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Development of helium vessel in CSNS

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Abstract. Helium vessel is one of important equipments in target station of CSNS, which maintains an inert environment （helium at a slight positive pressure）around the moderators, provides credited confinement functions, and provides access ports for the proton beam, 20 neutron beams and the target. Helium vessel components should be designed to last more than 40 full power years. Water cooling has been arranged in sections of helium vessel to remove the heat deposited by a 500kW beam. This paper describes the thermal analysis and thermal-solid coupling analysis which is performed to optimize structural design.

1. Introduction

CSNS is designed to accelerate proton beam pulses to 1.6GeV kinetic energy at 25Hz repetition rate, striking a solid metal target to produce spallation neutrons. The accelerator is designed to deliver a beam power of 100KW with the upgrade capability to 500kW by raising the linac output energy and increasing the beam intensity. Figure 1 shows a pictorial view of CSNS.

Figure 1. Pictorial view of CSNS

2. Overview

The functions of helium vessel system are to maintain an inert environment (helium at a slight positive pressure) around the moderators, provide a locating surface and structural support for target and proton beam window assembly, support the reflector plug, provide containment in the event of a failure of the target, moderators and reflector plug, and provide access for cooling water to reflector plug and moderators and access for liquid hydrogen line to moderators.

2.1 Design requirements

Helium vessel system components should be for 500kW beam power based on a proton beam energy of 1.6GeV and an average beam current on target of 312.5 uA. Non-replaceable components should have a design basis lifetime of 40 years, while replaceable components should be designed for maximum life within engineering and budget constraints. The mean design requirements are following.

- Inert atmosphere: Vessel should provides an inert atmosphere in the event of a hydrogen leak from the moderatos and containment of activated cooling water in the event of a water leak from the target or the reflector.
- Structural: Helium vessel system should be designed to carry the combined stresses due to coolant pressure, dead-weight loads, thermal effects, and seismic events.
- Thermohydraulic: The cooling water system must remove the heat deposited by a 500kW beam.
- Mechanical: The vessel should provide access ports for proton beam, neutron beams and target. The vessel should provide feedthrough ports for the reflector and moderators piping and connections for vessel utilities. The vessel upper head should allow for replacement of the reflector plugs.
- Remote maintenance: The vessel and neutron beam window should facilitate the use of remote handling equipments used to service the neutron beam window and reflector plugs.
- Seismic: All components should be designed such that the safety functions are maintained during a seismic event up to the 7 degree seismic intensity.
- Instrument and control: Systems will procure the sensors required to measure pressure, temperature and flow, and will provide mounts and taps as required for each instrument at locations throughout the system.
- Decommissioning: System should be designed for disassembly and decommissioning.
- Materials: Material for all structural components should be 316L & 304L austenitic stainless steel.
- Design standard: Vessel should be designed and fabricated according to China national standard JB4732-1995 (The Steel Pressure Vessel-Design by Analysis code).

2.2 Lay out

Helium vessel system (shown in Figure 2) is a vertical cylindrical geometry. It provides access for installing and removing the reflector assemblies vertically through the core vessel top opening, and for installing the target through horizontal ports in the core vessel. The whole system includes the core vessel, the support skirt, the outer reflector, and utility piping inside the core vessel (i.e., vacuum, helium, cooling piping).

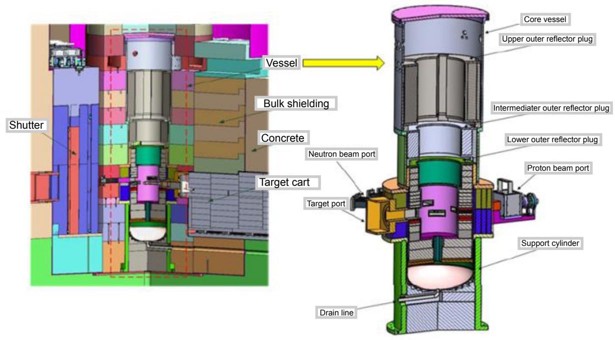

Figure 2. Helium vessel system layout

3. Detail design

3.1 The core vessel

As shown in Figure 3, the core vessel is made up of three components, the chimney assembly, the center section and the lower vessel that are welded together.

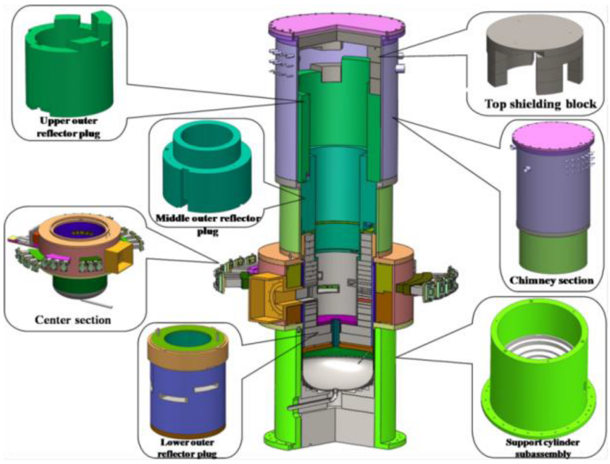

Figure 3. Helium vessel main parts

The chimney is a S30403 step-shaped cylinder structure with a nominal diameter of 2100/2280 mm and a height of 4350 mm. The nominal wall thickness is 50 mm.

The center section is jacket structure with a nominal diameter of 2900 mm and a height of 1400 mm. The nominal wall thickness is 50 mm. The jacket encloses the water-cooled shielding with holes machined for cooling water. The center section contains the proton beam interface, the target interface, and the neutron beam lines. The center section shown in Figure 4.

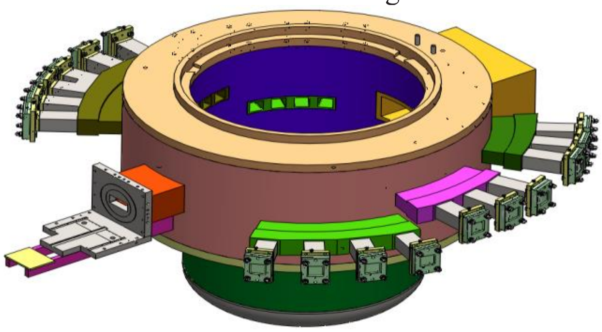

Figure 4. Lower core vessel

Proton beam window (PBW) separates the helium or rough vacuum environment inside the vessel from the high vacuum inside the proton beam line. The proton beam window will be replaced periodically because of accumulated material damage caused by proton fluence. To facilitate replacement of this intensely heated and irradiated structure, pneumatic (inert gas) seals and a vertical assembly and removal path are incorporated into the design. To minimize scattering losses, the window will be located outside the lower vessel, approximately 1890 mm from the center. The window will be located within a housing which also contains the proton beam diagnostics as shown in Figure 5. The sealing surfaces are inside the housing attached to the core vessel. The shelf, flange, and rectangular tube extension should be cooled by light water because of the heat generated by scatter from PBW. The cooling passage is produced by drill and plug. Small shelf is extended from the box for remote vacuum seal clamp to RTBT tube. The housing will support 5 tons load from PBW assembly.

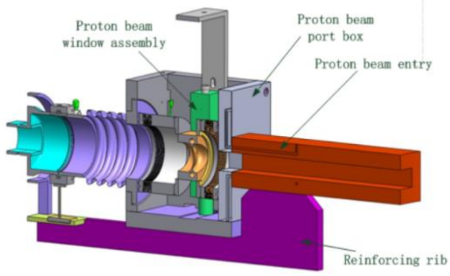

Figure 5. Proton beam port

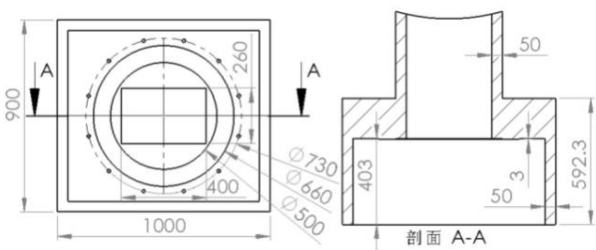

Figure 6. Target box

Target will be inserted into a target box are showed Figure 6. Inside surface of the box provides a mating surface for target inflatable seal, required surface roughness of Ra 0.2um.

Helium vessel has 20 neutron beam lines, eleven above the target, eight below the target and high energy neutron beam. The neutron beam slots which view the decouple moderators will be lined with decoupler material which is cadmium with thickness of 1mm. Neutron beam port windows with seals will be bolted to the flanges shown in Figure 7. These windows have the shape of a convex spherical surface (thickness 1.5mm, Al 6061). Double racetrack seals made of close-wound helical spring and aluminum jacket are used for seal. These windows are expected to have a long lifetime based on the experience of existing spallation facilities. So the design of the neutron beam windows will facilitate the remote handling.

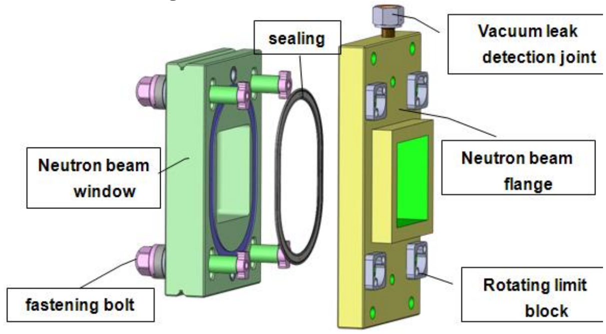

Figure 7. Neutron beam window

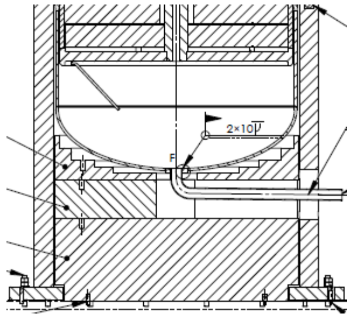

Figure 8. Drain line

The lower vessel is composed of lower cylinder and ellipse head. The collection volume attached to the lower vessel is designed to contain any water that might spill into the core vessel in the event of a failure of the target or reflector.

The drain line is allowed to remove any liquids spilled into the helium vessel. As shown in Figure 8, the drain line terminates in drain tank designed to accommodate the maximum feasible spillage of cooling water inventory. The drain line is a DN80 single wall pipe sloped down to the drain tank (hydraulic slope 2%), which is welded to core vessel when assembly. Ultrasonic and penetrant inspection must be performed after welding on site. Procurement initiated on the drain line so that section embedded in concrete will be available during building construction.

3.2 Support skirt

The support skirt with a nominal wall thickness of 150mm supports the core vessel and all vessel internal components independently from the external shielding, shown in Figure 9. The support skirt is tied into the foundation mat by studs threaded into the base plate embedded in the concrete. These studs bear shear and overturning moment created in a seismic event. A stainless steel layer is built on the upper surface of the support skirt by surfacing welding in order to prevent the interface between support skirt made of carbon steel and vessel made of stainless steel from corrosion.

Figure 9. Support skirt roundness correction

3.3 The outer reflector

The outer reflector plugs consist of top shielding, upper outer reflector plug, middle outer reflector plug and lower outer reflector plug. As shown in Figure 10, the outer reflector plugs with steps to prevent radiation streaming surrounds the inner plug.

The lower outer plug must be cooled with light water, while the other outer plugs do not need. The lower outer plug made of stainless steel is contained within the lower 1870mm-diameter core vessel and slots are cut for the neutron beam lines, the proton beam and the target assembly. The neutron beam slots will be lined with decoupler material similar to which in the inner plugs. Neutron decouplers, which can keep the pulse width short, are made from 1mm thick cadmium. The size of the proton beam hole will be close to that of the nominal beam profile so that, in off-normal cases, stray proton beam energy would be absorbed in this plug rather than in the moderators. A supply line within the plug will bring the light water to the bottom, and the return flow to the top will cool the stainless shielding. The weight of the outer plug assembly is 31 tones. It will be supported on a ring resting on the base of the lower core vessel.

The intermediate and upper outer plugs surround the inner plug and slots are cut for the reflector and moderator piping (cooling, helium and vacuum). The intermediate and upper outer plugs are made of carbon steel with aluminum coating (thickness ≥150 μm). The upper outer plug relies on conduction to the actively cooled components. To minimize the number of remote connectors of piping, the intermediate and upper outer plugs extend 3960 mm above the target center and all connections are located above the plugs.

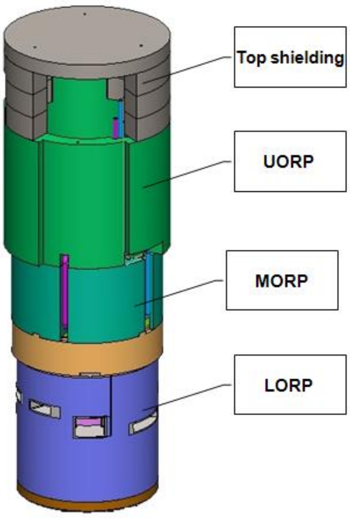

Figure 10. Outer reflector

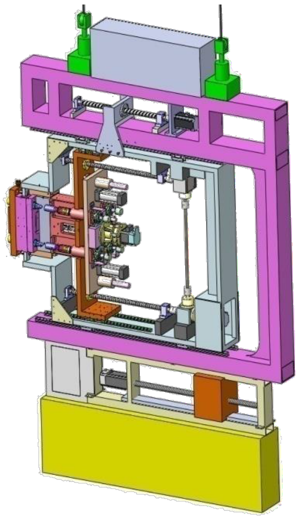

Figure 11. Remote handling device for neutron beam window

3.4 Remote handling device for neutron beam window

The neutron beam windows provide the pressure boundary at the inlets of the neutron beam ports. Studs in the helium vessel flanges and remotely installed nuts secure the window to the vessel flanges and provide the necessary sealing force. The windows are expected to have a long lifetime based on the experience of existing spallation facilities. However, design of the neutron beam windows should facilitate the remote replacement of this irradiated structure because of accumulated material damage caused by neutron fluence. As shown in Figure 11, remote handling device contains two components: bodies supporting frames and elevating section which includes hanger, window handling system and balancing system. Maintain operation will be performed in the gap between bulk shield interstitial blocks.

4. Analysis calculation

4.1 Thermal calculation

In order to study thermal deposition and power-density distribution of helium vessel, the model of target-moderators-reflectors-core vessel was built by MCNPX, and then calculates thermal deposition and power-density distribution of components in helium vessel. The thermal deposition of core vessel contains: lower outer reflector plug, center section of helium vessel and some passive-cooling shielding. Table 1 shows the thermal deposition of helium vessel and inner components.

Table 1. Helium vessel thermal deposition

Components	Heat deposition (500kW)	Cooling mode
Lower outer reflector plug	53kW	Water-cooling
Center section of helium vessel	12kW	Water-cooling
Middle and upper outer reflector	179.4W	Passive cooling
Passive-cooling Shielding	203.1W	Passive cooling
Total	65.04kW	

The maximum temperature below 64℃ present to target port tube due to high heat deposition at 500kW, Figure 12 shows the temperature distribution of center section and lower outer reflector plug after water-cooling as input data of thermal-solid coupling analysis. As a whole, the temperature was well-distributed and difference in temperature was less than 20℃, the temperature near proton beam port should be lower due to proton beam cooling structure.

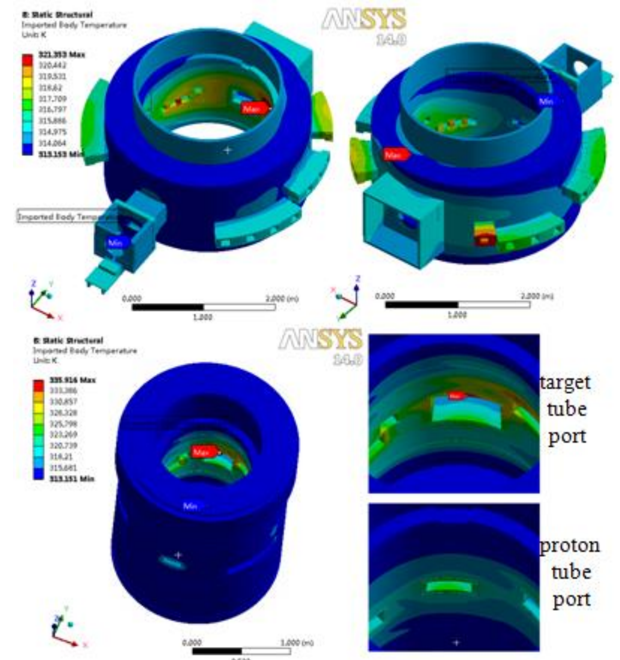

Figure 12. Temperature distribution of center section and lower outer reflector plug after water-cooling

4.2 Structure strength analysis

FEA analysis was performed using the helium vessel model compromise of shell and solid elements imposed appropriate loading according to different working conditions. Analysis criterion were as follows:

- The temperature has been predicted to reach a maximum of 65℃.
- The allowable design stress intensity for all forms of S30403 is 118MPa for any temperature less than 150℃ (JB4732-95).
- The allowable design stress intensity of Al6061T6 is 68MPa for any temperature less than 100℃ (JB4734-2002).
- The maximum displacement less than 2mm.

For integral model three different calculation conditions were considered, such as working condition, design condition and maintenance condition. There were four calculation conditions of lower outer reflector plug, such as working condition, design condition, maintenance condition and cooling failure condition.

4.2.1 Vessel working conditions structure strength analysis

Shows Integral model working conditions stress & deflection, for example, FEA analysis was initially performed using the full model of the vessel. Applied loads include:

- 0.0025 MPa internal overpressure
- 0.4 MPa pressure in the water jacket
- Gravity loads of all internal shielding and equipment
- 100 kN inflatable seal force in target port
- 50 kN inflatable seal force in proton beam port
- 5 Tons gravity load on proton beam port

Restraint: support skirt bottom plane full restraint, shown in Figure 13.

Conclusions: Figure 13 shows the maximum stress intensity appears on upper support plate groove for lower outer reflector plug alignment block, the maximum stress intensity is 47.854MPa. The maximum displacement is 0.264 mm in proton beam port. With the proper corner radius to reduce stress concentration at this location, the vessel satisfies the requirements of the allowable design stress intensity by the pressure vessel code. Vessel deflections are small.

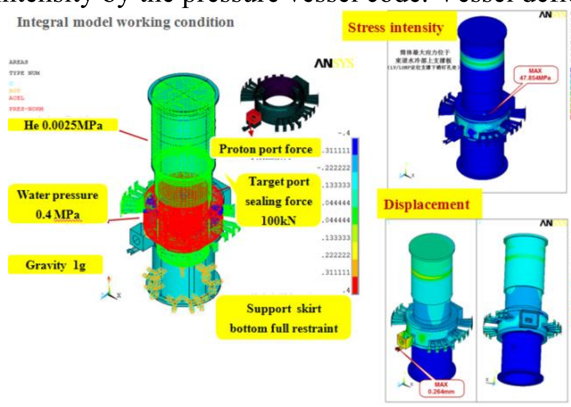

Figure 13. Vessel working condition FEA model

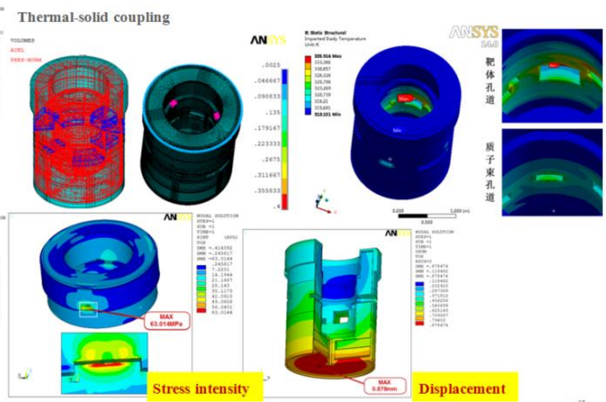

Figure 14. Lower outer reflector plug FEA model

4.2.2 LOPP working conditions thermal-solid coupling analysis

FEA analysis was initially performed using the model of lower outer reflector plug. Applied loads include:

- 0.0025MPa internal overpressure
- 0.5MPa pressure in the water jacket
- Gravity loads of all internal shielding and equipment
- shielding equivalent pressure 0.153&11.313MPa
- the temperature distribution of water-cooling, MAX temperature 62.916℃

Restraint: lower outer reflector plug alignment block groove side toroidal restraint and groove plane axial restraint, shown in Figure 14.

Conclusions: Figure 14 shows the maximum stress intensity appears on upper support plate groove for lower outer reflector plug alignment block, the maximum stress intensity is 63.014MPa. The maximum displacement is 0.878 mm in proton beam port. With the proper corner radius to reduce stress concentration at this location, the vessel satisfies the requirements of the allowable design stress intensity by the pressure vessel code. Vessel deflections are small.

4.3 Anti seismic calculation

CSNS located in Dong guan City, Guangdong Province where seismic fortification intensity is level 6. The helium vessel is defined as important facility, seismic fortification intensity of helium vessel is level 7. The seismic load will be represented by a 0.2G lateral acceleration (single direction, not vibrating). The purpose of this study is to document the stresses and deflections associated with a seismic event, FEA analysis was initially performed using the full model of the vessel. Applied loads include:

- 0.1MPa internal overpressure
- 0.6MPa pressure in the water jacket
- Gravity loads of all internal shielding and equipment
- 100kN inflatable seal force in target port
- 50kN inflatable seal force in proton beam port
- 5Tons gravity load on proton beam port
- 0.2g horizontal acceleration (along target direction)

Restraint: Support skirt bottom plane full restraint, shown in Figure 15.

Conclusions: Figure 15 shows the maximum stress intensity is 68.508MPa which appears on support skirt pin contact. The maximum displacement is 0.988mm at center of lid.

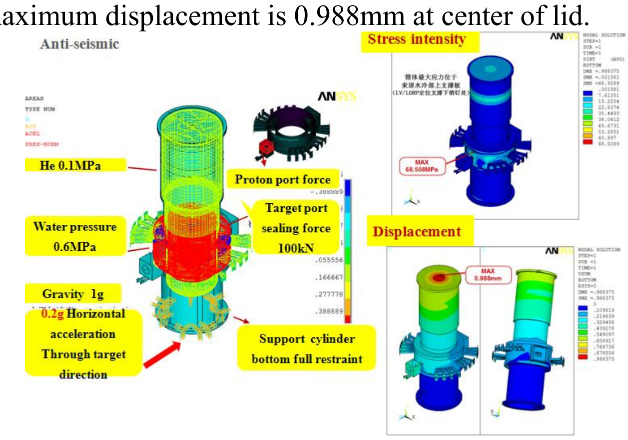

Figure 15. Vessel anti-seismic FEA model

5. Manufacture and installing

5.1 Manufacture progress

The helium vessel manufacturing process review was held in Nanjing on January 2013. The review content included manufacturing process scheme, quality plan and production schedule. The detailed engineering drawings of helium vessel were formally issued on January 2013, and formal processing was started.

5.1.1 Center section

Cylinder and the lower flange were assembled, fixed support in the cylinder upper opening, and welded after the cylinder rolling, welding, and roundness correction. The wall and end-face of the outer and inner cylinder were machined by vertical lathe, based on the lower flange surface, adjusting cylinder to coincide with the center of the turntable of CNC facing boring lathe, and then indexing to determining the location of the fan-shaped and square-shaped hole, boring the holes. Assembling and welding the tube blocks, shielding block, the upper flange, etc. Assembling error of all tubes are measured and adjusted to the allowable range. Welding deformation is the main factor causing manufacturing errors of all tubes. To reduce the welding deformation, fixing support, taking anti-deformation to ensure the correct position of each tube. Real-time monitoring the deformations and adjusting the welding sequence, lowering welding input and interpass temperature during the manufacturing process. Finishing the protons and the target tubes connecting flange, polishing to the requirement with the lower flange surface as the reference plane, Figure 16 & 17 shows center section is under assembling and welding.

Figure 16. Center section assembling

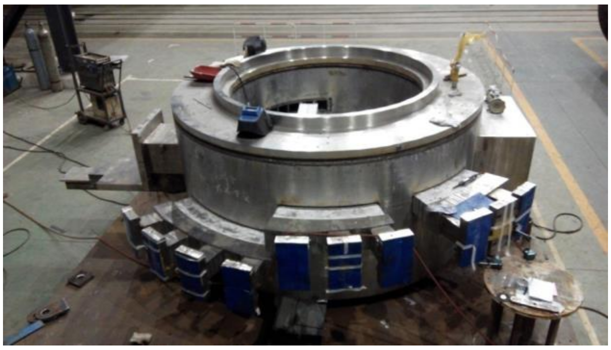

Figure 17. Center section welding

The neutron beam tube block consist of upper & lower plates and interval block, reserving machining allowance on the upper and lower plate thickness, the side face of outside plate, the interval block processed; sandwiching cadmium plate between those plates and stainless steel plate, and then bolting; assembling the plates, and inserting the square (114 × 114) mandrel to correct position of each plate, bolting and welding, plug welding thread sink hole on the interval block. Machining tube profile, positioning face and positioning stepped square hole with inner hole as reference. Inserting the square mandrel (H8/e8 fits) to assembling and welding the branch tube and confluence tube; taking anti-deformation measures to reduce welding deformation, finally finishing the flange face to the requirement.

5.1.2chimney section

Chimney section cylinder has been rolled, welded, roundness correction, vibration aging was proceeded, and then boring pipe openings according to piping layout design. Figure 18 shows Chimney section in assembling.

Figure 18. Chimney section welding

5.1.3 LORP

Cylinder and the lower flange are assembled, fixed support in the cylinder upper opening, and welded after the inside and outside cylinders rolling, welding, roundness correction. The wall and end-face of the outer & inner cylinder are machined by vertical lathe. Assembling and welding partially cooling plate, and the lower flange, fixing support in the cylinder upper opening to prevent deformation. Based on the lower flange face, adjusting cylinder to coincides with the center of the turntable of CNC facing boring lathe, and then indexing to determining the location of the fan-shaped and square-shaped hole, boring the holes. Assembling and welding the tubes, cooling plates, the upper flange, etc. Fixing support, taking anti-deformation measures to ensure the correct position of each tube. Finishing the outer wall of the cylinder, positioning groove and end face by vertical lathe.

5.2 Installation of support skirt

Before installation of support skirt, installation error of the base plate was reinspected. Use pins in the base plate to positioning the support skirt. Use four screws in the foundation ring of the support skirt to adjust the upper surface elevation of the support skirt to 1.1m (error is less than 0.5mm), All installation and adjustment were monitored by laser tracker. Installing inner shielding block in the support cylinder, then welding drain line. Figure 19 shows support skirt after installation.

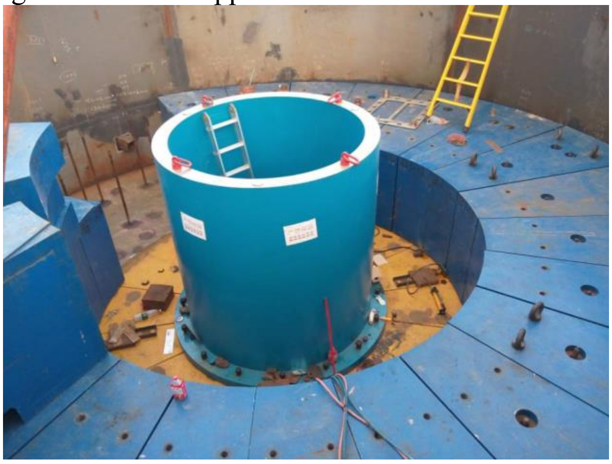

Figure19. Support skirt installment

5.3 Acceptance Testing Requirement

After completion of installation and prior to commissioning with the proton beam, a series of tests shall be performed on the Vessel Systems to insure and demonstrate their readiness for operation. The following tests shall be performed as part of acceptance testing:

- Demonstrate leak tightness of assembled water piping;
- Demonstrate leak tightness of the core vessel pressure boundary for both vacuum and helium environments;
- Demonstrate ability to install the proton beam window using remote handling equipment;
- Demonstrate ability to make and break pipe and structural joints required for maintenance of equipment;
- Demonstrate that the coolant flow through the vessel is within design parameters;
- Demonstrate ability of inflatable seal to seal against the proton beam window box fitting;
- Demonstrate ability of inflatable seal to seal against target assembly;
- Demonstrate ability to install the neutron beam window using remote handling equipment; and
- Demonstrate functionality of core vessel drain system.

6. Conclusion

- The design of helium vessel was reasonable, and met physical requirements.
- The machining and welding quality are under control in fabrication procedure.
- The progress of helium vessel meet the requirements of construction schedule
- The manufacture of helium vessel will be completed in the end of 2014.

References

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