Fusion Engineering and Design 146 (2019) 822–826

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Assembly and final dimensional inspection at factory of the JT-60SA Cryostat Vessel Body Cylindrical Section

José Botija[a,*], Javier Alonso[a], Santiago Cabrera[a], Pilar Fernández[a], Mercedes Medrano[a], Francisco Ramos[a], Esther Rincon[a], Alfonso Soleto[a], Antonino Cardella[b], Kei Masaki[c], Akira Sakasai[c], Yusuke Shibama[c], Alberto González[d], Aitor Rodriguez[d]

[a] Association EURATOM – CIEMAT, Avda. Complutense 40, 28040, Madrid, Spain
[b] Fusion for Energy, JT-60SA European Home Team, 85748, Garching bei Munchen, Germany
[c] National Institutes for Quantum and Radiological Science and Technology (QST), Naka-Ibaraki, 311-0193, Japan
[d] ASTURFEITO S.A., Parque Empresarial Principado de Asturias, Av. de la Siderurgia, 33417, Avilés, Spain

ARTICLE INFO

Keywords:
JT-60SA
Cryostat
Cryostat Vessel Body Cylindrical Section

ABSTRACT

The superconducting tokamak JT-60SA is currently being assembled at the QST laboratories in Naka (Japan). Within the European contribution in the framework of the Broader Approach, Spain has been responsible for providing JT-60SA cryostat. The cryostat is a large vacuum vessel made up of 304 stainless steel which encloses the tokamak providing the vacuum environment to reduce thermal loads on the components at cryogenic temperature. It must withstand the external atmospheric pressure during normal operation and the internal overpressure in case of an accident. Due to functional purposes, the cryostat has been divided in three assemblies: the Cryostat Base (CB), the Cryostat Vessel Body Cylindrical Section (CVBCS) and the Top Lid. For transport and assembly reasons the cryostat is made up of 20 main parts: 7 making up the CB and 13 making up the CVBCS (including the top lid). The joints between them rely on bolted flanges together with light seal welds, non-structural fillet welds performed from inside and/or outside of the cryostat. The single wall is externally reinforced with ribs to support the weight of all the ports and port plugs and also to withstand the vacuum pressure. The material is SS 304 (Co < 0.05 wt%) with a permeability (μ_{rel}) below 1.1. The CVBCS made of a single wall is a stainless steel shell with a thickness of 34 mm. The CB was manufactured and assembled in-situ in 2013, while the CVBCS has been manufactured, assembled, measured by a Spanish company (ASTURFEITO S.A) and delivered to Japan in November 2017. The paper summarizes the assembly and final measurement of the CVBCS at the factory.

1. Introduction

The main parameters and features of the cryostat (Fig. 1) are summarised in Table 1. The cryostat has many openings, some as large as 2322 mm x 1152 mm, where ports have been welded to accommodate the ducts to the vacuum vessel (VV), magnet service components (cryogenic terminal boxes, valve boxes), manholes with lids to get inside, and where assembly of sensor boxes, in-cryostat feeders, etc. will be fitted. Large bellows are used in between the cryostat and the VV to accommodate differential thermal expansion and fabrication tolerances of both structures. The CVBCS supports the weight of all the ports, port plugs, the top lid as well as the loads from the operation of the experiment in normal/abnormal conditions (such us vacuum pressure/overpressure, electromagnetic loads) or external events such as seismic loads.

Due to the transportation constraints posed by the port of entry in Japan and the QST site, the cryostat assemblies had to be suitably segmented. The CB [1] comprises seven pieces and the CVBCS [2] is subdivided in two main assemblies (Fig. 2): the bottom part (consisting of 8 sectors) and the top part (consisting of 4 sectors). After the fabrication of the individual sectors the CVBCS was assembled at the factory, adjusted and dimensionally inspected before being shipped to Japan, where it will be finally assembled on-site (next year 2019). The CVBCS sectors were packaged independently and appropriately to be shipped to the port of entry in Japan.

Special attention has been paid to protect the delicate surfaces such as machined surfaces, flanges, reference marks, etc. during transport.

The CVBCS is built by cylindrical sections connected by truncated-

* Corresponding author.
E-mail address: jose.botija@ciemat.es (J. Botija).

https://doi.org/10.1016/j.fusengdes.2019.01.090
Received 25 September 2018; Received in revised form 8 January 2019; Accepted 17 January 2019
Available online 13 February 2019
0920-3796/

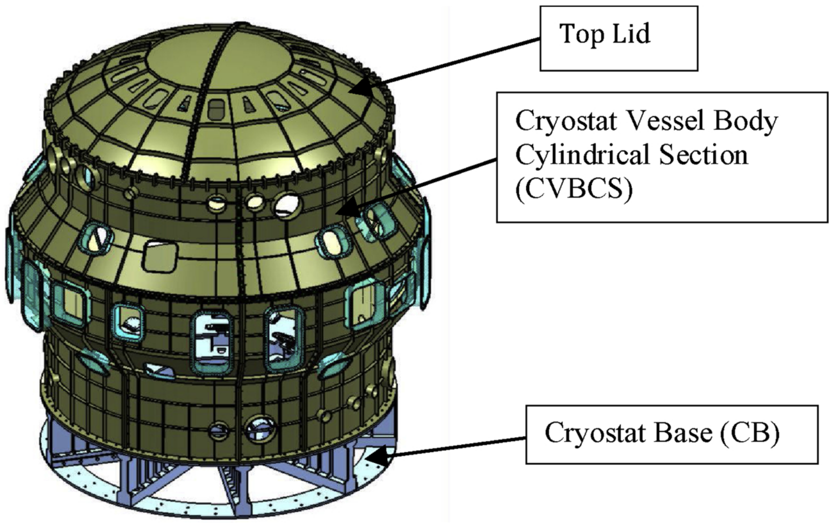

Fig. 1. JT-60SA Cryostat.

Table 1
Cryostat main parameters and features.

JT-60SA Cryostat	
Cryostat dimensions	Ø 13.47 m x 15.85 m height
CVBCS dimensions	Ø 13.47 m x 11 m height
Operational pressure	Vacuum, 10^{-3} Pa
Volume	1410 m^3
Cryostat/CVBCS weight	˜468/175 tons
Surface exposed to vacuum	1368 m^2
Design temperature	293 K

conical elements. It consists of a single-shell vessel (34 mm thickness for shielding purposes) externally reinforced with 20 mm thick ribs. Each sector is surrounded by 80 mm thick bolted flanges which connect the different sectors of the vessel body. The vacuum tightness of the CVBCS will be done by thin non-structural welds performed between sectors from inside/outside of the cryostat during the final assembly in Naka. The individual sectors turned out to be very flexible components due to their open geometry, relatively thin wall and a large number of openings/ports of different dimensions. Nevertheless the related tolerance requirements, for the entire CVBCS, are very tight: ± 4 mm in height, ± 4 mm in radius on main flanges and ± 0.25 mm flatness on machined surfaces. The cryostat shell has a tolerance of ± 10 mm in radius and the centre of the ports must maintain its absolute position within a tolerance of ± 8 mm. In Naka the CVBCS will be assembled onto the CB while its upper side will be closed by a lid provided by QST.

The base material for the fabrication of the CVBCS, S30400 with some special requirements (Co < 0.05 wt%, magnetic permeability μrel ≤ 1.1 on surface and surface finish Ra ≤ 12.5 μm), was manufactured by Outokumpu (Sweden) and supplied to QST. The thickness of the plates ranges from 20 mm to 100 mm. The filler material for welding is AISI 308LSi.

The design was validated by Finite Element Analyses [3] (buckling, elastic and load limit analyses) according to ASME BPVC 2007, Section VIII, Div. 2.

2. Manufacturing

The manufacture included the detailed design and the fabrication of the CVBCS. The fabrication plan comprised the following steps: qualification of specified welding and non-destructive examination (NDE), design and manufacturing of welding frames, jigs and fixtures, cutting of plates by water jet machine, bevelling for welds preparation, forming parts, welding phases, NDE tests and stress relieve cycles, different machining phases, assembly at factory, intermediate and final dimensional survey by laser tracker, cleaning and packaging.

Manufacturing started after the approval of technical documents including manufacturing drawings, technical procedures, and qualification reports (welding procedure specification WPS, procedure qualification record PQR, etc.). The QA comprised documentation schedule, manufacturing schedule, quality plan, risk management plan, progress reports, changes and non-conformity records, list of subcontractor and minutes of the meetings.

Full penetration welds have been extensively performed with the exception of the external ribs, having fillet welds. To achieve the best possible tolerances the machining of the sectors was carried out in three phases: a) opening of all the holes and tack welding of ports where they are, b) machining of port flanges and c) machining of contour flanges.

Each CVBCS sector is a fully welded piece in which the strict tolerances must be kept during manufacturing. In order to compensate the expected deformations produced by the welding process extra material was provided in the connection flanges to ensure the design dimensions during the final machining. The temperature differences during machining were compared with the reference temperature (20 °C), being compensated by varying the dimensional parameters.

3. Final assembly at factory

The aim of the assembly of the CBVCS at factory was to place and adjust the 12 sectors, within the required tolerances, following the procedure approved for use at the Naka-site. This procedure considers the assembly of the lower sectors in the tokamak, one by one, verifying its final position. Moreover the set of the 4 upper sectors will be previously preassembled in the assembly hall and later positioned on top of the lower sectors. In Naka-site the order of assemblies is pre-established. The final dimensional survey at factory was conducted when the CVBCS best geometry was obtained, once the final adjustment between sectors was performed. To carry out the assembly, two dummy pieces were fabricated for this purpose. One for the lower sectors (to reproduce the CB coupling flange) and the other for the upper sectors (to replicate the seating surfaces for upper sectors). Each dummy piece, formed by 4 pieces each, was mounted onto 18 identical supports anchored to the floor. Between each support and the dummy piece a levelling system based on screw type mechanism was used to obtain the required planarity in the upper surface of the dummies, measured by laser tracker (LT).

The lower sectors were assembled (Fig. 3), adjusted, bolted together

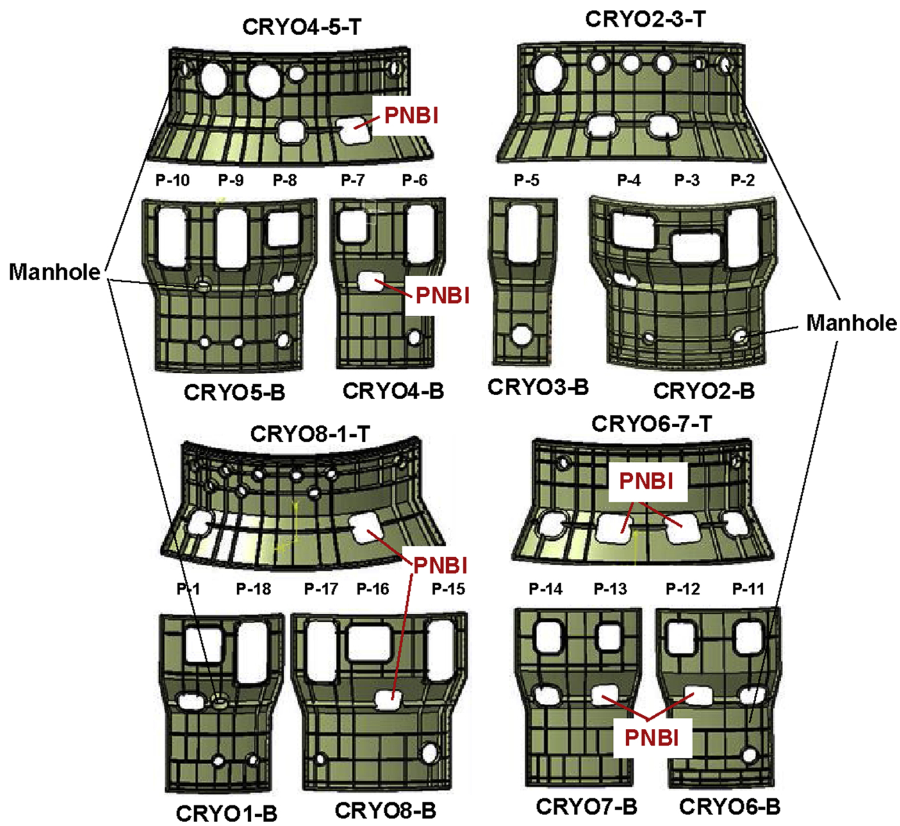

Fig. 2. CVBCS Sectors.

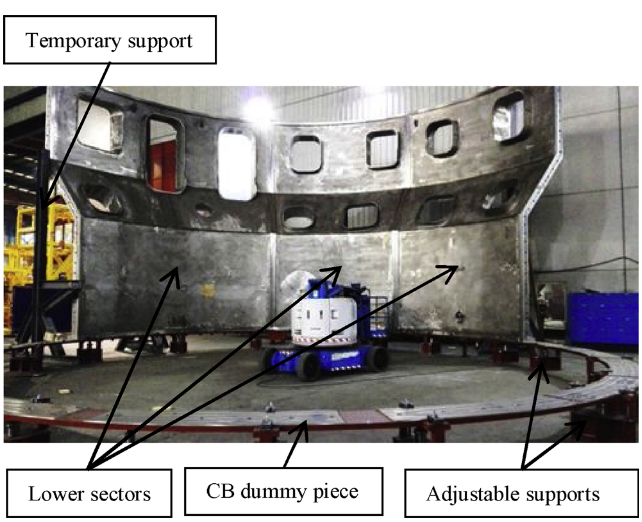

Fig. 3. Assembly of lower sectors.

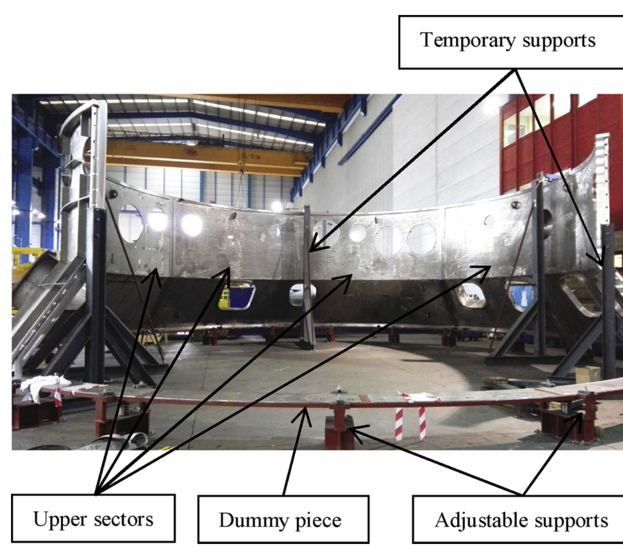

Fig. 4. Assembly of upper sectors.

and measured the complete set, remaining in place until the set of upper sectors were put in position. Once the upper sectors were assembled (Fig. 4), adjusted, bolted together and measured they were assembled and adjusted on the lower sectors (Fig. 5).

To place each sector in position, lower or upper, on its corresponding dummy, some tools/jigs were designed, manufactured and used properly (Fig. 6). For example using centering pins to position the sectors on the dummies. Moreover dedicated lifting beams/tools were also used to perform the assembly. These tools were certificated (CE machine directive) and tested in view of their usage for the assembly-disassembly in the tokamak. Several pins were inserted and fixed at the end of this assembly at factory, in order to facilitate its final assembly in Naka-site.

Fig. 7 shows a lifting tool used for the assembly-disassembly of all lower sectors.

A set of reference points were marked in the sectors to facilitate the assembly at Naka-site. Some of the marks were drawn during the machining of individual sectors and the rest after the final assembly at factory, with the help of the laser tracker.

4. Final dimensional inspection at factory

The official final Dimensional Inspection (DI), made by the manufacturer, has been performed with a 3D coordinate high precision measuring machine LEICA Laser Tracker AT 960. The measurement is

Fig. 5. Assembly of upper sectors on the lower sectors.

based on a polar method which consists in measuring the direction with two angular optical encoders and the distance with a single beam laser interferometer and a high precision absolute distance-meter, between the tracking head and the reflector, placed on the point to be measured. The calculations of the coordinates of the points and the further operations were carried out with the software Metrolog X4 V5SP2. A Thommen sensor was used to obtain the inputs of temperature, pressure, humidity and cleanliness of the atmosphere which affect the refractive index of the air, causing a change in the velocity and wave length of the laser beam.

The theoretical accuracy on a 3D coordinates is 15 μm ± 6 μm/m.

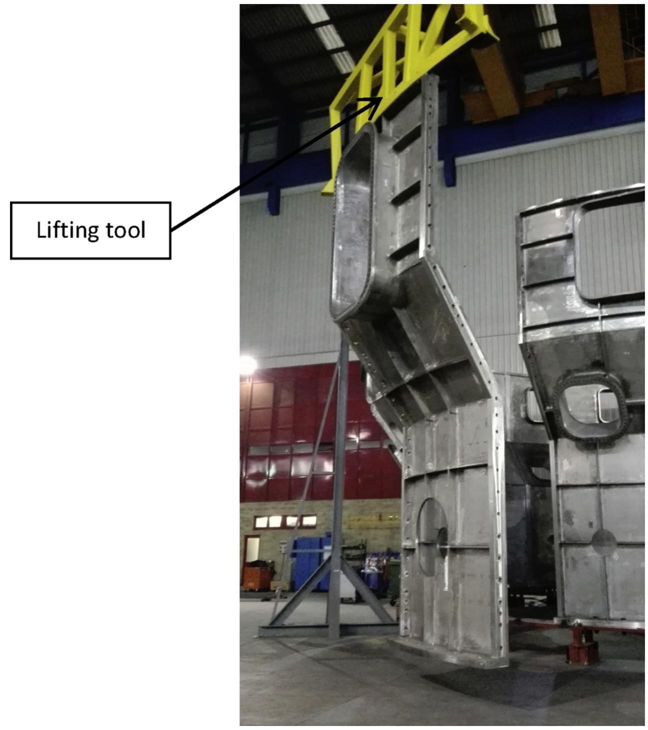

Fig. 7. Lifting tool: assembly of lower sectors.

To achieve this accuracy, environmental stability, measurement system stability and controlled part stability must be kept under control. According to the requirements, tolerances must be measured at room temperature (20 °C). Since there is not temperature-controlled area available for this purpose, due to the CVBCS dimensions, the actual temperature of the CVBCS must be checked and compensated by software considering the material thermal expansion coefficient (17 μm/m/ºC).

The DI covered not only the whole CVBCS but also the two dummies and the two sub-assemblies of the lower/upper sectors. Previously all the lower and upper sectors have also been dimensionally controlled, during machining and individually supported on a rigid platform. This platform was designed and manufactured exclusively to perform the DI of the individual sectors [4].

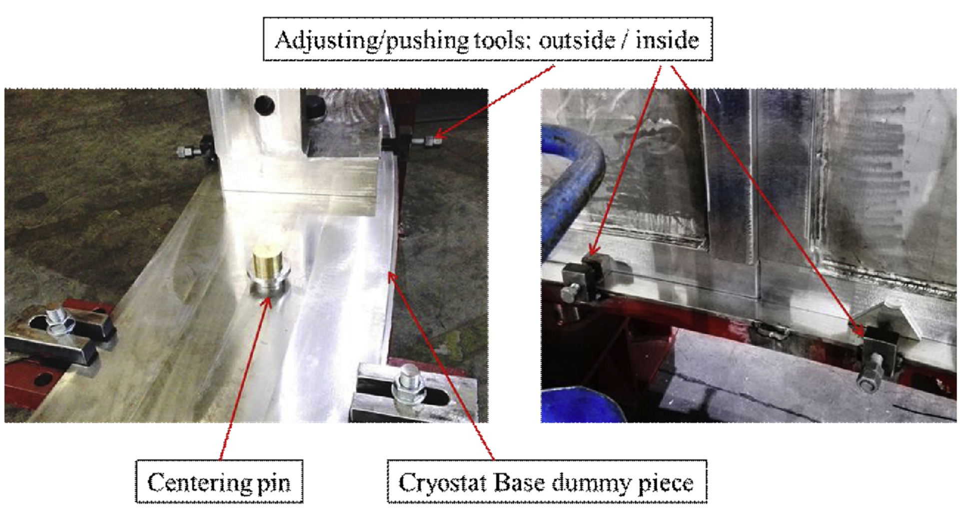

Fig. 6. Details of assembly of lower sectors.

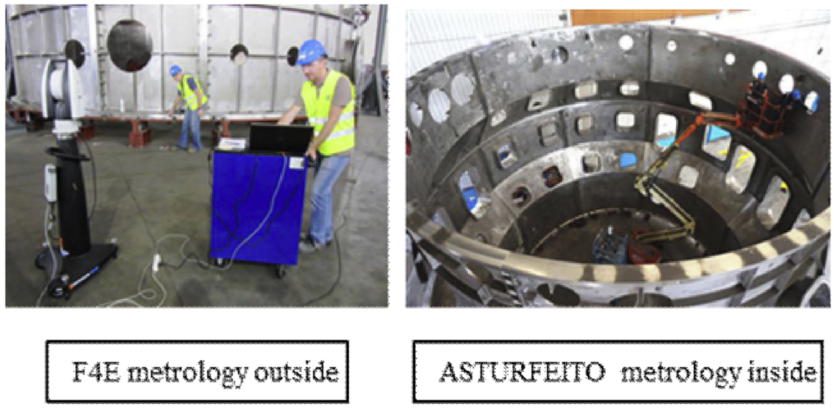

Fig. 8. Final dimensional inspection.

Table 2
Comparison of main required tolerances versus measured values.

Parameter	Required tolerance	Measured tolerance (max. deviation)
CVBCS assembly inner radius (main flanges)	± 4 mm	−2.32 mm
CVBCS assembly total height	± 4 mm	−0.60 mm
Lower sectors height	± 2 mm	−0.53 mm
Upper sectors height	± 2 mm	−0.13 mm
Flatness vertical/horizontal flanges	0.5 mm	1.24 mm
Parallelism between horizontal flanges	0.5 mm	1.63 mm
Cryostat Port Flanges:		
Radial distance tokamak vertical axis	± 4 mm	6.23 mm
Flatness	0.4 mm	0.77 mm
Angular tolerance port flange-port axis	± 0.1º	0.367 º

An extensive complete DI, official metrology, has been successfully performed from inside the CVBCS, positioning the LT at different heights (using a rigid column and different tools as scale bar, T-probe, etc.). Fusion for Energy (F4E) has made a final DI, as independent verification, but only on the external geometry of the CVBCS (Fig. 8). Both metrologies, for external geometry, gave similar results. Minor deviations, with respect to the specified tolerances and accepted by QST/F4E, were detected in several locations. A non-conformity report has been issued with all deviations. The parameters measured in the CVBCS assembly were: a) Upper, intermediate and lower flange flatness, inner radius and intermediate/total height, b) Parallelism between main horizontal flanges, c) Position of holes of upper and lower flanges, d) Planarity, angle and dimensions of ports, port flanges and openings as well as their absolute position, e) Location of particular points on the shell, f) Reference marks.

Table 2 shows the comparison between the main required tolerances for the CVBCS and the measured values (maximum deviations). Taking into account the number of sectors, their low rigidity and their large dimensions, the tolerances obtained were considered acceptable.

5. Conclusions

The manufacturing and assembly at factory of the entire CVBCS was successful. The assembly followed, as much as possible, the final assembly at Naka-site. For this purpose two dummy pieces have been designed and manufactured. The final dimensional tolerances, with several unimportant exceptions (approved by QST/F4E), are within specified tolerances.

The ex-works delivery of the component was in November 2017.

References

[1] M. Medrano, et al., Manufacturing of JT-60SA cryostat base, Fusion Eng. Des. 88 (2013) 711–715.
[2] J. Botija, et al., Manufacturing of the JT-60SA cryostat vessel body cylindrical section, Fusion Eng. Des. 123 (2017) 54–58.
[3] J. Botija, et al., Structural analysis of the JT60-SA cryostat vessel body, Fusion Eng. Des. 88 (2013) 670–674.
[4] S. Cabrera, et al., Pre-assembly and dimensional inspection at factory of JT-60SA of cryostat vessel body cylindrical section, Fusion Eng. Des. 124 (2017) 537–541.