Abstract
The HT-7U superconducting tokamak is under constructing. It is expected to complete the fabrication and installation in future 2 to 3 years. Overall configuration of the device is described in other paper.[1] The vacuum vessel is full welded with “D” shaped cross-section and double wall. It consists of 16 segments and support by 8 flexible multiple plate supports. Ports are distributed at top, bottom and middle plan. Low stiffness supports, and two sections of bellows on each port allow the vacuum vessel can move a little in radial direction to accommodate the expansion during the vessel bake-out to 250°C. Some R&D of the vacuum vessel is completed, and fabrication is in progress.

1. Vacuum Vessel Design[2]

1.1 Overall Structure
The vacuum vessel is torus-shaped with “D” shaped cross-section, double wall, upper vertical ports, lower vertical ports, horizontal ports and flexible supports. It shows as Fig1. The torus consists of 16 segments and each segment consists of inner shell, outer shell, ribs and ports. Two ribs separate outer shell and inner shell, and give the required mechanical strength. The ribs are spiccato welded to inner shell and slot welded to outer shell. At each end of the segment a rib (end rib) is tight welded both to inner shell and outer shell. Ports’ connections stub tight welded to shells are necessary before the device assemble. Ports will be welded to ports’ connection stub when the device is assembled. Each port will be connected both to cryostat and peripheral equipment. Eight flexible multiple plate supports are symmetrical distribute around the torus and connect to lower vertical ports.

The space that formed by shells and ribs will be filled with boride water both for vessel cooling and reduce neutron radiation. One octant is a cycle unit. Water inlet is on inner shell at vessel bottom, boride water will along the channels formed by ribs and shells and through holes on ribs go to outlet. During bake-out hot nitrogen gas go through the same way.

1.2 Material of Vacuum Vessel

The principle of choice of material for vacuum vessel has a significant influence on performance, fabrication characteristics, mechanical strength at operating temperature, chemistry properties, and low cost relative to other candidates. Compared with Ti6Al4V, Inconel, SS-316LN and SS-304L, 316L stainless steel has lower cost, good mechanical properties, good chemistry properties and good fabrication characteristics in deferent extent. It is selected as main material of the vessel. Table 1 shows the main parameter of vacuum vessel and material.

2. Structure Analysis

2.1 Model and Analyses
Consider symmetrical of vacuum vessel. A model of 1/16 vacuum vessel shows as Fig2 is employed for structure analyses. Bellows on ports and low stiffness supports are considered as spring components. At each end of ports in X, Y, Z directions proper rigidity was applied on. The value is showed as table2. Rotate freedom degrees of each port end ware not confined. From working conditions are described in next paragraph it can be seen under load condition 3 and 5 stress is quite high. In these cases thermal deformation is the main reason that cause peak stress at each port end is higher than that under other load conditions. But detail analyses indicate peak stress was caused by stress concentration.
2.2 Load and stress Description and Values
The vacuum vessel must withstand many individual and combined loading conditions during vacuum test, normal and off-normal operation. Because the vessel is double wall, several different working conditions must be considered. During vacuum test space between double wall will be pumped into vacuum, during operation space between double wall will be filled with shielding water, and during bake out hot nitrogen will flow through the interlayer. Being superconducting tokamak when the device in operation both inside and outside of the vessel will be pumped into vacuum. While plasma breakdown and disruption electromagnetic forces is much strong. Table 3 shows different load conditions, load values and stress values.

2.3 Bulking
The vacuum vessel is considered as thin wall vessel. To check its stability is necessary. The loads affect stability including dead weight, atmospheric pressure, borated water pressure and EM loads. Atmospheric pressure and borated water pressure is uniform and EM load is non-uniform. Peak EM load caused by eddy current in toroidal direction is 3.95kg/cm², in normal direction is 3.9kg/cm², in poloidal direction is 3.9kg/cm², and peak EM load caused by halo current is 2kg/cm². Analysis considered all load conditions described in paragraph 2.2.

Linear buckling analysis indicates the double wall structure is safe enough for stability. Table4 shows different thickness of vacuum vessel wall can withstand different buckling load.

3 R&D
For the vacuum vessel a testing system was set up to check the reliability of bellows on ports and multiple plate support is necessary. Fig3 shows the testing system. Two section of bellows, port which connect to multiple plate supports and one set of multi plate support was fabricated. A testing platform, which can simulate bellows and supports deformation during vacuum vessel bake-out, was set up. During test stress on bellows and supports was measured by resistance strain gauges and photo-elastic test. Compare stress value from structure finite element analyses and stress value of testing measured 10% difference exists. Consider the life of HT-7U device fatigue of bellows and support was test on the same testing system. The bellows and supports were made to simulate bake-out distortion 100 times, and didn’t find any damage. The testing demonstrated the structure of vacuum vessel supports and bellows is proper for the device.

4 Baking and Cooling
The vacuum vessel should bake-out to 250°C to degassing helium and hydrogen in structure material. Because vacuum vessel is double wall structure, hot nitrogen will be employed to go through the channel formed by vacuum vessel inner shell, outer shell and ribs for vacuum vessel bake-out. Consider symmetrical of vacuum vessel one octant was select for hot gas recycling unit. A thermal analysis model of one octant has been set up and analysis was finished. Fig4 shows the temperature distribution when the highest temperature on the model is 550K. The average temperature on the octant is 536K and the biggest temperature difference is 27K. This is satisfied the requirements of vacuum vessel bake-out. Table5 shows the parameters of hot nitrogen gas and temperature situation. During the device operation the vacuum vessel will be maintain 90-95°C. Boride water recycling system is possible to be used to adjust temperature of vacuum vessel.

5 Fabricate
The vacuum vessel consists of 16 segments. But the vacuum vessel is not a 16-sides polygon; it is “D” shape contour rotate round axis of the device obtained. During fabricate each segment will be made separately. Along the poloidal direction inner shell and outer shell make into 4 pieces. Each piece will be model press to obtain the required shape. When the shell pieces and ribs are assembled, first of all to fix inner shell pieces on an assemble model which has been machined to required shape and weld inner shell
pieces into “D” shape, put outer shell pieces on another assemble model and weld into “D” shape shell, then weld enhance ribs to inner shell, then weld outer shell to ribs, then weld end ribs both to inner shell and outer shell. After these welds were completed machine holes for ports and weld port connections in the holes. Vibration aging is necessary for each segment before it take off the model. Model press inner shell and outer shell to required accurate and welding distortion control are important and has some difficult during the fabrication. The first segment of the vessel is under fabricate and expect to be completed at the end of 2002.

6. Conclusion
HT-7U vacuum vessel was designed for long pulse and steady state plasma operation. It should withstand various loads during normal and abnormal operation. During fabrication the points that stress is high should consider optimize structure to avoid stress concentration. Testing on first segment is necessary to demonstrate peak stress is below warning value.

Reference
Table 1 Vacuum Vessel Parameters

<table>
<thead>
<tr>
<th>Size:</th>
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<tbody>
<tr>
<td>- Toroidal Extent of Sector</td>
<td>16°</td>
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<tr>
<td>- Shell Thickness</td>
<td>8 mm</td>
</tr>
<tr>
<td>- Rib Thickness</td>
<td>15 mm</td>
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<tr>
<td>Material</td>
<td>SS-316L</td>
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<table>
<thead>
<tr>
<th>Surface Area/Volume:</th>
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<tbody>
<tr>
<td>- Interior Surface Area (Include Ports)</td>
<td>162.4 m²</td>
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<tr>
<td>- Interior Volume</td>
<td>36.1 m³</td>
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<tr>
<td>- Interlayer Volume</td>
<td>5.2 m³</td>
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<table>
<thead>
<tr>
<th>Mass:</th>
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<tbody>
<tr>
<td>- Main Vessel</td>
<td>13.2 Tons</td>
</tr>
<tr>
<td>- Ports, Flanges and Supports</td>
<td>20.1 Tons</td>
</tr>
<tr>
<td>- Shielding Water</td>
<td>5.2 Tons</td>
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<td>- Total</td>
<td>38.5 Tons</td>
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<table>
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<tr>
<th>Resistance:</th>
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<tr>
<td>- Toroidal</td>
<td>~85.4 μ Ω</td>
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<tr>
<td>- Poloidal</td>
<td>~20.7 μ Ω</td>
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Table 2 Stiffness of each end of port (N/mm)

<table>
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<tr>
<th>Directions</th>
<th>Vertical ports</th>
<th>Horizontal ports</th>
<th>Supports</th>
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<tbody>
<tr>
<td>X</td>
<td>1492</td>
<td>2630</td>
<td>1603</td>
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<tr>
<td>Y</td>
<td>32</td>
<td>2577</td>
<td>58479</td>
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<td>Z</td>
<td>1680</td>
<td>160</td>
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Table 3 Different load conditions

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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tr>
<td>Pressure Inside vacuum vessel</td>
<td>vacuum</td>
<td>0.1MPa</td>
<td>vacuum</td>
<td>0.1MPa</td>
<td>vacuum</td>
</tr>
<tr>
<td>Pressure Outside vacuum vessel</td>
<td>0.1MPa</td>
<td>vacuum</td>
<td>vacuum</td>
<td>0.1MPa</td>
<td>vacuum</td>
</tr>
<tr>
<td>Pressure in interlayer</td>
<td>0.1MPa</td>
<td>0.1MPa</td>
<td>0.1MPa</td>
<td>vacuum</td>
<td>0.2 MPa</td>
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<tr>
<td>temperature</td>
<td>300K</td>
<td>300K</td>
<td>523K</td>
<td>300K</td>
<td>367K</td>
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<tr>
<td>EM load</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>Halo current load and eddy current load</td>
</tr>
<tr>
<td>Peak Stress</td>
<td>82.5 MPa</td>
<td>82.8 MPa</td>
<td>561 MPa</td>
<td>48.8 MPa</td>
<td>492 MPa</td>
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Table 4 Buckling load with different thickness

<table>
<thead>
<tr>
<th>Model cases</th>
<th>Wall thickness (mm)</th>
<th>Buckling load(MPa)</th>
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<tr>
<td>1</td>
<td>8</td>
<td>1.26</td>
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<tr>
<td>2</td>
<td>9</td>
<td>2.09</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>3.45</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>6.41</td>
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<td>5</td>
<td>20</td>
<td>14.49</td>
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Table 5 Parameters of hot nitrogen

<table>
<thead>
<tr>
<th>Inlet temperature</th>
<th>Inlet pressure</th>
<th>Outlet pressure</th>
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<tr>
<td>550K</td>
<td>0.2MPa</td>
<td>0.18MPa</td>
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Fig. 1 Configuration of Vacuum Vessel

Fig. 2 Structure Analysis Model

Fig. 3 Bellows and Supports Testing

Fig. 4 Temperature distribution during bake-out