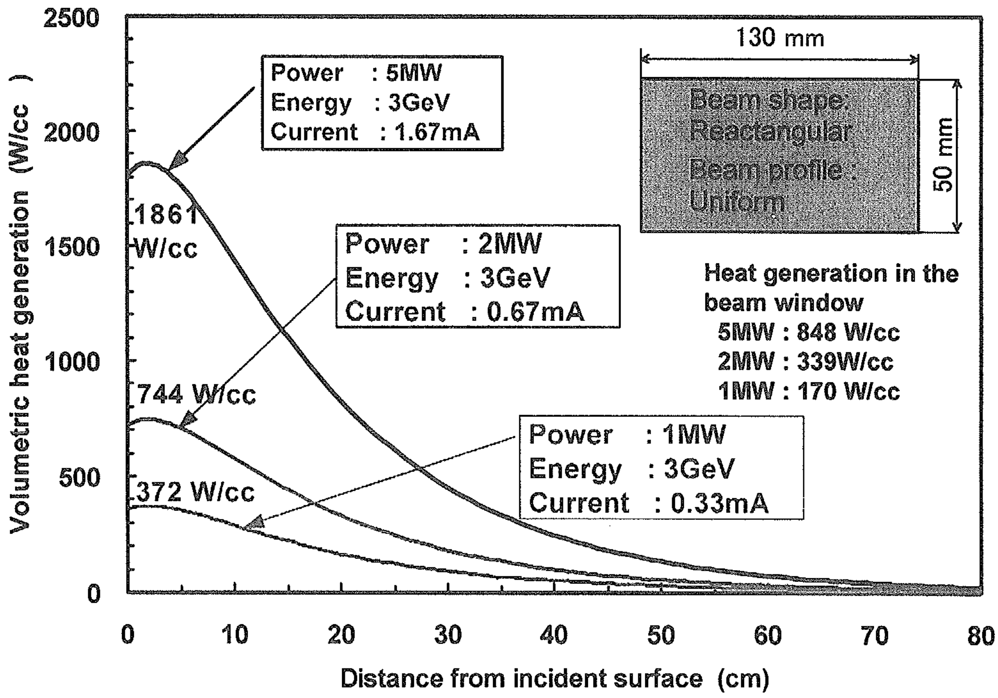
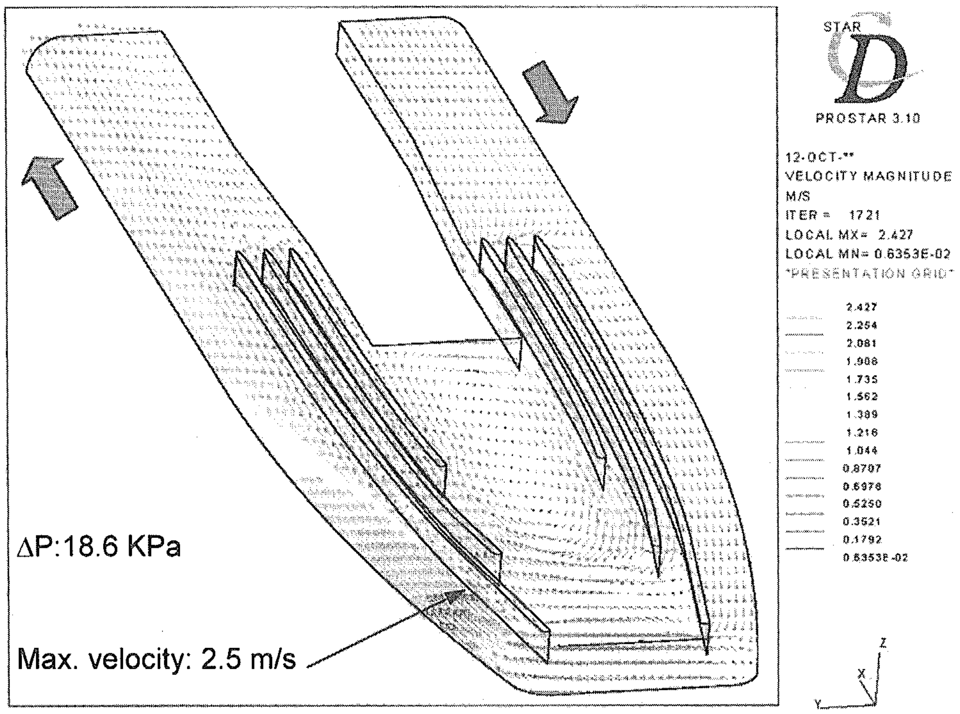



Figure.1 Cutaway view of cross-flow type mercury target with safety hull

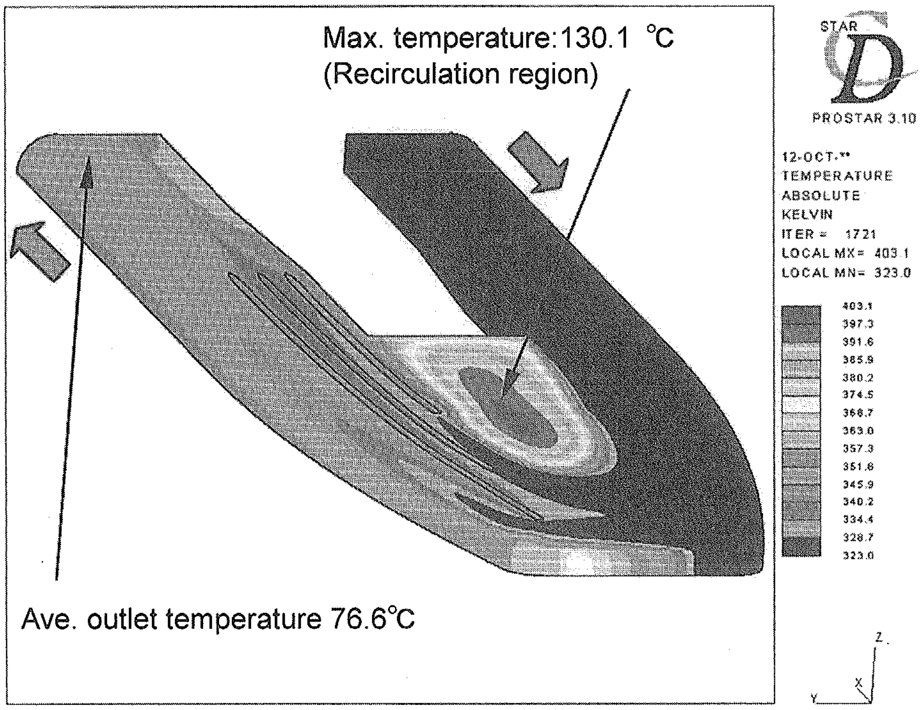



**(54.7 kJ of heat deposit per pulse was assumed [ 30% of margin included])**

Figure.2 Volumetric heat generation along the axial length of mercury target

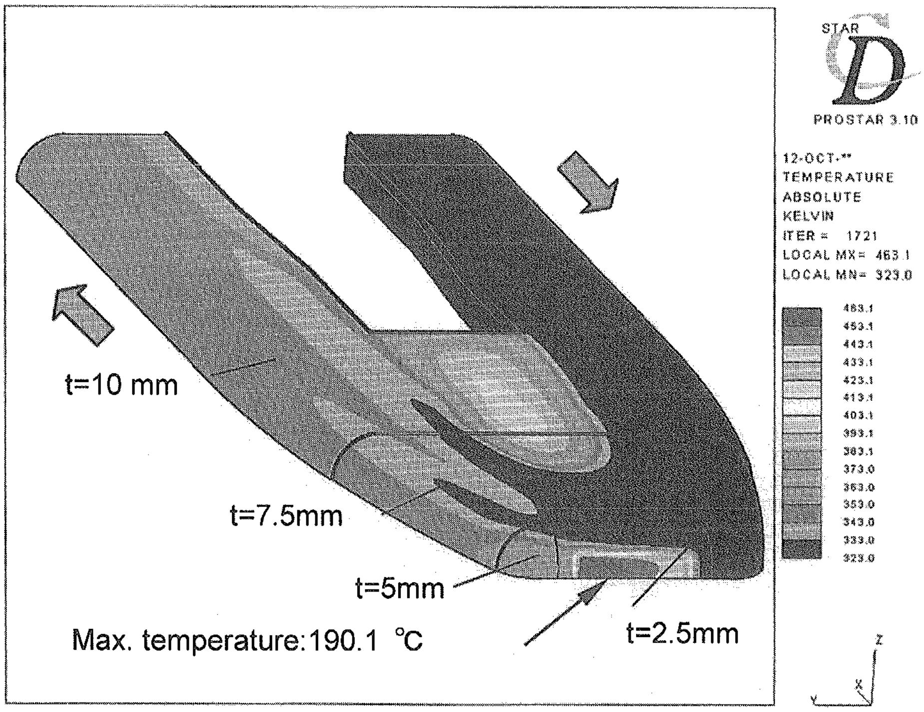



(a) Velocity distribution

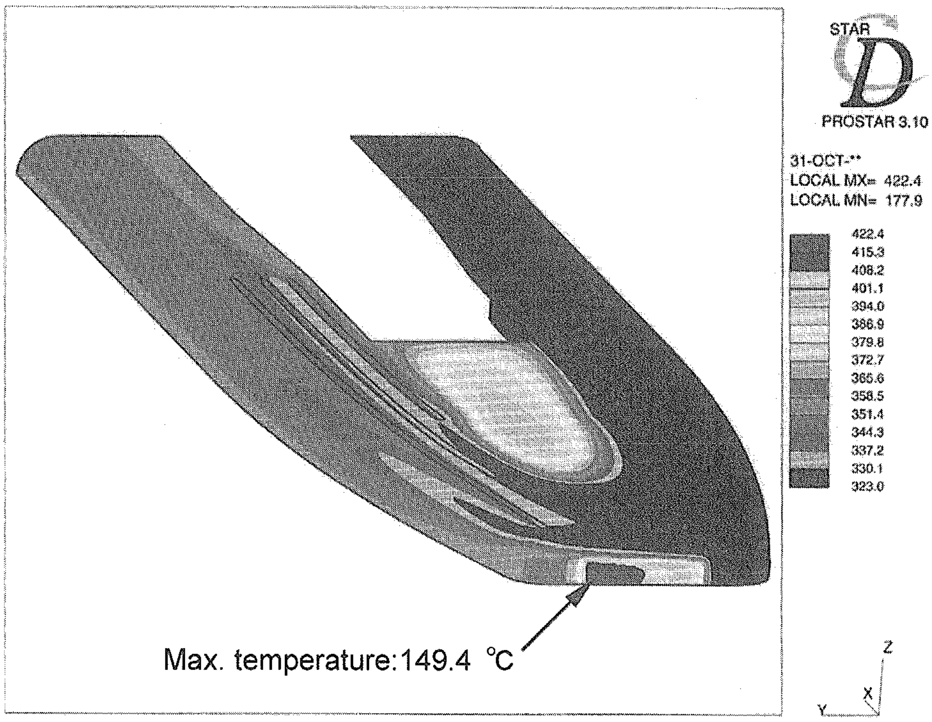



(b) Temperature distribution

Figure.3 Analytical results of velocity and temperature distribution in the CFT target under the 1MW operation (Inlet mercury velocity:1m/s)

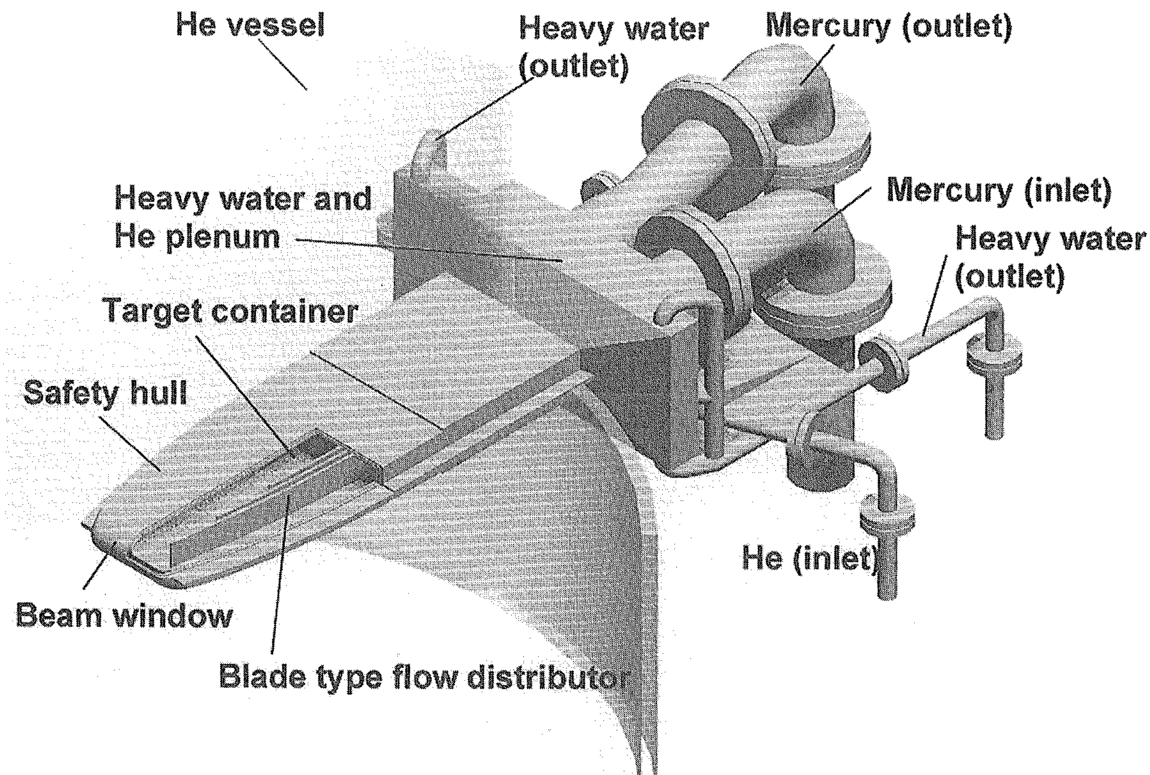



(a) Outer surface temperature distribution




(b) Inner surface temperature distribution

Figure 4 Analytical results of inner and outer surfaces of the CFT target vessel under the 1MW operation (Inlet mercury velocity:1m/s)




**Material** : **SUS316L**
**Dimensions : Target vessel 80mm(height), 200-500mm(width), Effective length800mm**
**Safety hull 100mm(height) , 300-650mm(width), length1500mm**

Figure 5 Outer and cutaway view of integrated CFT mercury target with safety hull

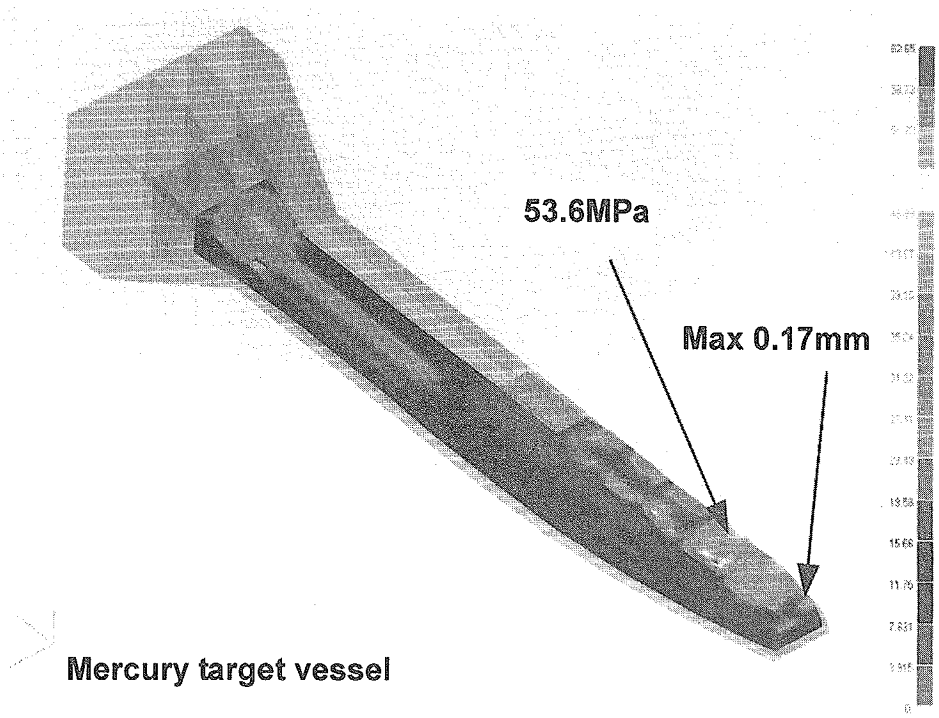



Figure 6 Structural analysis results of mercury vessel under static pressure of 0.5MPa

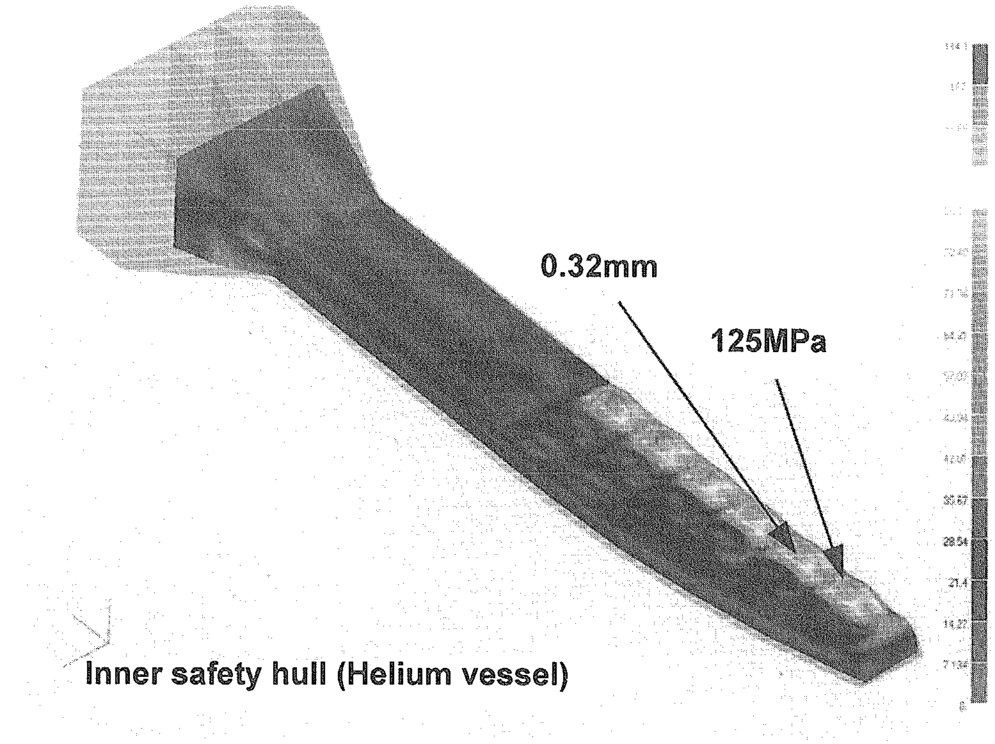



Figure 7 Structural analysis results of helium vessel under static pressure of 0.5MPa

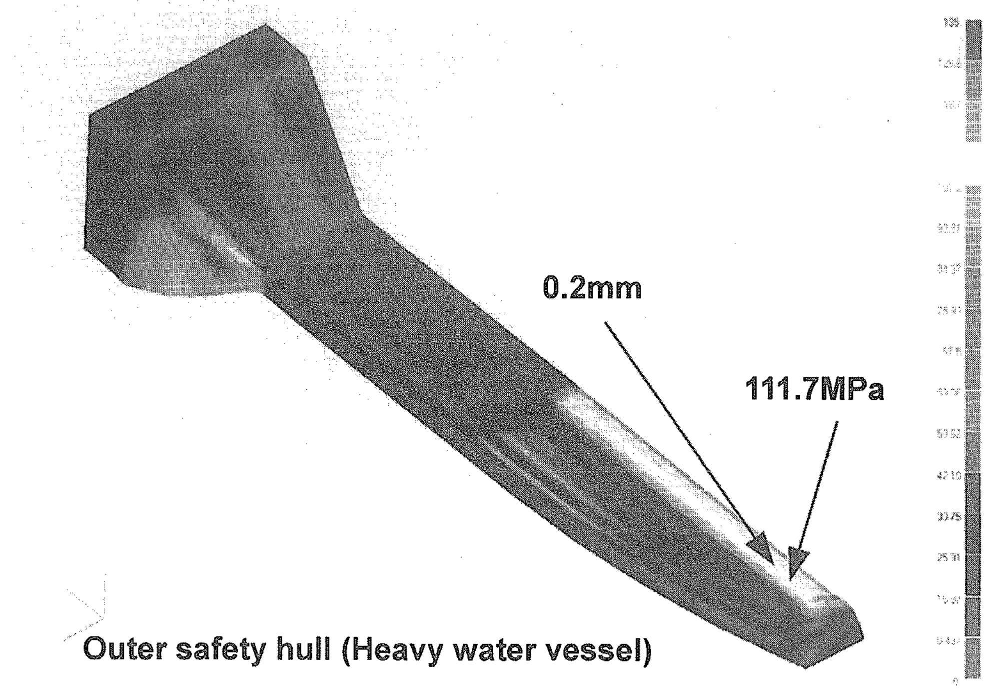



Figure 8 Structural analysis results of heavy water vessel under static pressure of 0.5MPa