Design of Mercury Target System

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Design of the Mercury Target System

We have been developing the MW-scale mercury target along our strategy intending to upgrade the proton beam power up to 5MW.

The 1MW mercury target system is currently being developed and designed as the first step of the joint project.

- **Concept of the mercury target**
- **R&Ds to obtain and verify design parameters**
  which has been carried out to optimize the target structure from the viewpoint of thermal-hydraulic performance
- **Analytical results obtained under 1MW proton beam operation**
  Flow rate and temperature distributions of mercury and container etc.
- **Target trolley including mercury circulation system**

Mechanical strength of the target including cavitation-erosion is shown in another session.

Cross-Flow Type (CFT) Target

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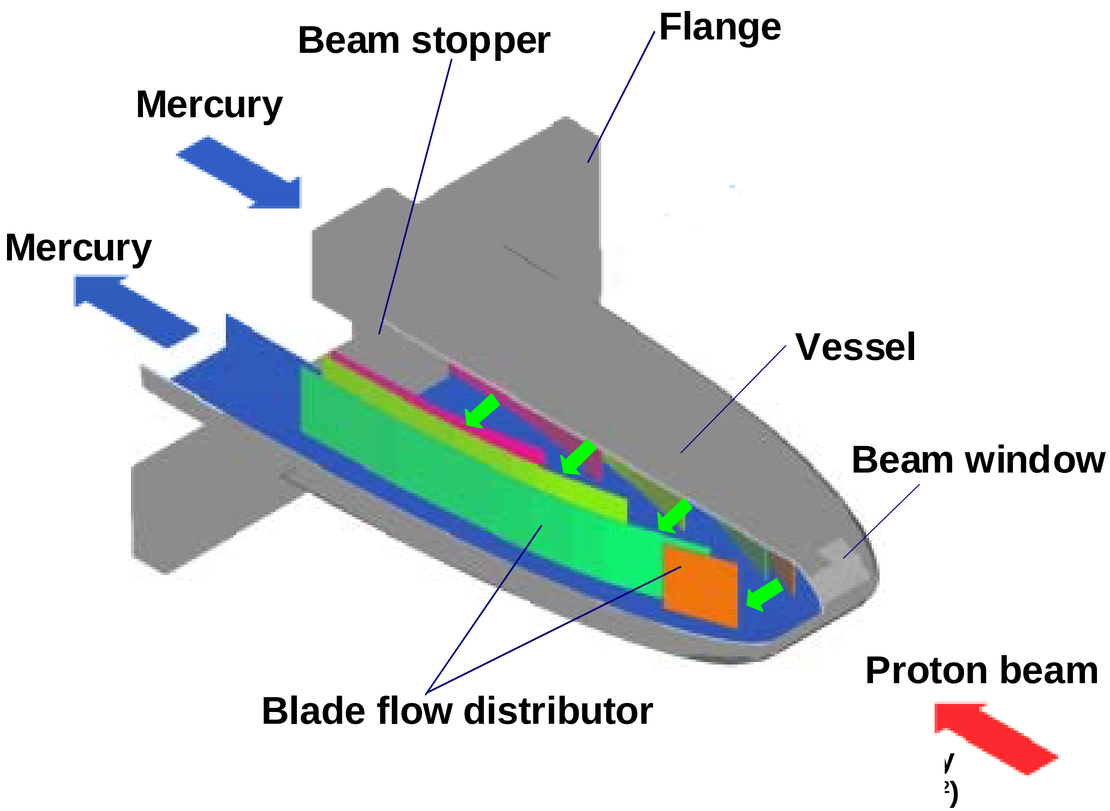
- Major technical issues in developing the mercury target from the view point of thermal hydraulics are; the prevention of the re-circulation and the stagnant flows affecting the local temperature rises (so as not to cause flow boiling); the suppression of the erosion at the target beam window by the mercury flow.

- To solve the above technical issues, a Cross-Flow Type (CFT) mercury target was devised.



Concept of CFT target for 1MW operation

Cross-Flow Type mercury target

Mercury flows into the container along the blades so as to optimize mercury flow rate distribution, crosses the proton beam, and flow away to the mercury loop. Then, mercury flow inside the target can be distributed according to the axial distribution of the heat deposition rate in the target by using flow distributors which also work as reinforcement components.

Thermal-Hydraulic Tests to Obtain and Verify Design Parameters

- **Water flow test with a full-scale target model**

  to verify existing turbulent models such as the standard k- ε model and the RNG model under very high Reynolds number region for predicting velocity distributions accurately.

- **Thermal-hydraulic tests with the JAERI mercury test loop**

  (the maximum flow rate of 20 liters/min)

  to determine the turbulent Prandtl number (Prt) which is indispensable for the thermal-hydraulic analyses of the mercury target, and

  to investigate pressure loss characteristics and erosion rate.

Water Flow Tests - Comparison of velocity distribution between analytical and experimental results

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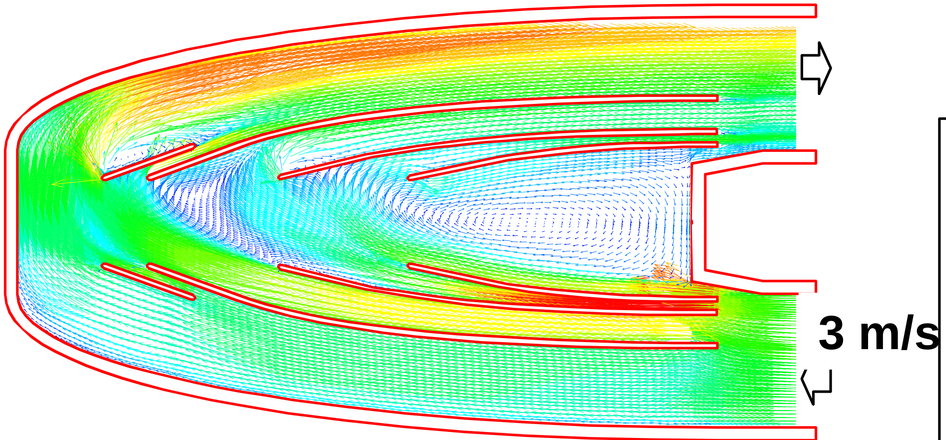
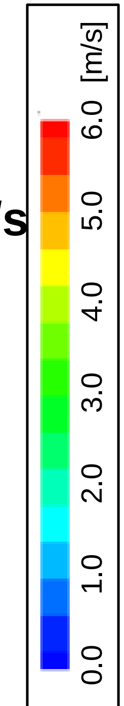
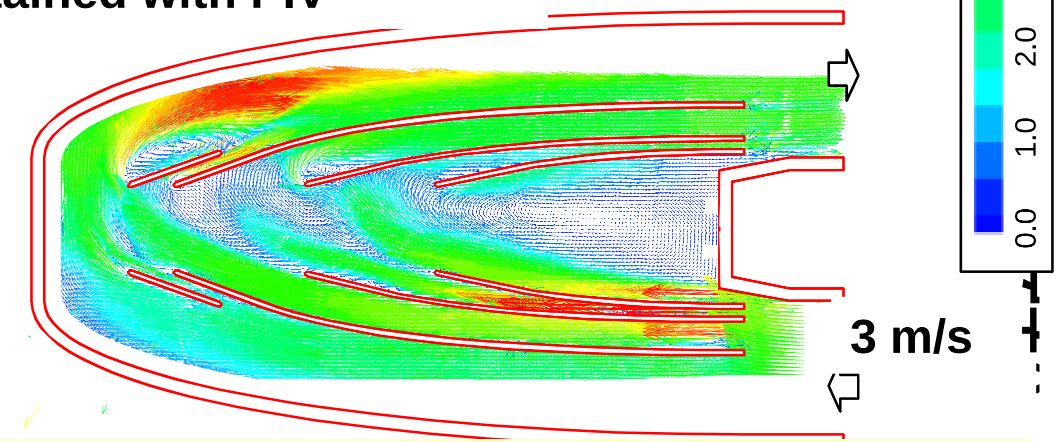
Analytical result obtained with the standard k- ε model

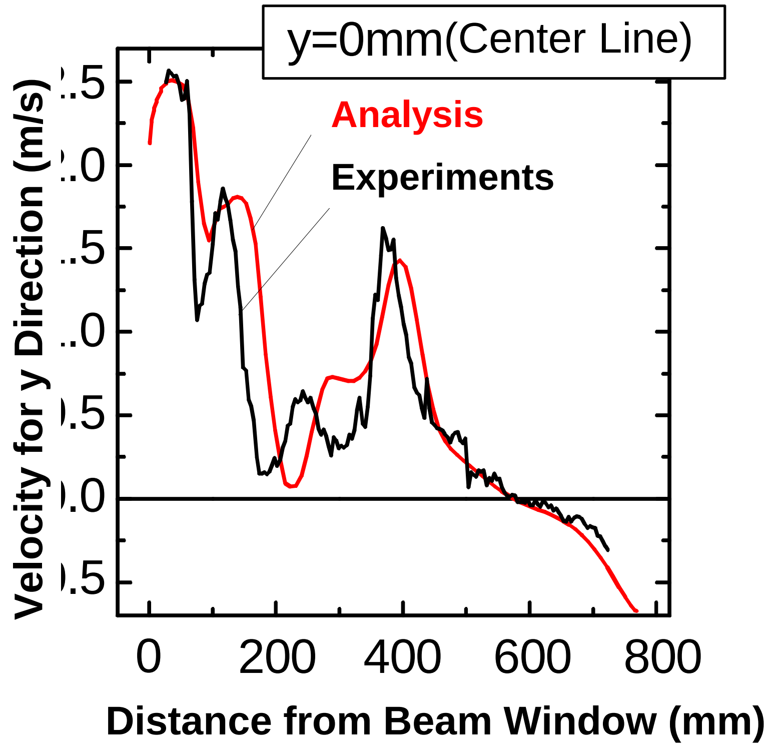
(V_{in} =3.0 m/s, Re=3x10^5)





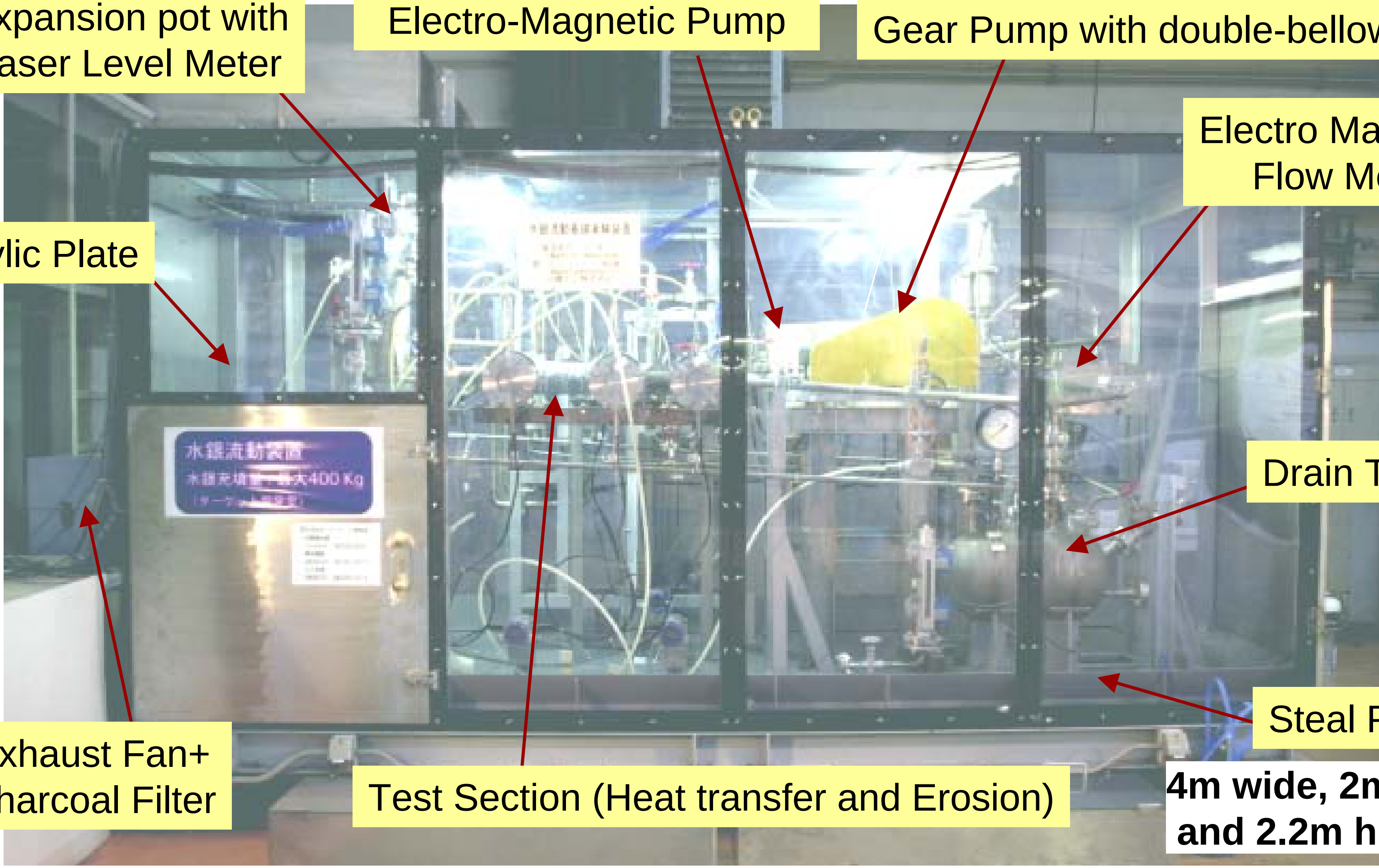
Experimental result obtained with PIV





Turbulent models were also verified through the benchmark tests with ORNL.

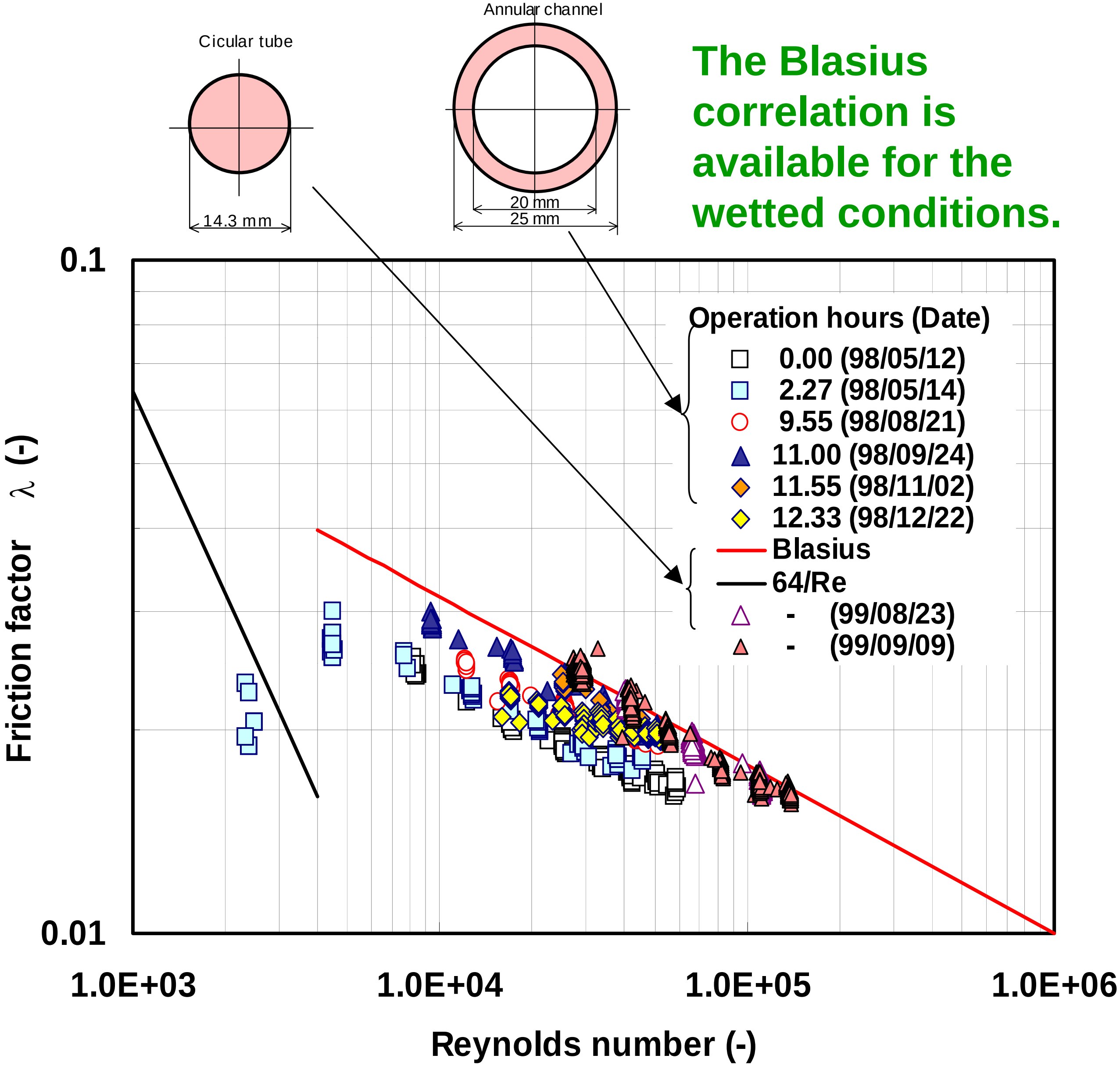
Outer View of JAERI Mercury Test Loop



Flow rate of mercury : 20L/min , Inventory of mercury : 400kg (maximum)

The mechanical gear pump has showed much better performance on the mercury circulation than the EM pump.
The gear pump is to be used in the practical mercury circulation system.

Experimental Results of Wall Friction Factor



The Blasius correlation is available for the wetted conditions.

Wall friction factors increase with an increase of the operating hours of the mercury loop.

⇩

This is caused by the change of surface conditions between the piping and the mercury.

At the beginning of the experiment, the surface was not wetted well and the mercury flow caused some erosion of the piping as well as removing the oxidized membrane of the piping.

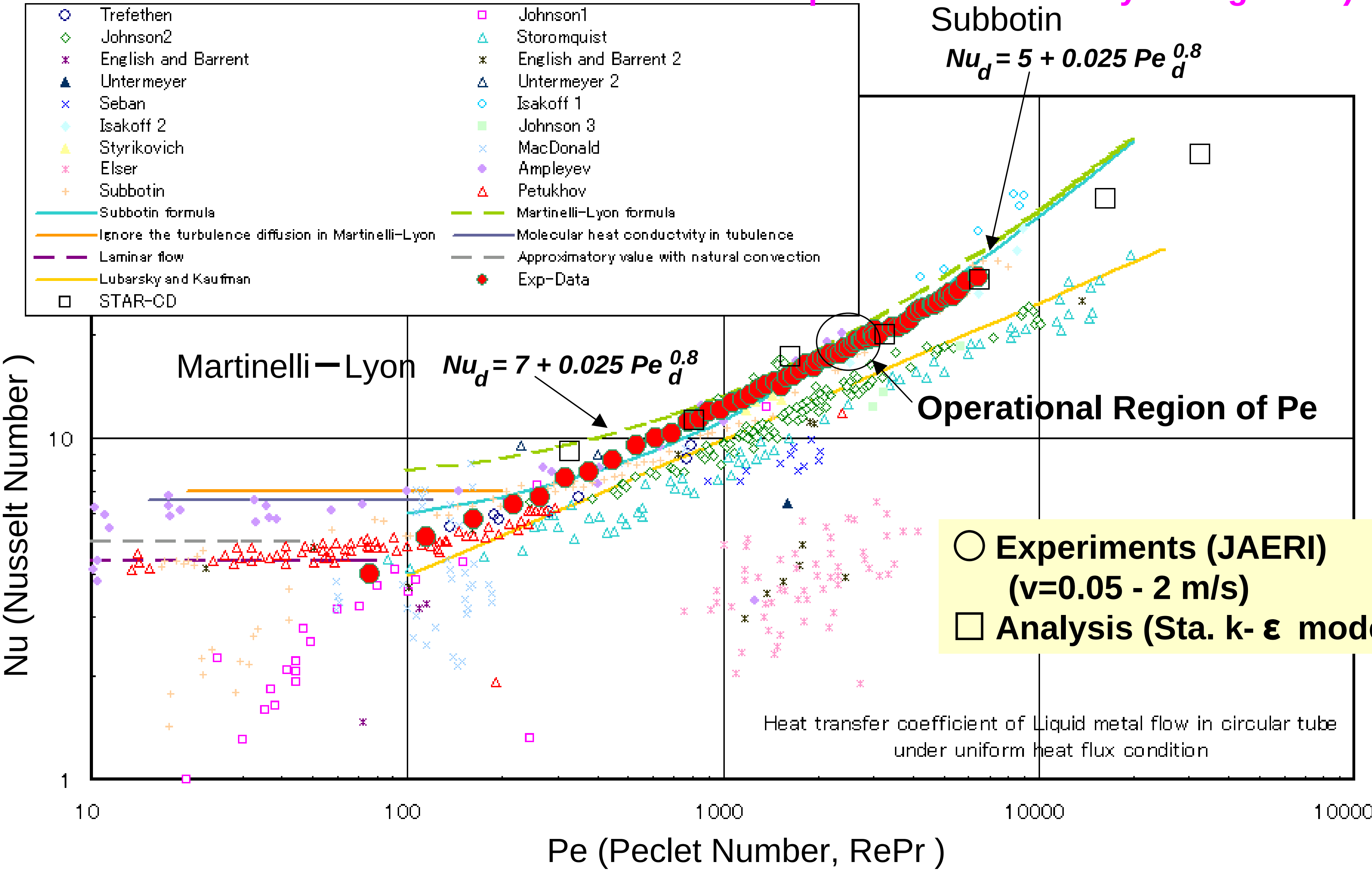
⇩

The surface condition was changed from non-wetted to wetted after 12 hour operation.

The practical mercury circulation system is to be operated for more than 12 hours before the proton beam injection in order to ensure the wetted condition.

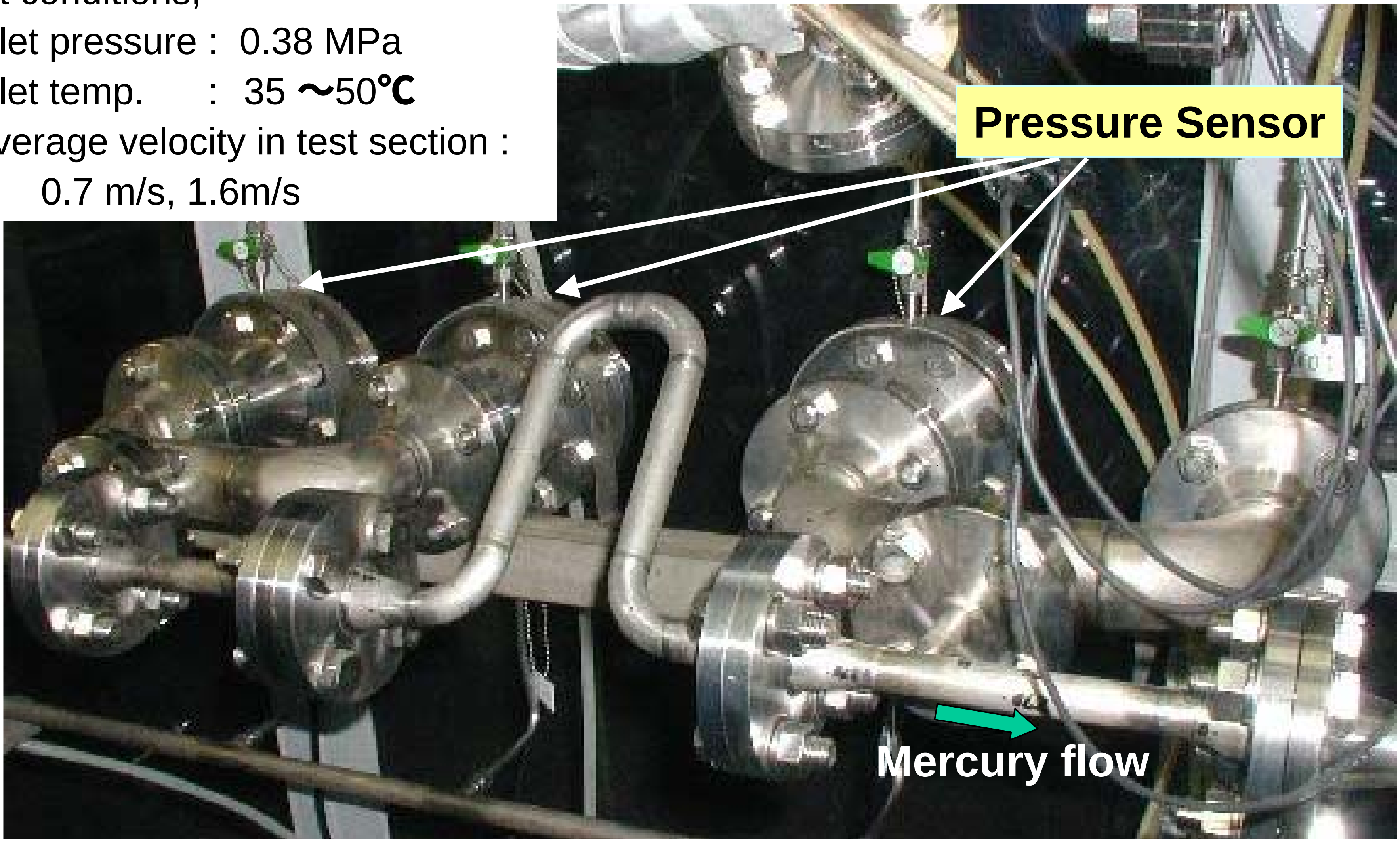
Comparison between Experimental and Analytical Results of Dimensionless Heat Transfer Coefficients (Nu)

We can predict Nu well with 1.5 of Prt (derived with the empirical correlation by Kasagi et al.)



Erosion Tests Using the JAERI Mercury Test Loop
- Outer view of the test section –

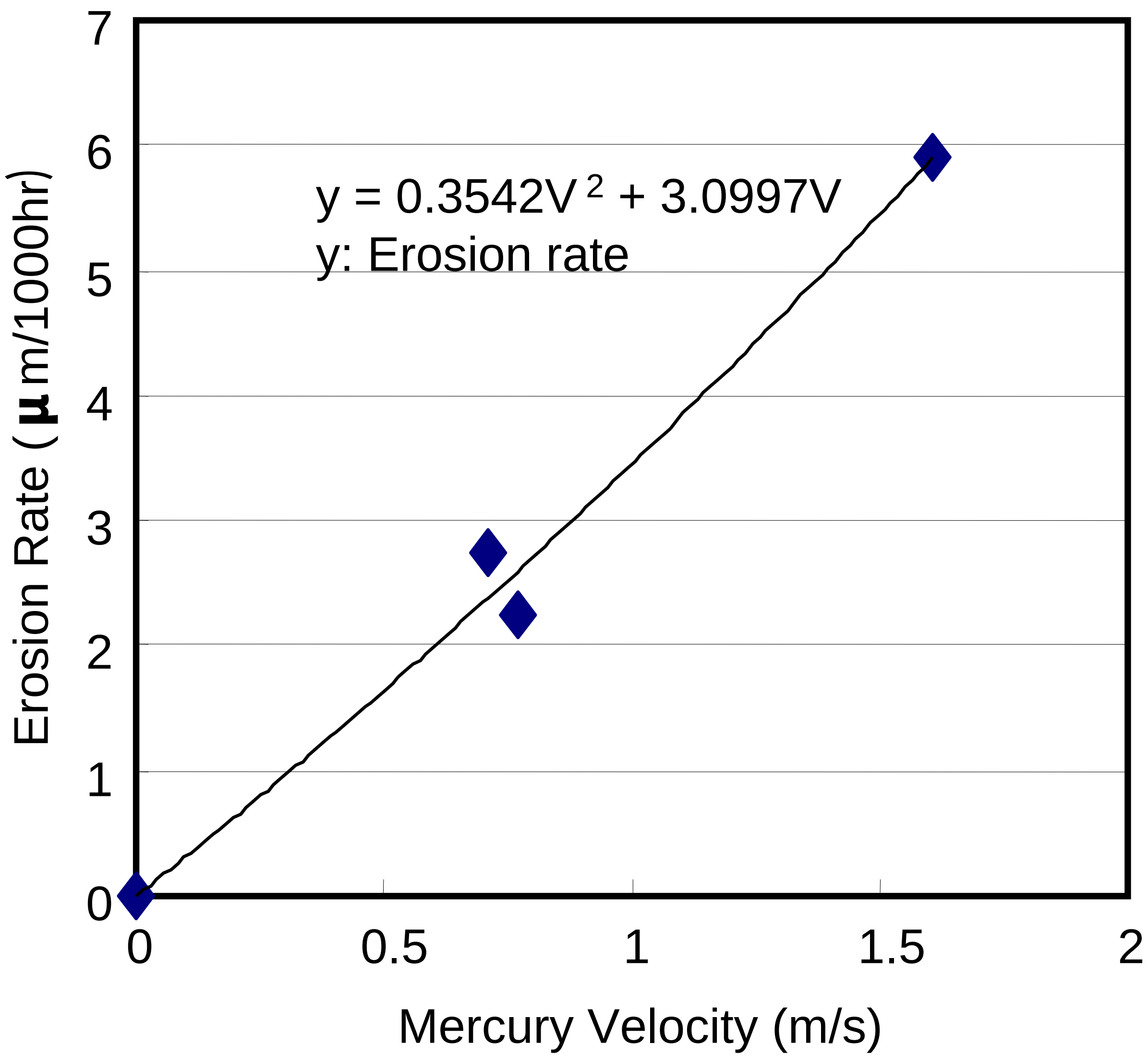
Test conditions;
Inlet pressure : 0.38 MPa
Inlet temp. : 35 〜50℃
Average velocity in test section :
0.7 m/s, 1.6m/s



This erosion test section consists of straight pipes and bends;
14.3mm of Inner dia., 21.7mm of outer dia., 1332mm of total length

Relationship between Average Erosion Rate and Mercury Velocity Obtained with Straight Pipes

Wall thickness was measured every 1000 hours by using an ultra sonic gage with resolution of 1 μm.



Tests period:
2000hrs under 0.7m/s
1000hrs under 1.6m/s.

Based on the empirical correlation, the average decrease of wall thickness after 4000hr operation (one-year operation time of the facility) was estimated to be only 14 μm under 1m/s of mercury velocity.

⇩

Erosion could not affect the mechanical strength of the thin-walled beam window of 2.5mm thick.

Cutaway View of Mercury Target

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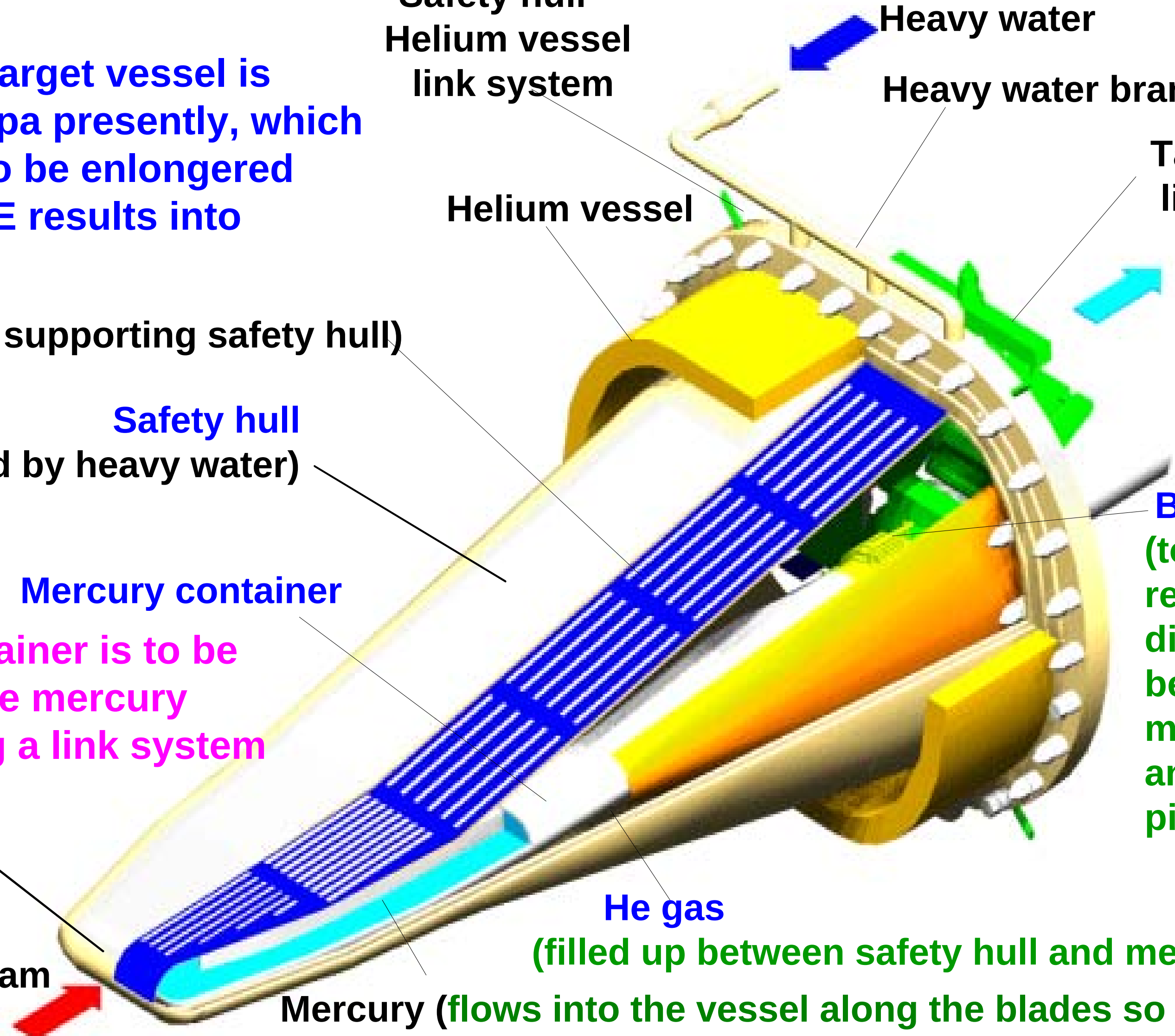
A mercury container is covered with a water cooled safety hull to prevent the leakage of mercury to inside of a helium vessel. This multi-walled concept is the same concept as the SNS and ESS mercury targets.

Lifetime of the target vessel is limited up to 5dpa presently, which would be able to be enlongered taking future PIE results into consideration.

The mercury container is to be connected with the mercury pipelines by using a link system with bellows.



Heat Density Distribution in the Mercury Target - 1MW proton beam power -

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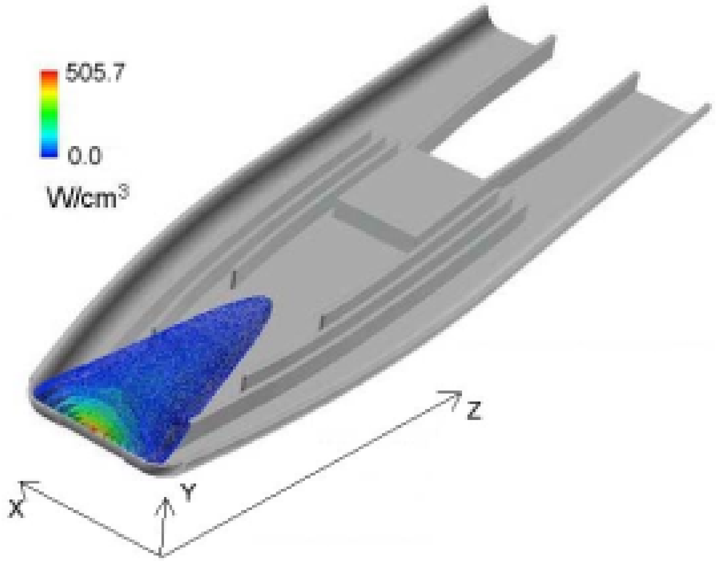
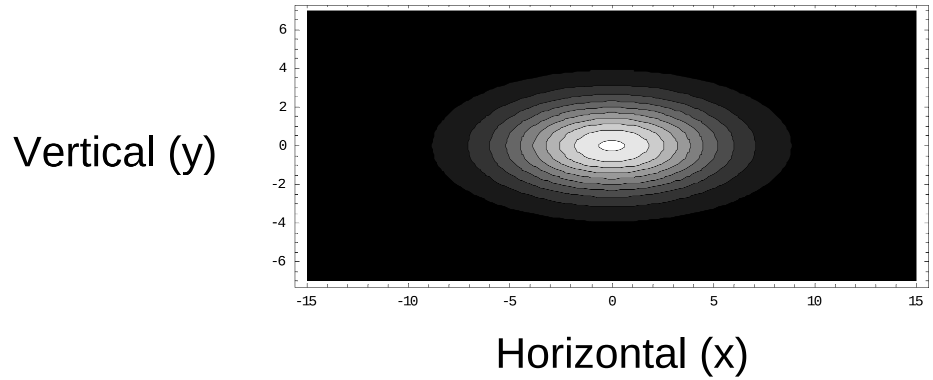
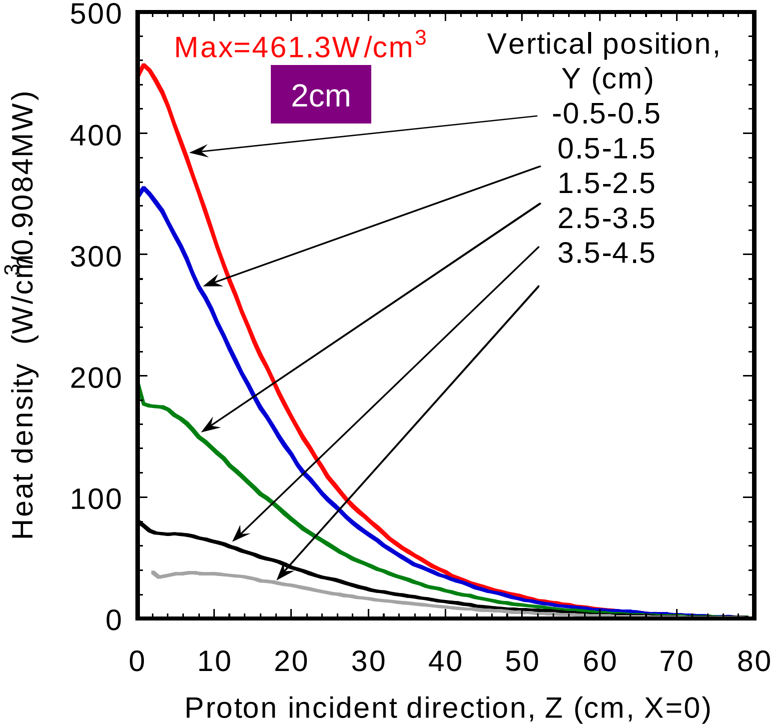


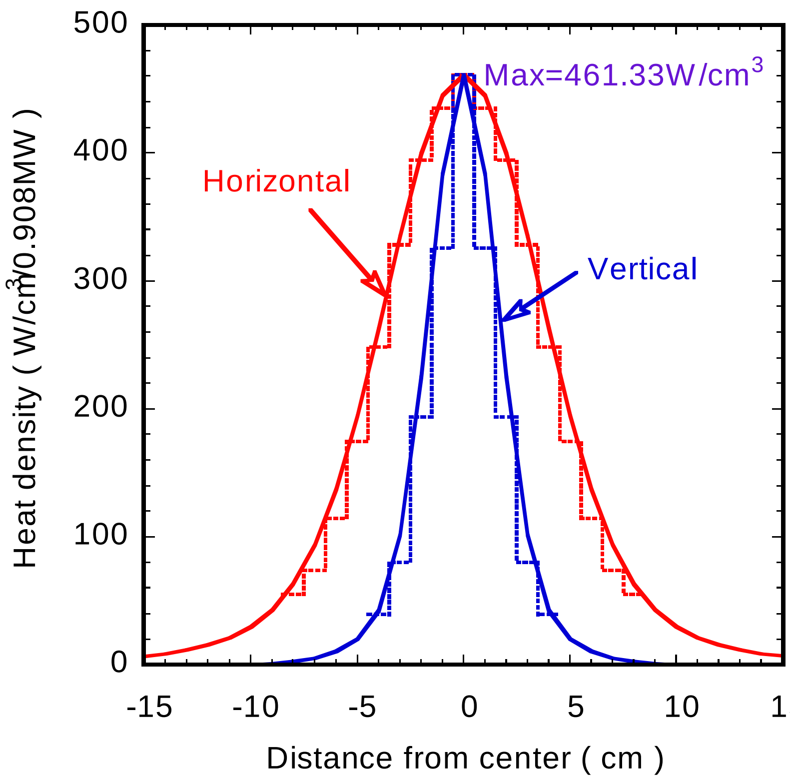
In the thermal hydraulic design, 10% of margin was considered for neutronic analysis.





Heat generation distribution in the x-y plane at **z=2cm**

which has maximum heat generation in axial direction



3-D Thermal - Hydraulic Analysis Results

- Velocity and temperature distributions of mercury in the practical target -

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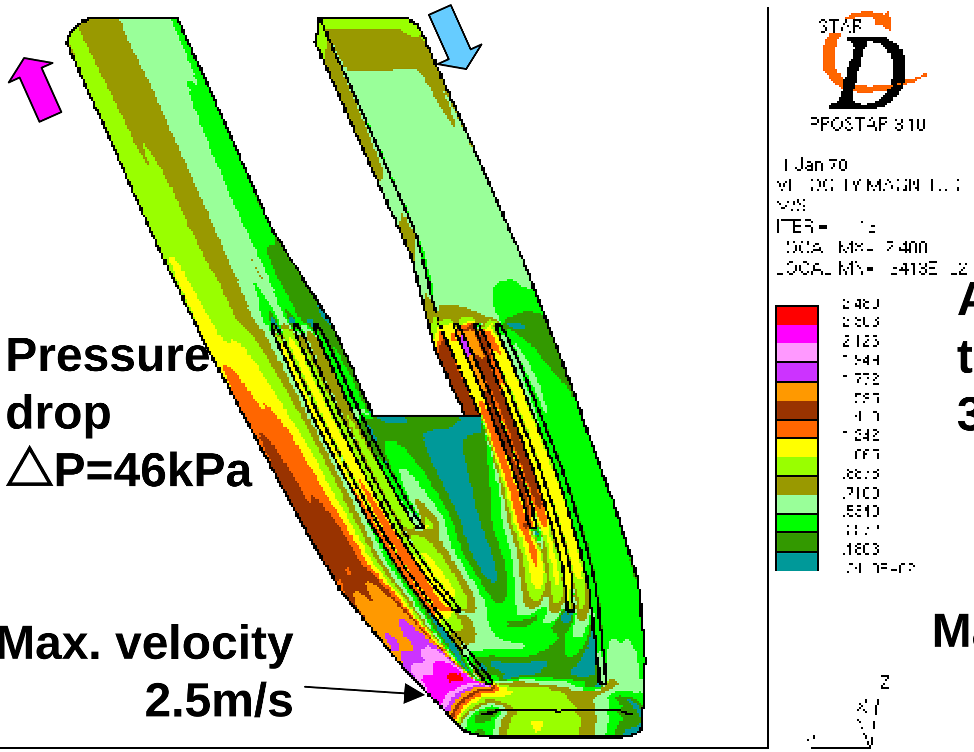
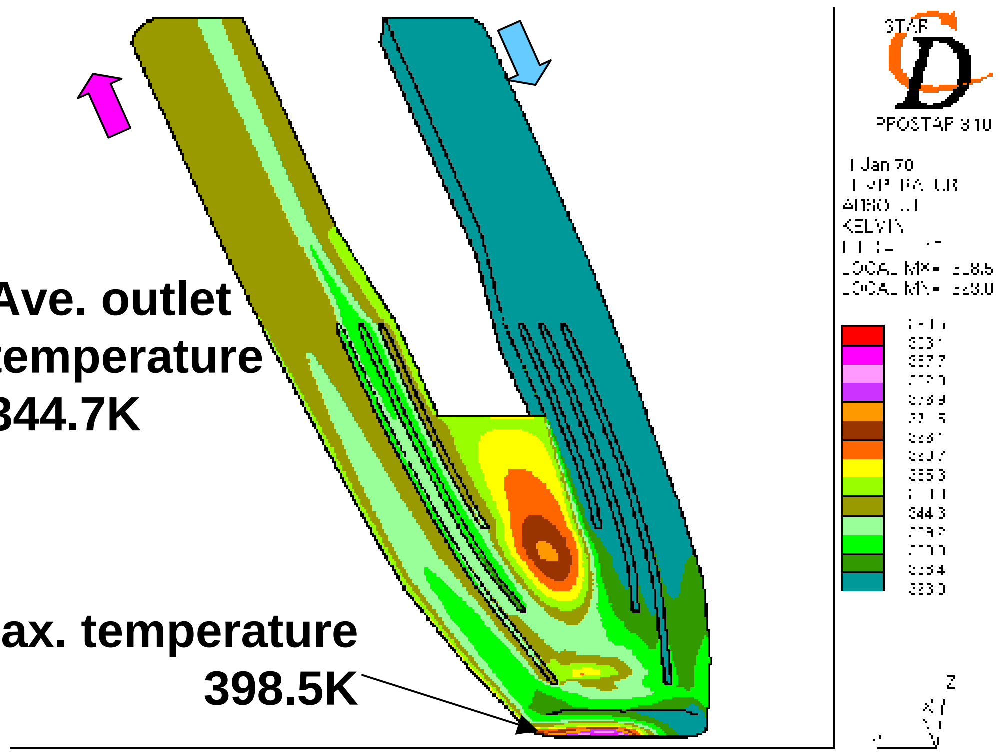
Analytical code : Star-CD

- Target inlet mercury temperature : 50℃, Mercury flow rate 41m^3/h
- Average mercury velocity : 1.0 m/s, Outside boundary condition : Thermally isolated
- Beam window thickness : 2.5 mm (316 Stainless-steel)

Velocity distribution



Temperature distribution



- Erosion rate caused by 2.5m/s could be ignored during the lifetime up to 2000hrs.
- Pressure drop in the target is 46 kPa.
- The maximum temperature of 398.5K is far below the mercury saturation temperature of 629K (at 0.1MPa).

3-D Thermal - Hydraulic Analysis Results
- Inner and outer temperature distributions of mercury container -

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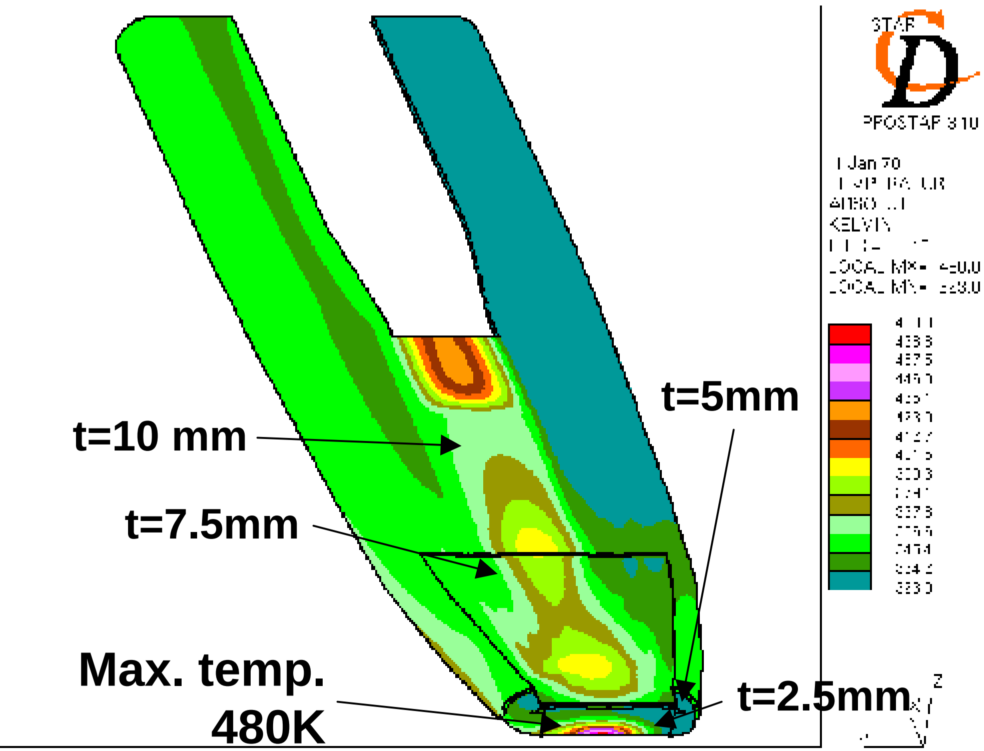
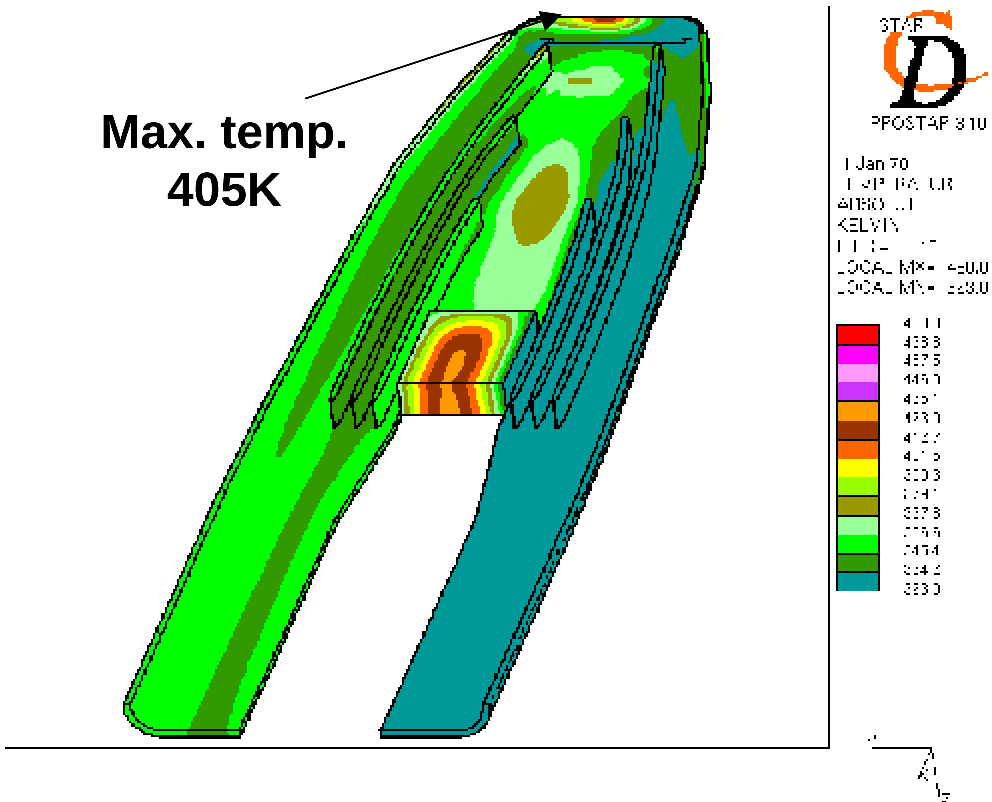
Analytical code : Star-CD

- Target inlet mercury temperature : 50℃, Mercury flow rate 41m^3/h
- Average mercury velocity : 1.0 m/s, Outside boundary condition : Thermally isolated
- Beam window thickness : 2.5 mm (316L Stainless-steel)

Outer wall temperature distribution



Inner wall temperature distribution



- The maximum outer wall temperature 0f 480K occurred at the center of the beam window, and then the maximum temperature difference in the window was 75K.

Thermal Stress Distribution

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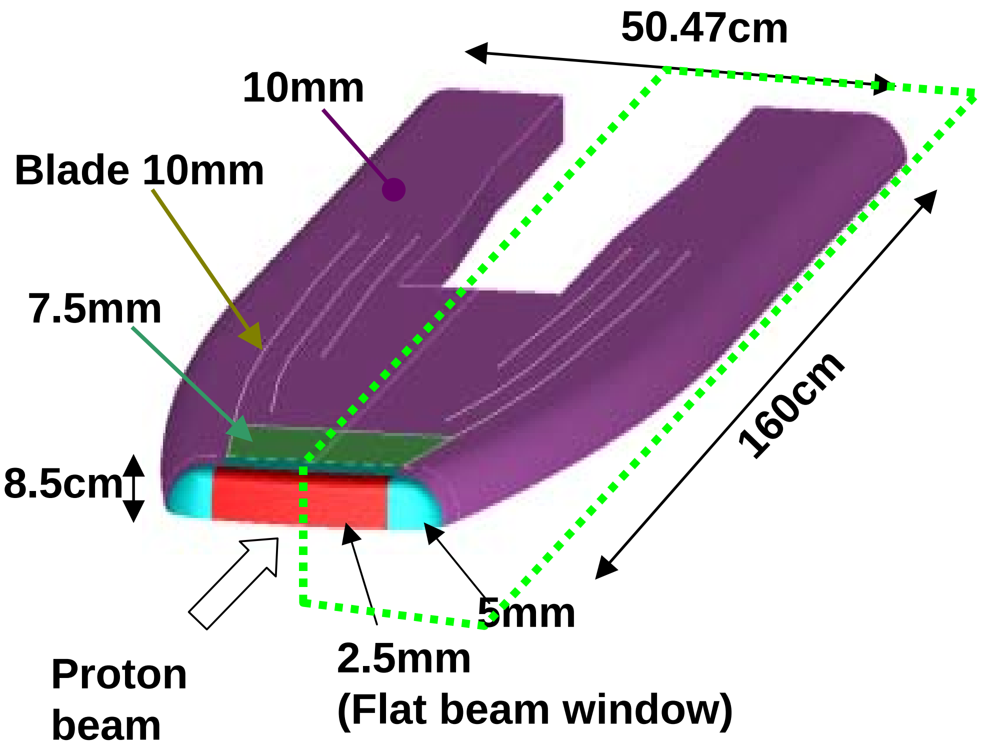

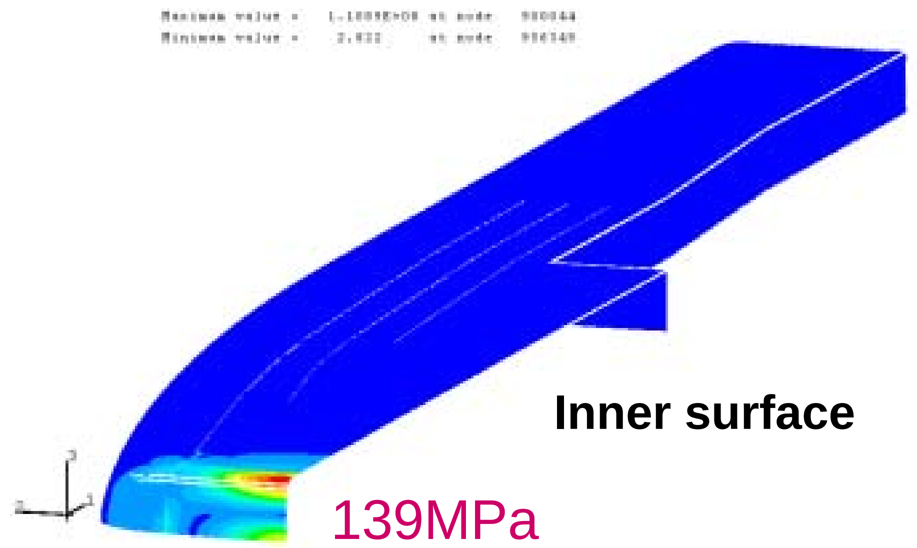

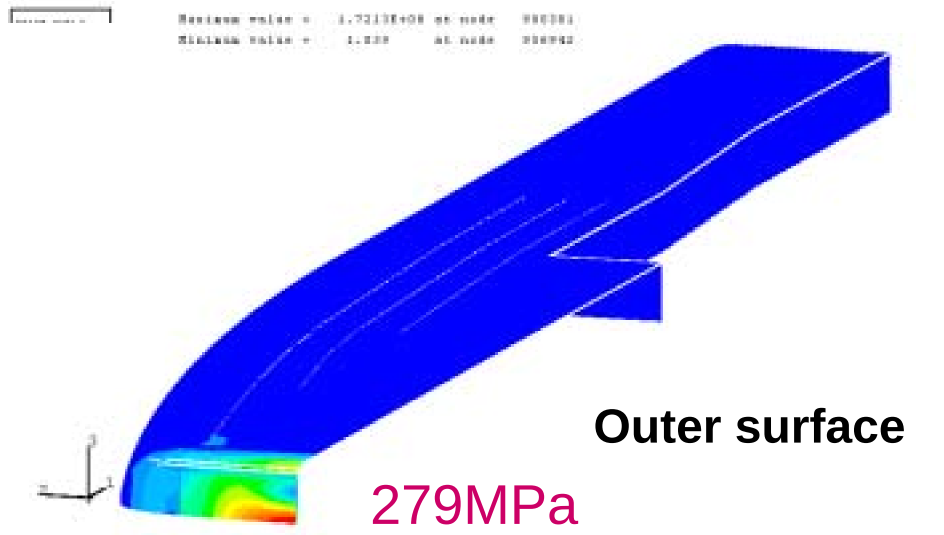

Analytical model; 1/4 model

Target vessel (SUS316L);

Shell (51,600 elements)

E=196GPa, n=0.3, r=8030Kg/m^3

Thermal stress

< Allowable stress (3Sm)=345MPa

Schematic Drawing of Mercury Target

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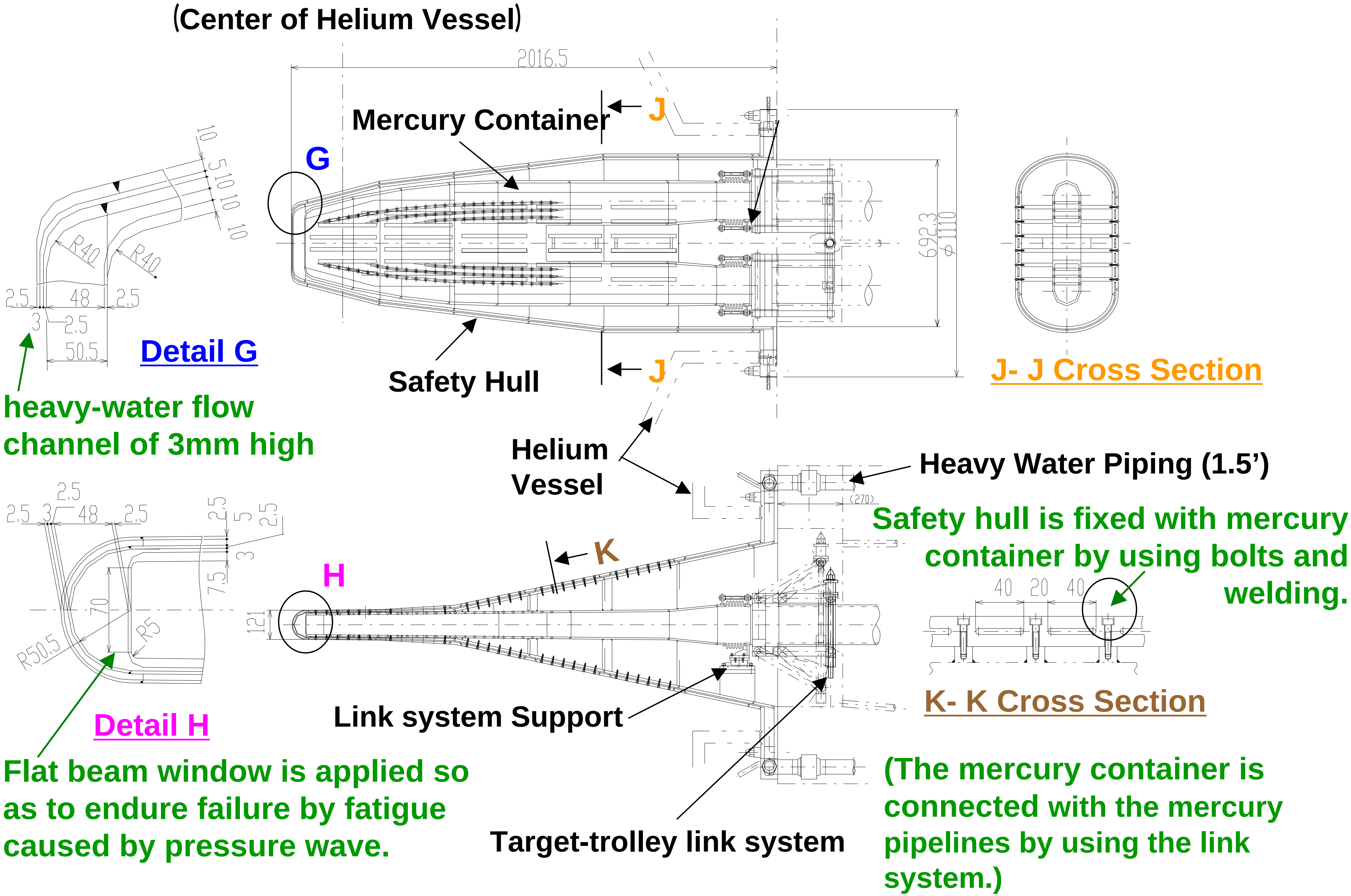
This drawing is used for thermal-hydraulic and mechanical-strength analyses.

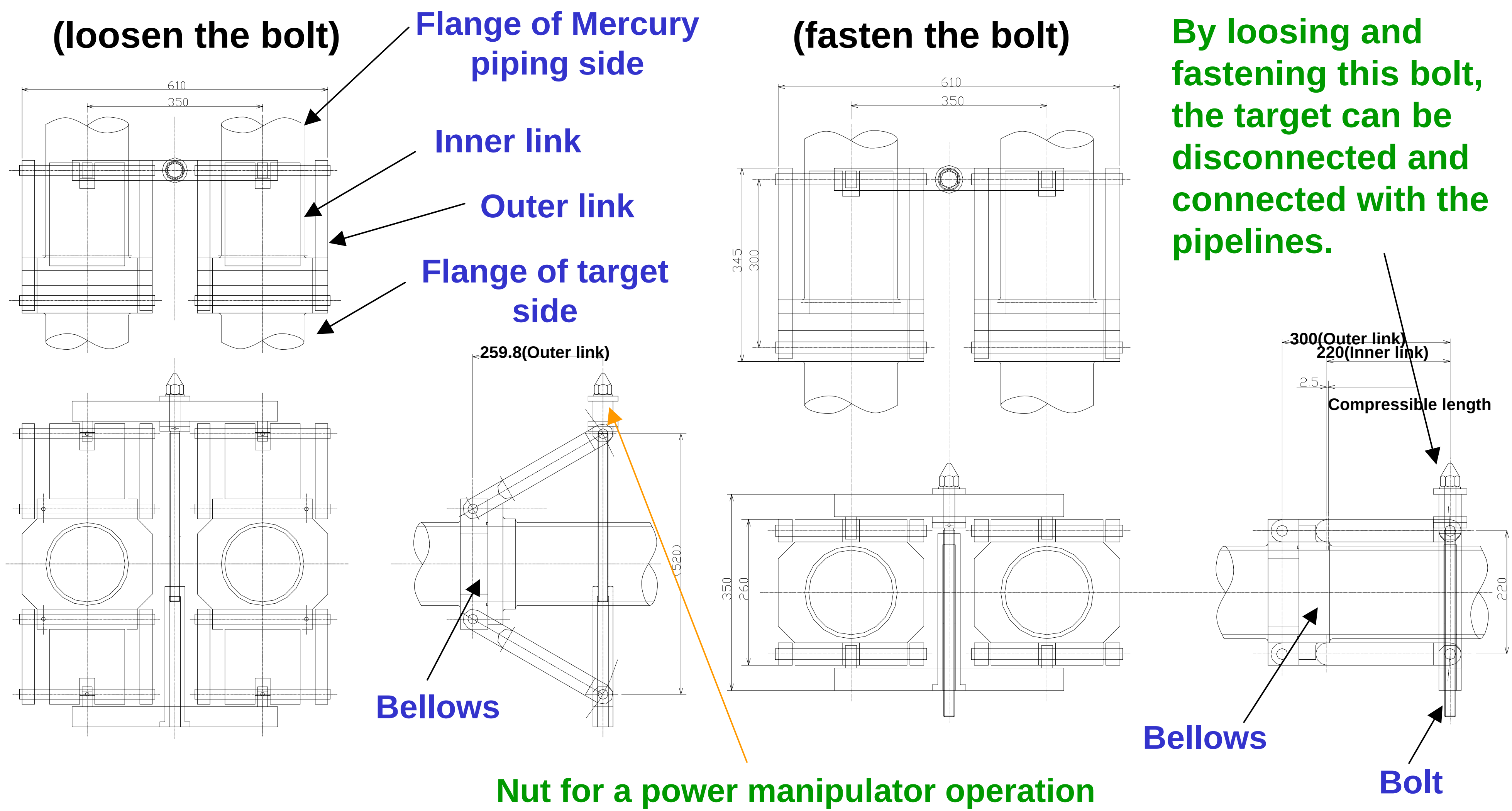


Target-trolley Link System

Disconnection **(loosen the bolt)**

Connection **(fasten the bolt)**

By loosing and fastening this bolt, the target can be disconnected and connected with the pipelines.



This link system is based on the concept of the one-touch vacuum connector so as to be operated (fasten and loosen) with a power-manipulator.

This system is to be verified with a mock-up model.

Schematic Drawing of Mercury Target - Safety Hull -

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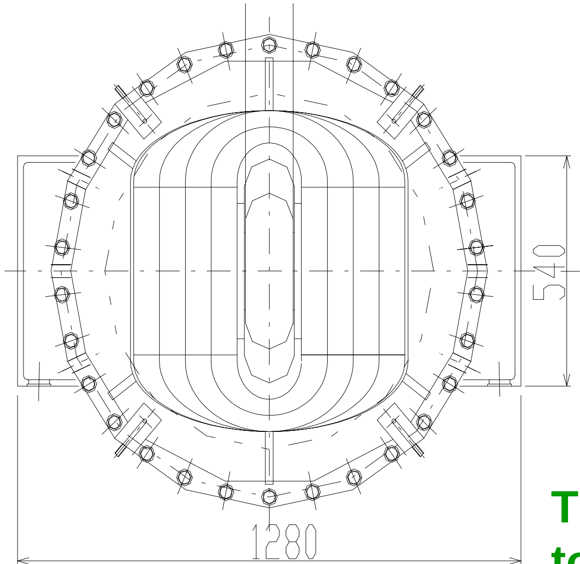
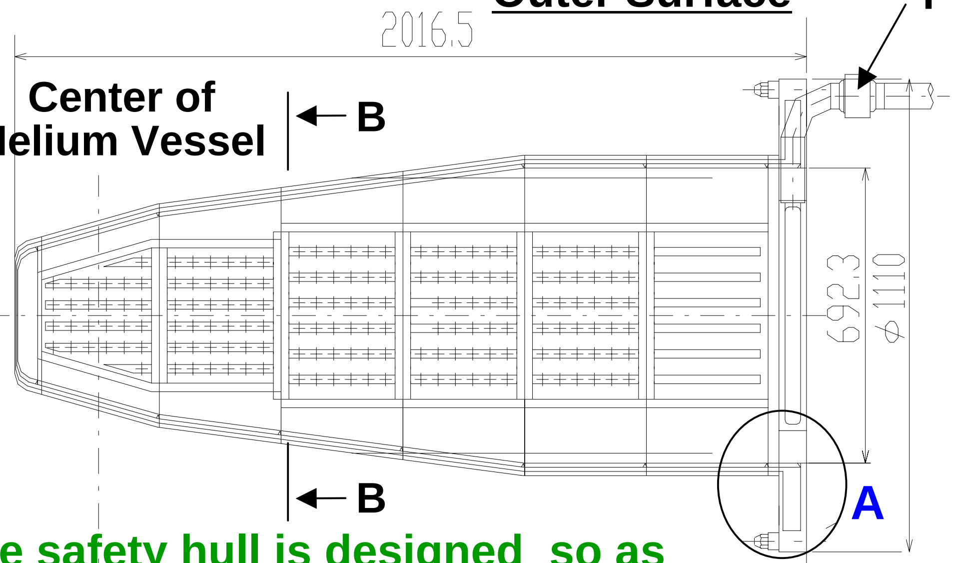
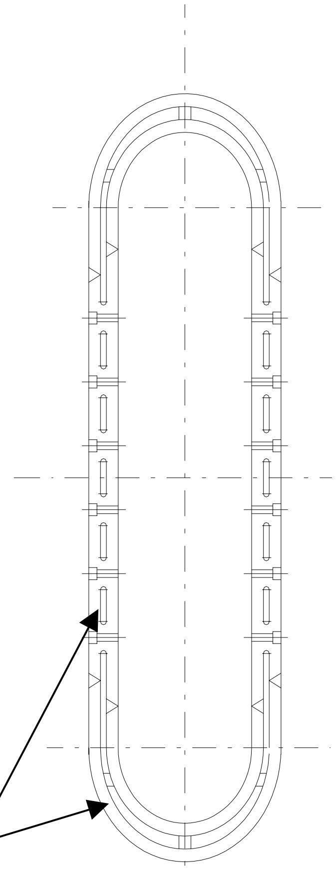
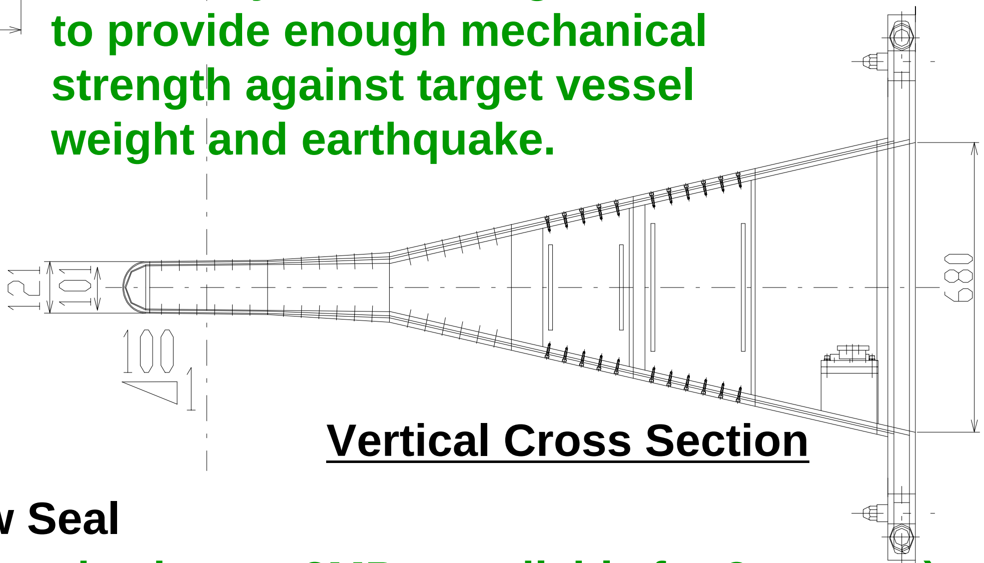
The safety hull works as a support of the target vessel and a boundary of the helium vessel.

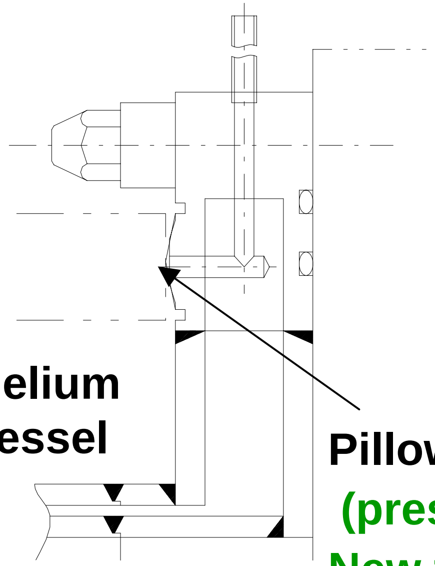






The safety hull is designed so as to provide enough mechanical strength against target vessel weight and earthquake.





(pressurized up to 2MPa, available for 3mm gap)

New type sealing available for large gap more than 10mm is under design from the viewpoints of target positioning and machine protection

Bird's-eye View of Mercury Target Trolley

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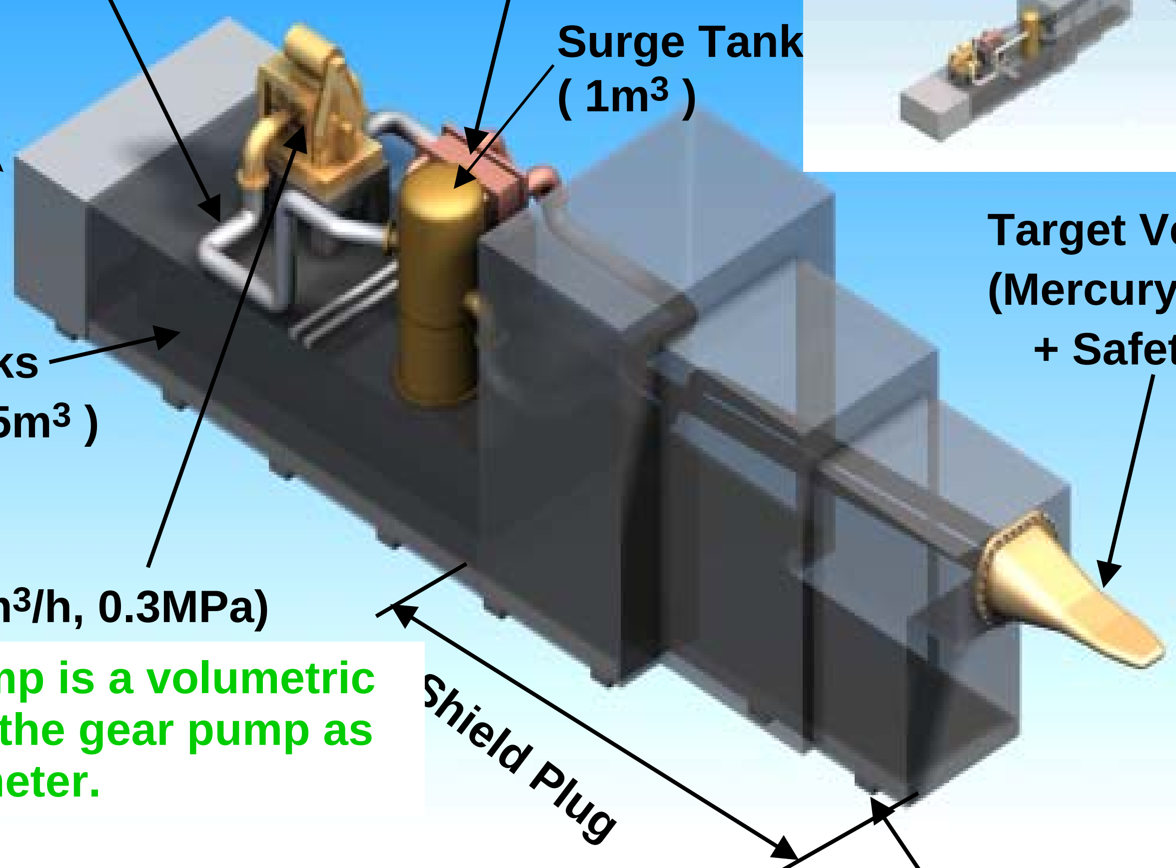
The plate-type heat exchanger has a rated cooling capacity of 550kW, and has a double wall structure sandwiched with He gas between mercury and water cooling plates.



Since the gear pump is a volumetric pump, we will use the gear pump as an auxiliary flow meter.

The trolley can move horizontally on linear motion guides at a maximum speed of 20mm/s.

Schematic Drawing of Target Trolley

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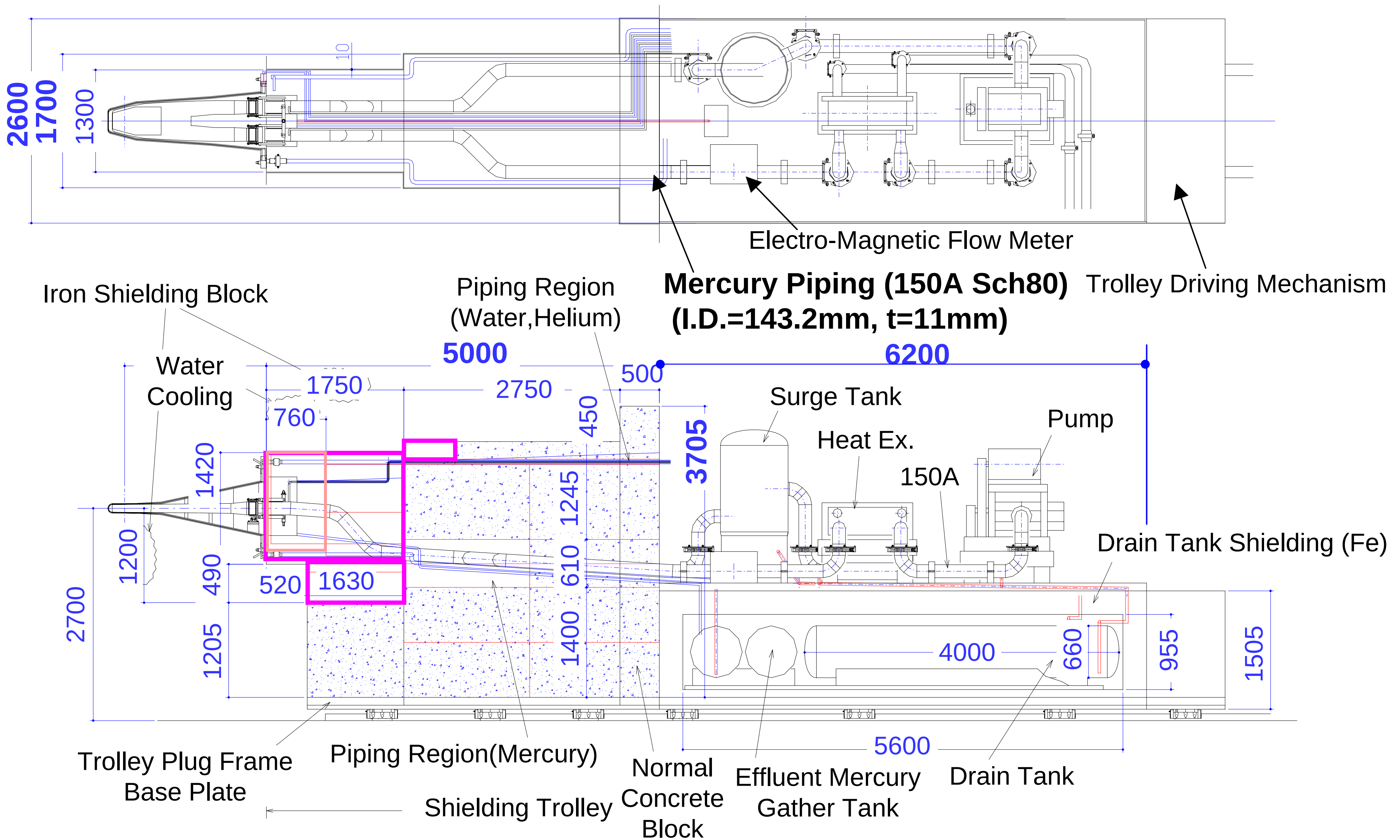
- Target trolley has a dimension of 12m long, 2.6m wide and 4m high at maximum.
- Total weight except mercury is 286ton.



Main material of the mercury circulation system is SS316L.

Overview of the Target Trolley

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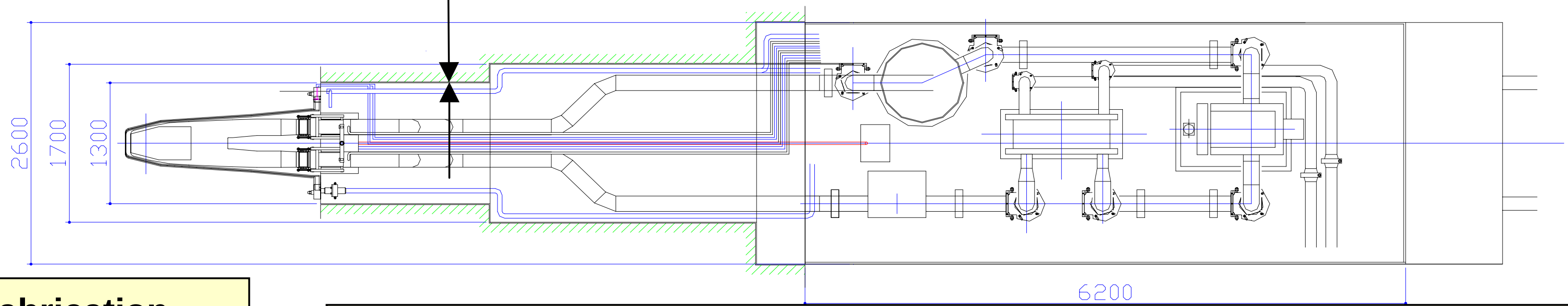
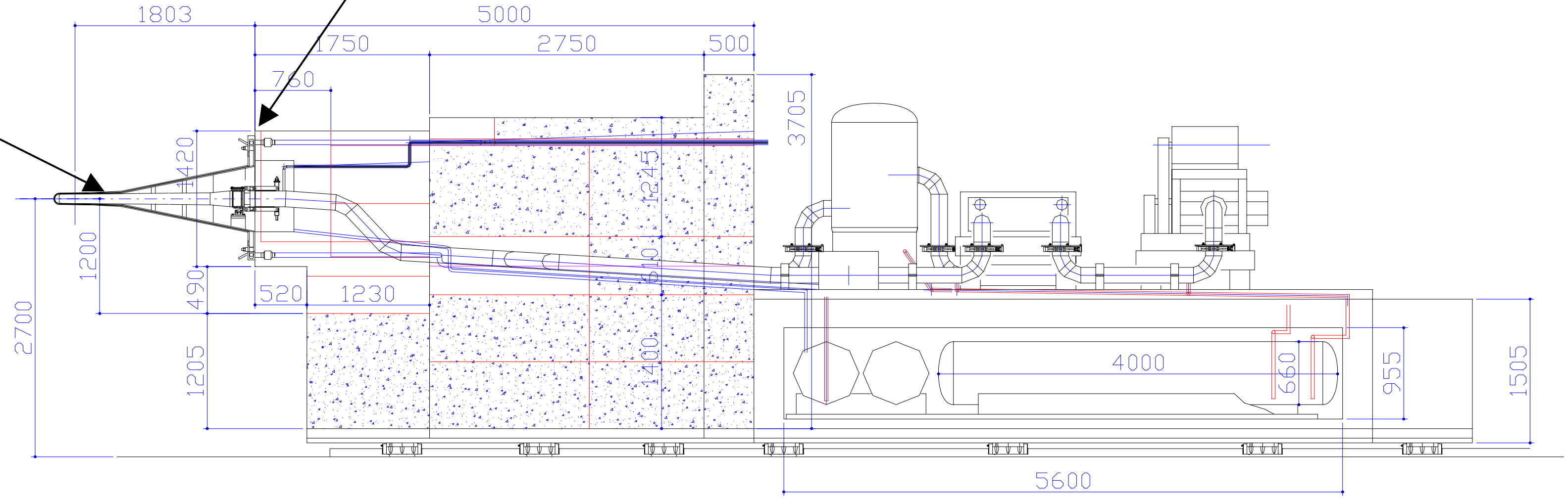
Gap between trolley and liner : 20mm



Target vessel fabrication accuracy : +0mm, -2mm

Trolley positioning is to be controlled : ±1mm forward, ±5mm backward

Target vessel can be adjusted its position :
Vertical ±5mm,
Horizontal ±5mm



Piping Diameter	156	mm
Thickness	11	mm
Cross Section	141	cm^2
Mercury Flow Rate	50	m^3/h
Flow Velocity	1	m/s

Trolly Rail	LM Guide	
Trolly Driving Mechanism	Rack & Pinion	
Moving Velocity	20	mm/s
Motor Power	20	kW
Moving Length	Max.19	m
Positioning Accuracy	Forward 1	mm
	Backward 5	mm

Schematic Drawing of Target Trolley Shielding Block

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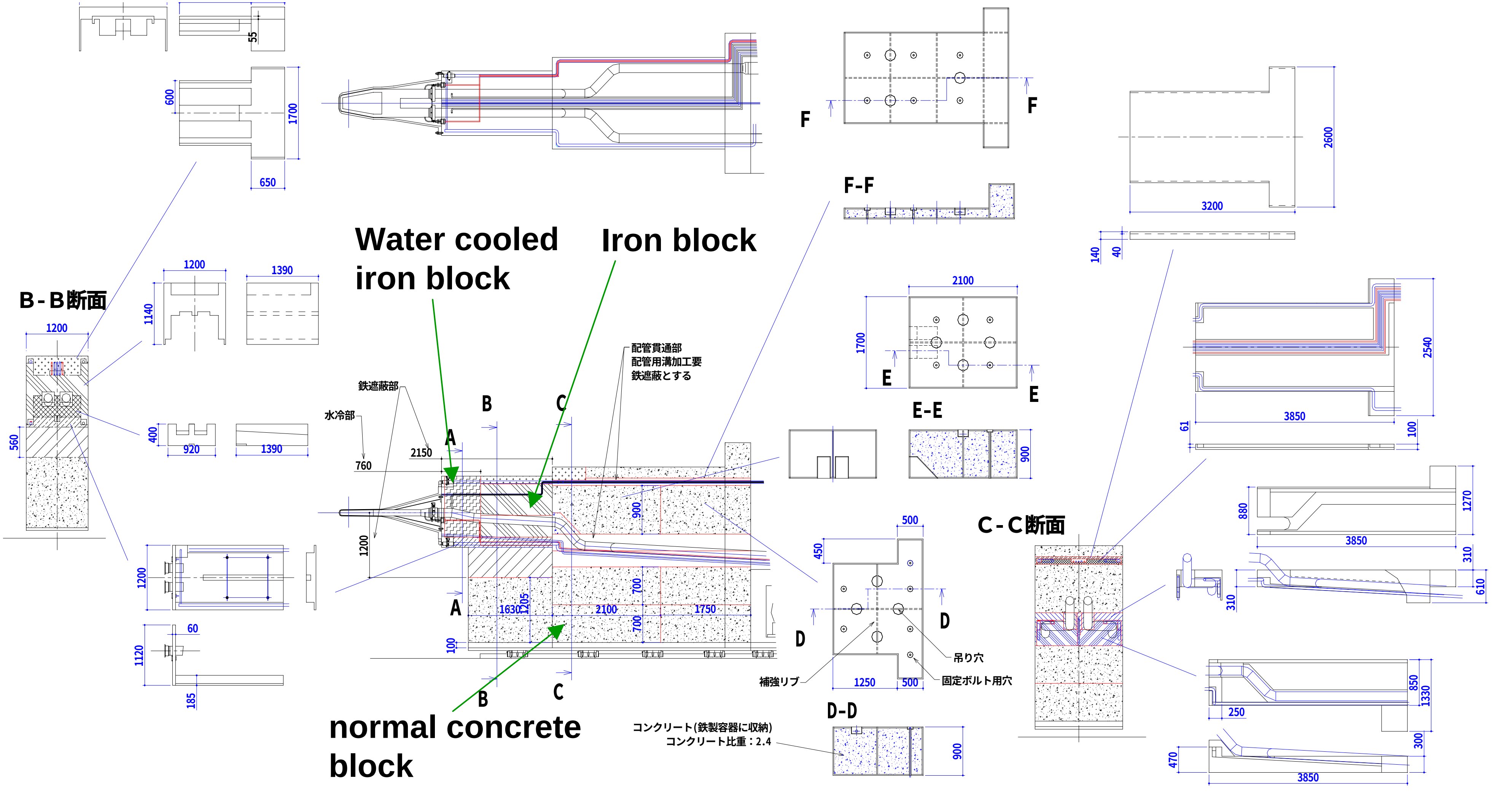
- Shielding blocks divided into pieces are to be made of iron and normal concrete.
- These blocks including water cooled iron blocks are to be assembled on the trolley base plates and frames.
- This assembling work will be carried out in a hot cell (target handling room) .



Setting of Secondary Piping and Cables Using Cable-veyor

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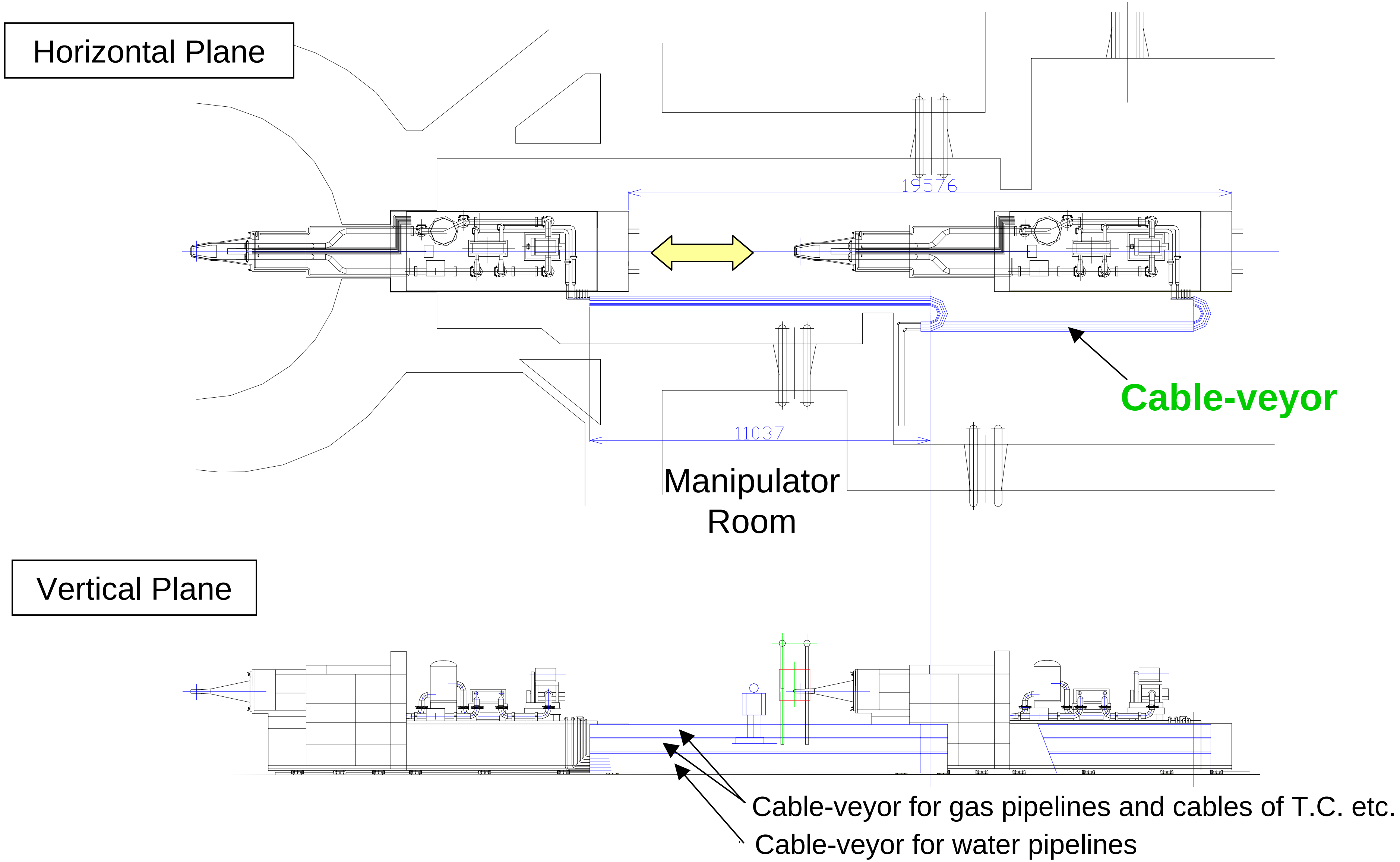

All the pipelines of water, helium and cables led from the trolley are to be set on cable-veyors so as to make the trolley move freely without disconnecting these pipelines and cables.

Base Structure of the Target Trolley

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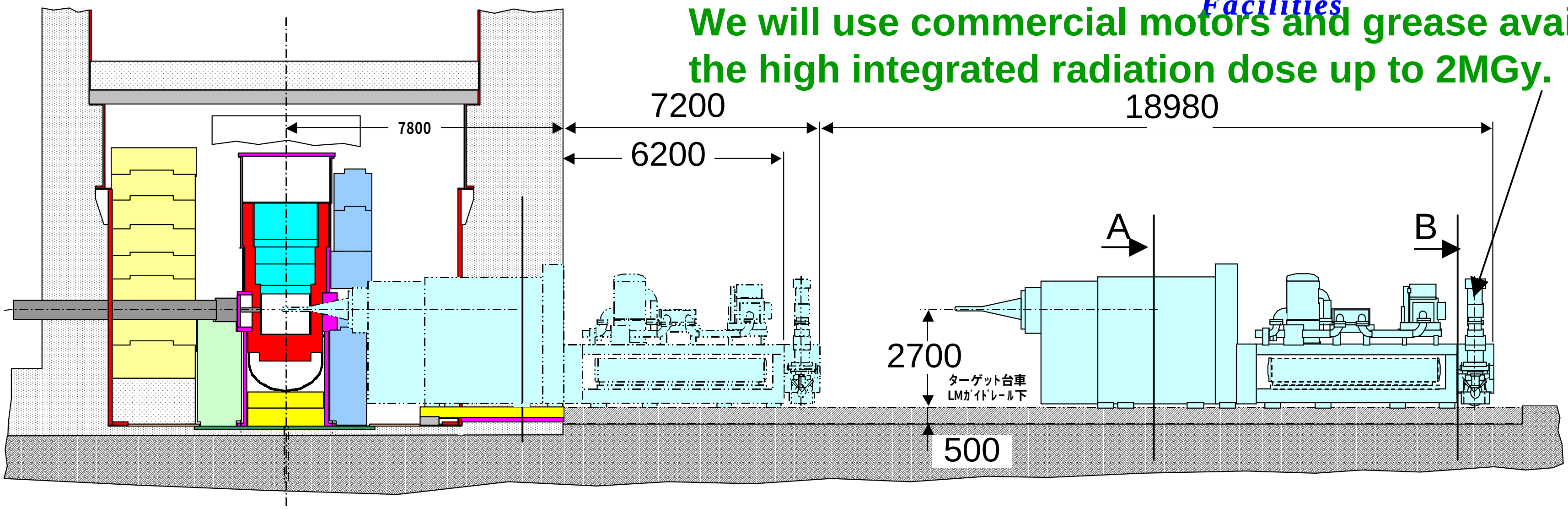
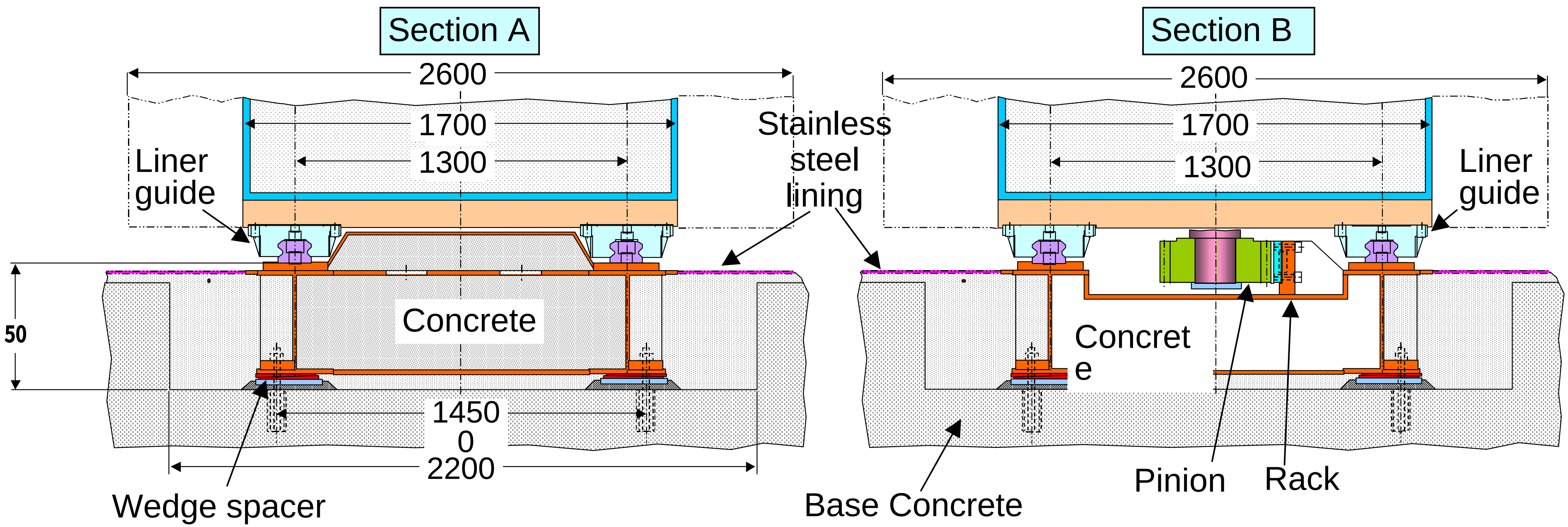
We will use commercial motors and grease available for the high integrated radiation dose up to 2MGy.





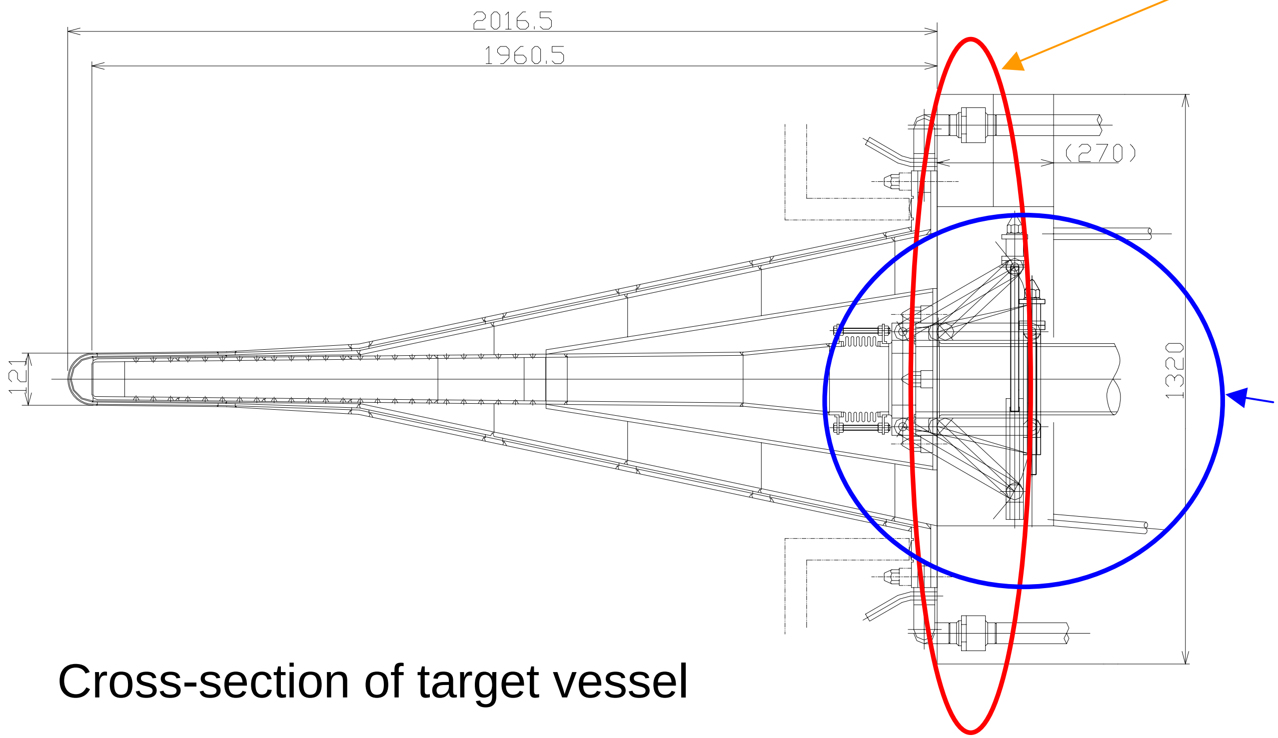
Vacancy between the trolley and the floor is to be filled up with normal concrete.

The rack & pinion to drive the trolley is being optimized from the viewpoint of positioning control.

Concluding Remarks and Mock-up Model Tests

- We will fabricate the mercury target system based on introduced concepts. Until the end of next March, we will make clear the feasibility of seal performances at the connections, the cable-vayor etc.

- To verify the seal performance, two kinds of mock-up models are to be fabricated, and the tests is to be started next February.



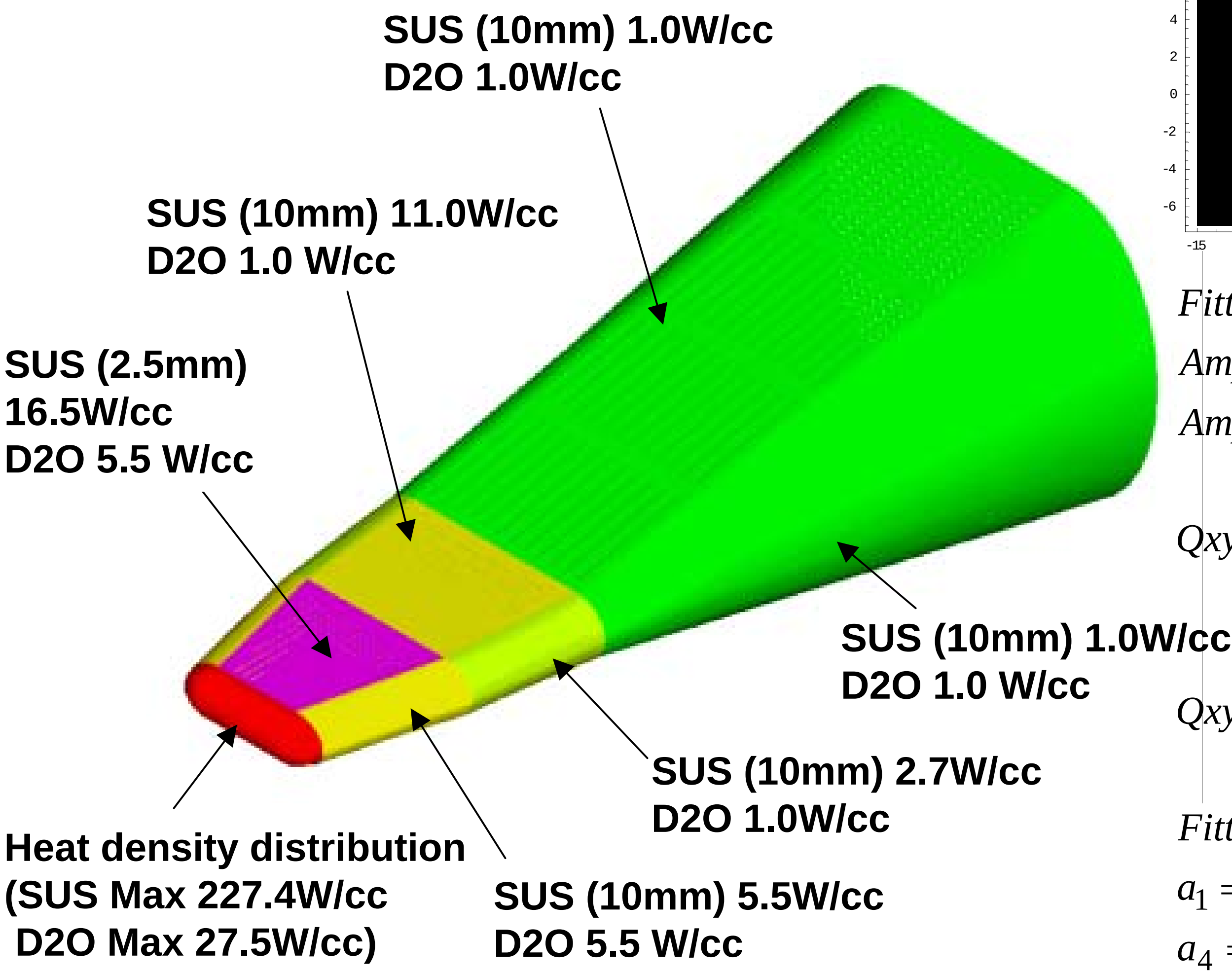
Cross-section of target vessel

① A target vessel flange model to estimate seal performance between a helium vessel and the target vessel flange which works as a boundary of helium atmosphere.

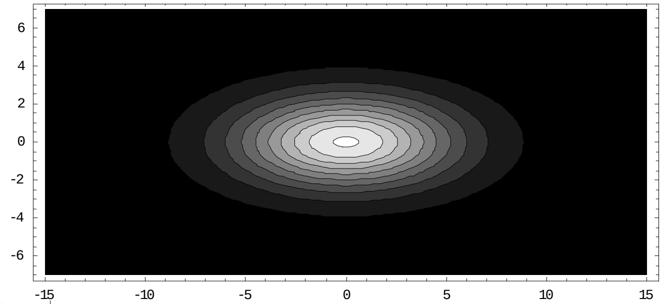
② A mercury connecter model with bellows to verify its operability and to estimate seal performance between the mercury container and the mercury pipelines fixed in the trolley.

Appendix

Heat Density Distribution In Safety Hull
- Gaussian proton beam profile -



Fitting for **Gaussian** distribution.



Fitting for x – y distribution.

$Amp_1 = 400.0, \quad \alpha_1 = 5.0, \quad \beta_1 = 2.2$

$Amp_2 = 61.33, \quad \alpha_2 = 10.0, \quad \beta_2 = 4.5$

$$Qxy_1 = Amp_1 \times Exp\left[-\left(\left(\frac{x}{\alpha_1}\right)^2 + \left(\frac{y}{\beta_1}\right)^2\right)\right]$$

$$Qxy_2 = Amp_2 \times Exp\left[-\left(\left(\frac{x}{\alpha_2}\right)^2 + \left(\frac{y}{\beta_2}\right)^2\right)\right]$$

Fitting for z distribution.

$a_1 = 1.2891, \quad a_2 = 1.7942, \quad a_3 = -0.16017,$

$a_4 = 10.136, \quad a_5 = -0.072889, \quad a_6 = -2.4339$

3D distribution.

$$Q_{xyz} = \left(Qxy_1 + Qxy_2\right)$$

3-D Thermal - Hydraulic Analysis Results

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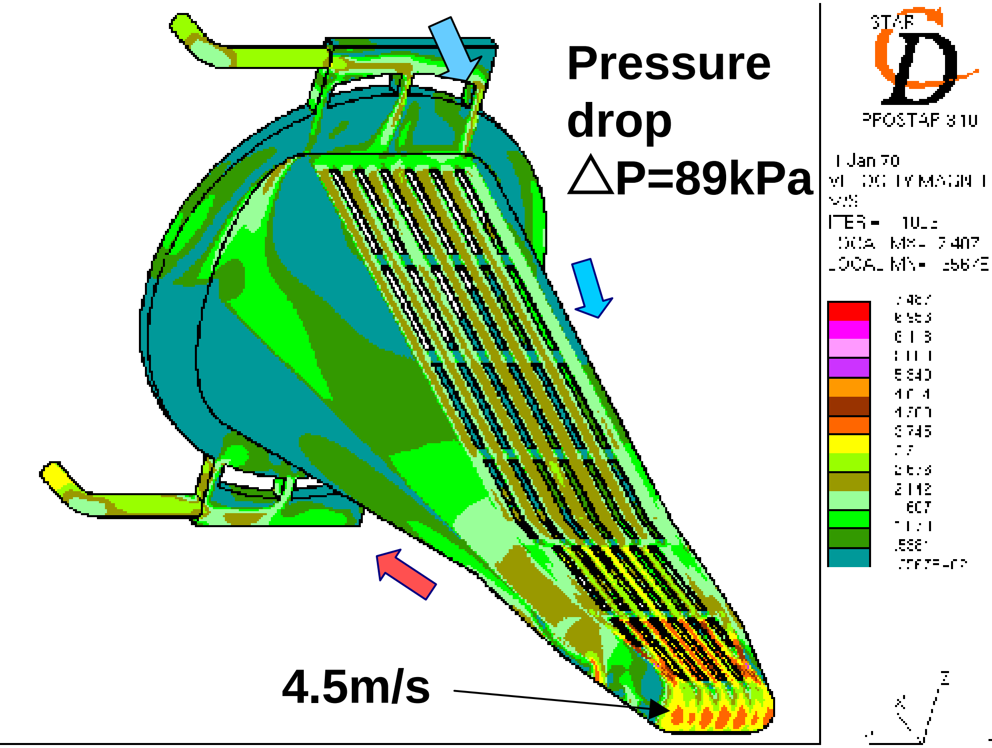
- Velocity and temperature distributions of heavy water in safety hull -

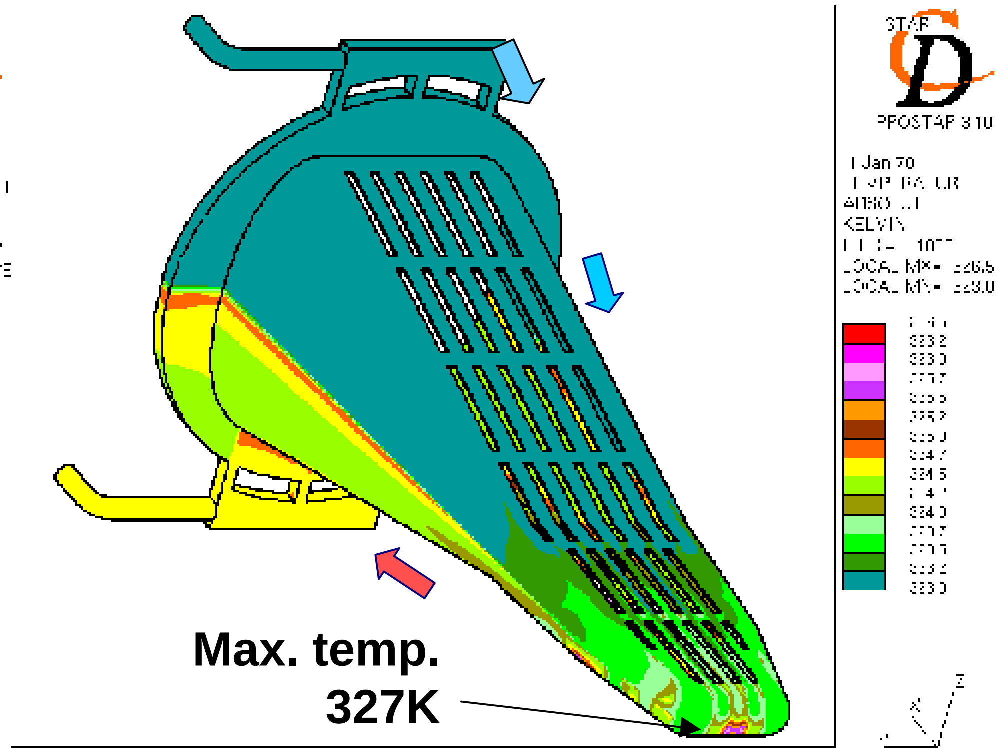
- Inlet heavy water temperature and flow-rate : 50℃, 11.3m^3/h
- Vessel wall boundary condition :
  Constant Heat flux distribution (inner wall)
  Adiabatic condition (outer wall)

Analytical code : Star-CD

Velocity distribution

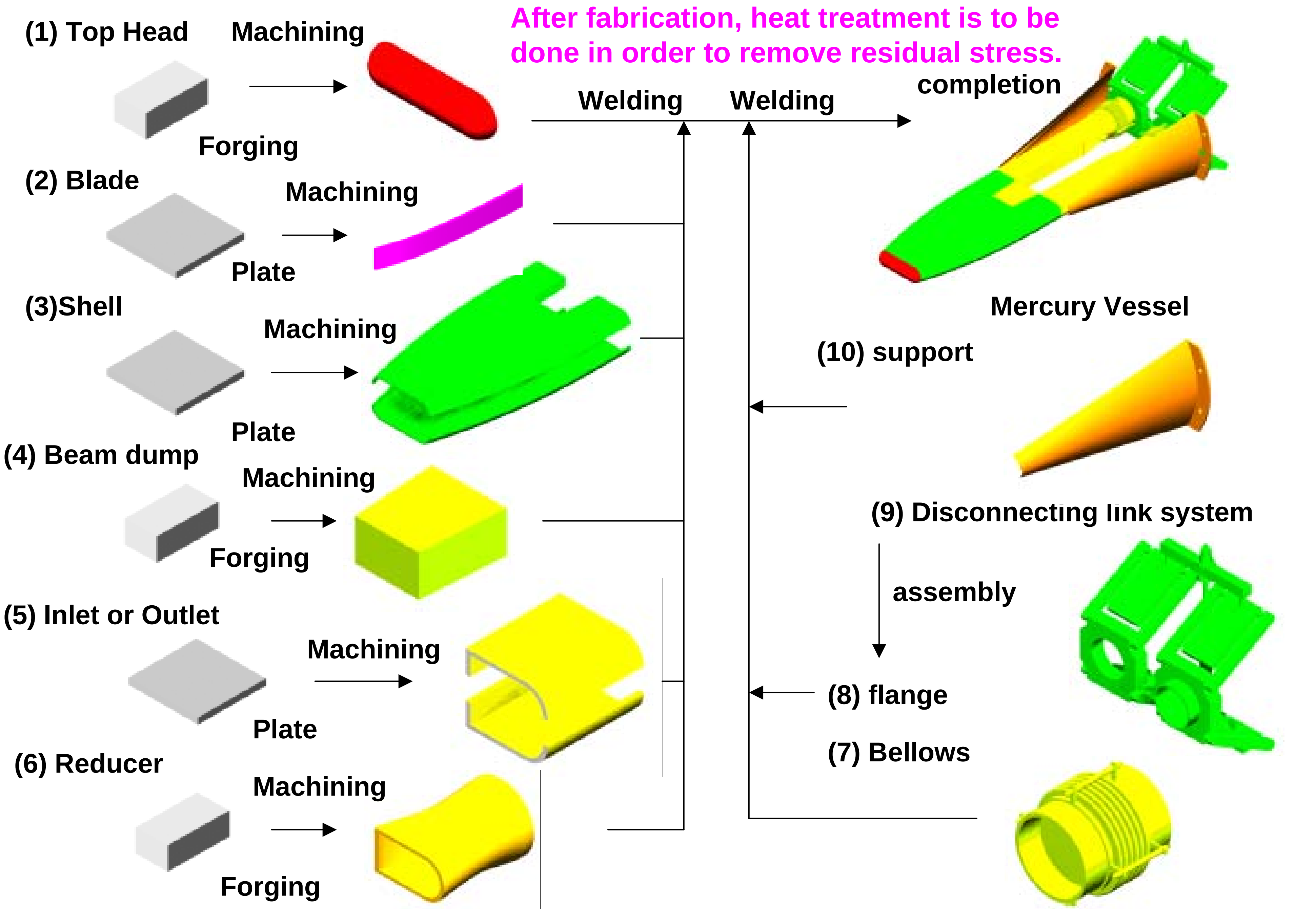


Temperature distribution



- The maximum temperature of 327K is far below the water saturation temperature of 403K at 0.5MPa. (This analytical results are conservative.)

Draft of Fabrication Sequence of Mercury Target



Piping Installed on Target Trolley

Piping with Target Trolley

No.	Piping	Size	Fluid	
1	Mercury for Target INLET	150Ａ	Hg	
2	Mercury for Target OUTLET	150Ａ	Hg	
3	Safety Hull INLET	40A	D_2O	
4	Safety Hull OUTLET	40A	D_2O	
5	Trolley Front Shielding INLET	25A	H_2O	
6	Trolley Front Shielding OUTLET	25A	H_2O	
7	Safety Hull Cover Gas INLET	10A	He	
8	Safety Hull Cover Gas OUTLET +Mercury Drain	20A	He Hg	Helium Gas inside Safety Hull doesn't flow
9	Surge Tank Cover Gas INLET	10A	He	
10	Surge Tank Cover Gas OUTLET	10A	He	
11	Dorain Tank Cover Gas INLET	10A	He	
12	Drain Tank Cover Gas OUTLET	10A	He	
13	Target Vent Pipe	10A	-	
14	Pump Vent Pipe	10A	He	
15	Heat Exchangetr Vent Pipe	10A	He	
16	Mercury Loop Drain Pipe	25A	Hg	
17	Heat Exchanger ＩＮLET	80A	H_2O	Secondary Coolant
18	Heat Exchanger OUTLET	80A	H_2O	Secondary Coolant

Seismic Analysis of Mercury Piping
- Analytical Results -

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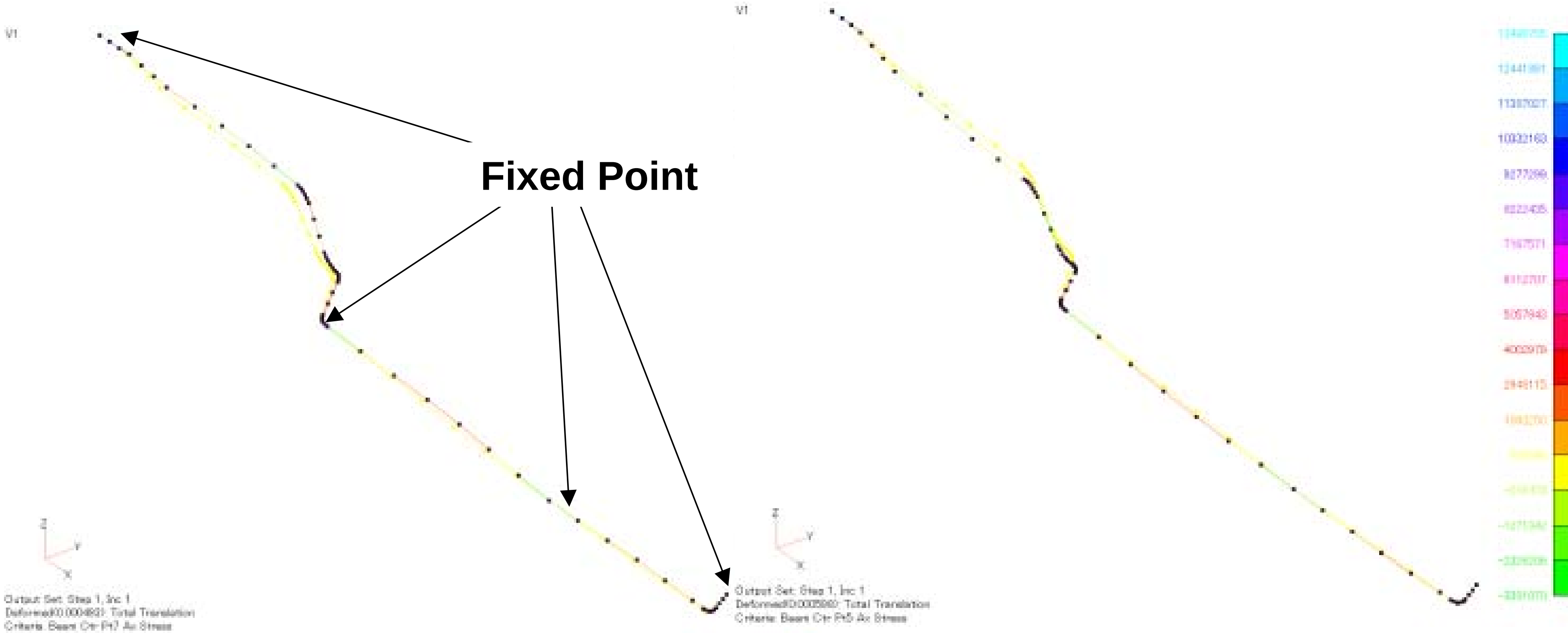

Piping 150A Sch80
Condition **Horizontal Acceleration(1G)**
Max. Deformation (mm) ：0.5
Max. Stress (MPa)：13.7

Piping 150A Sch80
Condition **Vertical Acceleration(1G)**
Max. Deformation (mm) ：0.6
Max. Stress (MPa)：13.5

It will be able to suppress large deformation and stress caused by 1G acceleration with only 4 fixed points

Schematic Drawing of Cable-veyor

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つばきケーブルベヤ
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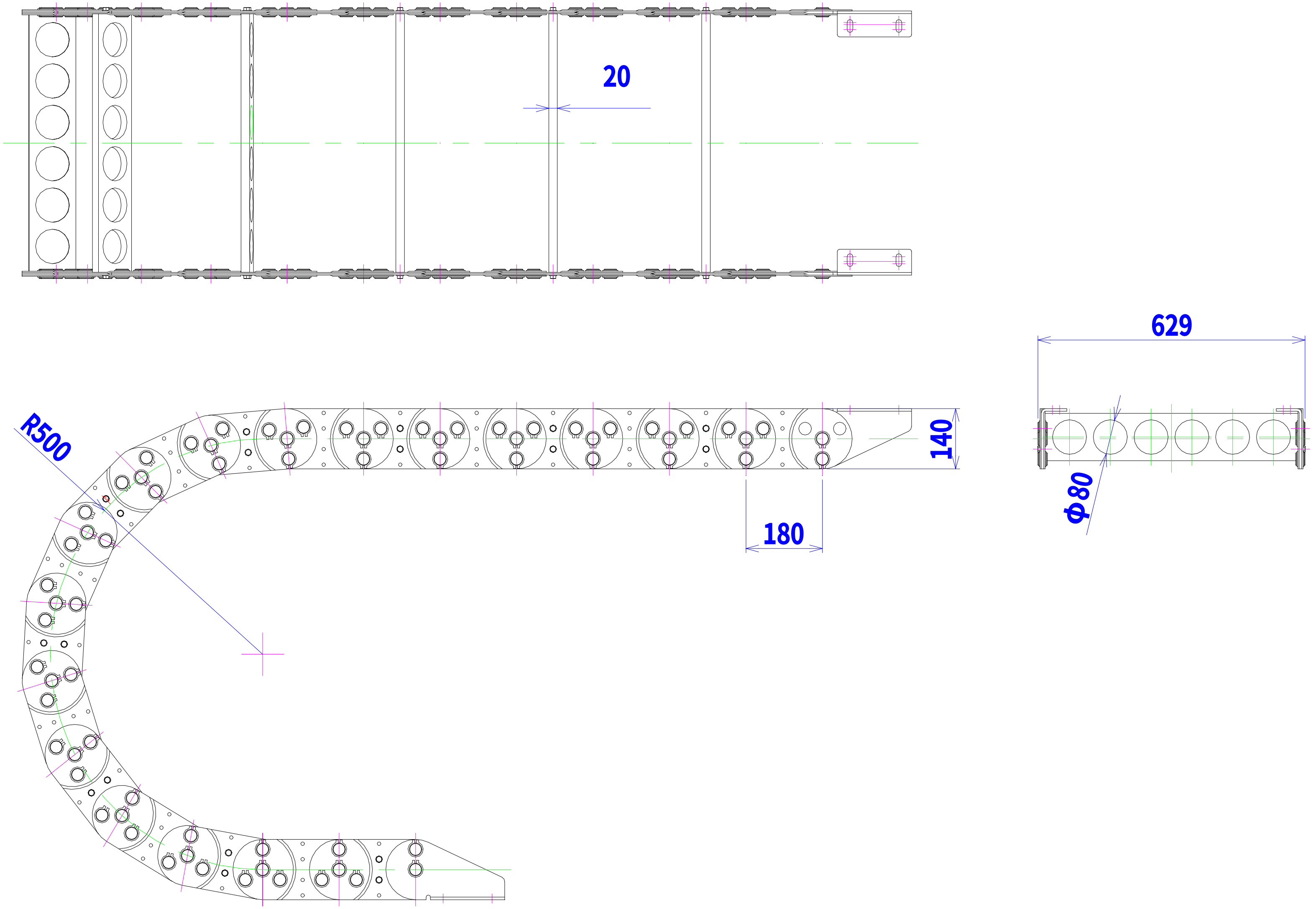

Mock-up Model of Mercury Connectors

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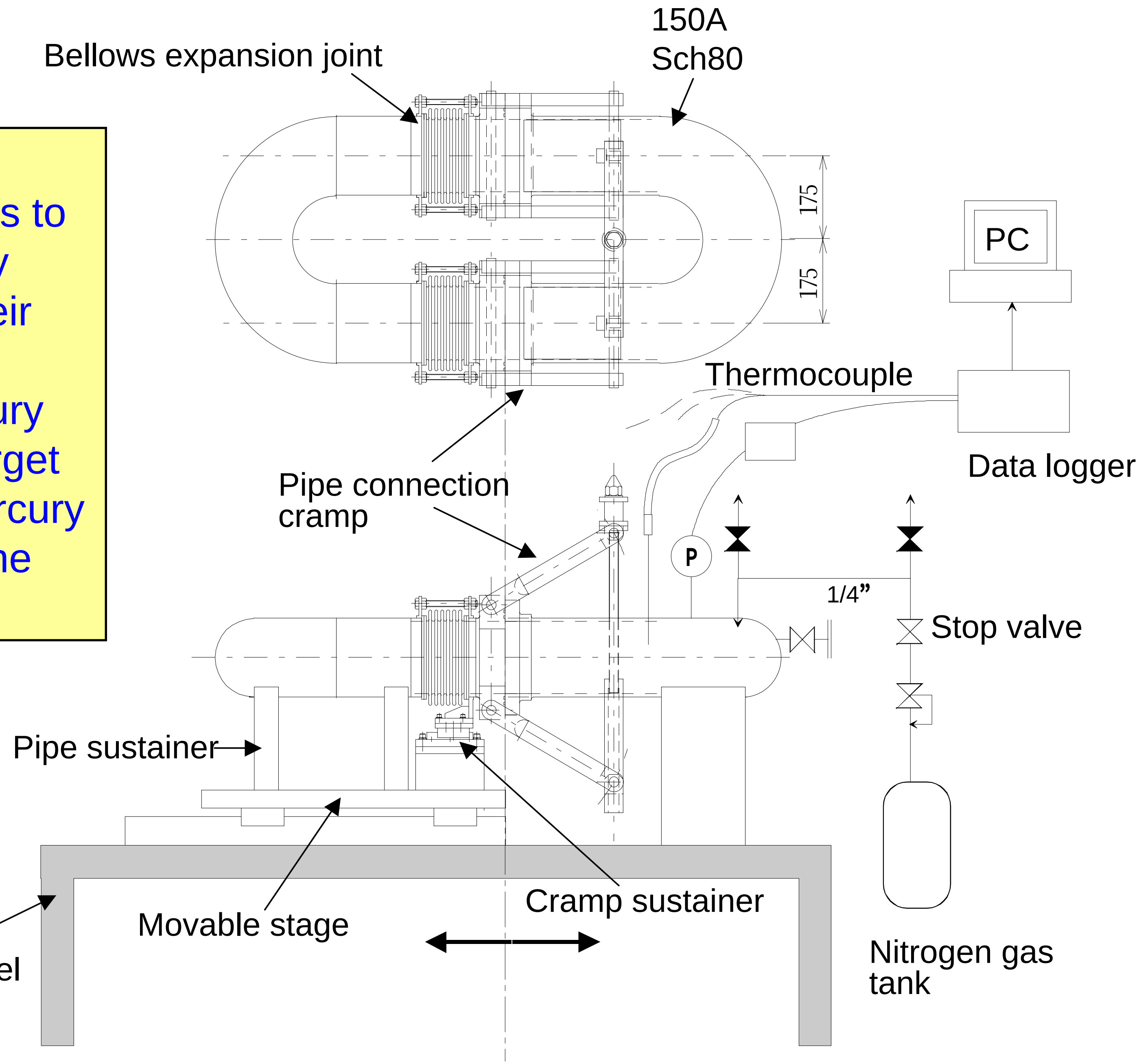
Mock-up model of mercury connectors to verify its operability and to estimate their seal performance between the mercury container of the target vessel and the mercury pipelines fixed in the trolley



Mock-up Model of Target Vessel Flange

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Mock-up model of the target vessel flange, which works as a boundary of helium atmosphere, in order to estimate its seal performance against the helium vessel