# The Procurement and Testing of the Stainless Steel In-Vessel Panels of the Wendelstein 7-X Stellarator

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320 In-Vessel water cooled stainless steel panels, poloidal closure plates and pumping gap panels, covering an area of approximately 100 $m^2$, are used in Wendelstein7-X to protect the plasma vessel. The panels are manufactured at Deggendorf, Germany by MAN Diesel & Turbo SE. The panels consist of a laser welded sandwich of stainless steel plates together with a labyrinth of cooling channels and have a complicated geometry to fit the Plasma Vessel of Wendelstein 7-X. The hydraulic and mechanical stability requirements whilst maintaining the tight tolerances for the shape of the components are very demanding. The panels are designed to operate at up to an average heat load of 100 $kW/m^2$ and a maximum heat load of 200 $kW/m^2$ with a water velocity of approx 2 $m.s^{-1}$. High heat flux testing of an un-cooled panel at a time averaged load of 200 $kW/m^2$ for 10s were successfully performed to support the start up phase of Wendelstein 7-X operation. Extensive testing both during manufacture and after delivery to IPP-Garching demonstrates the suitability of the delivered panels for their purpose.

Keywords: Wendelstein 7-X, in vessel components, first wall, manufacturing, testing.

## 1. Introduction

The Wendelstein 7-X (W7X) Stellarator aims to demonstrate the suitability of the stellarator concept for long pulse operation and is therefore designed for operation with up to 30 minute pulses. The W7X plasma vessel has a cooling capability significantly less than the expected thermal loads coming from the W7X plasma and the direct heating from the electron and ion cyclotron resonance heating and neutral beam injection systems. The plasma vessel (PV) walls are protected from these heat loads by the plasma facing components [1, 2]. For areas of the plasma facing components well away from the plasma and where the heat loads are lower and conducted heat loads are unlikely, it was decided to use stainless steel panels similar to those used in Tore Supra [3]. Approximately 70 $m^2$ of the surface area of the 220 $m^2$ of the PV is covered in this way. Originally it was intended to coat the panels with $B_4C$ as low Z plasma facing material but this was later dropped although the technology was developed and is still available [4, 5]. Panels are also intended to be used for the protection of the PV below the divertor pumping gap and for the poloidal section of the sub-divertor volume closure [1], both these area are subject only to radiative heat loads.

After manufacture the panels were subject to stringent testing, at both the manufacturer and at IPP Garching, to demonstrate that the panels fulfilled the requirements for geometrical accuracy, pressure drop, spread of pressure drop, leak tightness under operational conditions and a demonstration of the ability to withstand over pressure.

The paper summaries the experience gained during the manufacture and testing of these panels, identifying the areas where there were particular manufacturing problems and the solutions that were found to remedy these problems.

## 2. Types of panel

The panels discussed in this paper are used in three different areas of the PV. The main wall panels of which there are 20 per machine half module, i.e. 200 panels in total, followed by the divertor pumping gap panels of which there are 3 basic types and the poloidal closure panels, of which there are 9 basic types. The details of the panels are shown in table 1, with variants. The number of variants was significantly increased when the PV was modified by the closure of a variety of ports.

| Panels type | No per half Module | Total Number | Number of variants |
|---|---|---|---|
| Main wall panels | 20 | 200 | 94 |
| Divertor pumping gap | 3 | 30 | 5 |
| Poloidal closure panels | 9 | 90 | 17 |
| Total | 32 | 320 | 116 |

Table 1: Different panel types and variants

The panels had to be modified to protect the PV in this area and affected all of the three basic types of panel. The panels described here all have the same basic design, i.e. 5 mm thick stainless steel plate, type 1.4435 with <500 ppm cobalt content and a magnetic permeability <1.01 facing the plasma, 1.5 mm thick plate providing the quilting and operating with a water velocity of approx 2 m.s$^{-1}$. The panels are intended to operate at up to an average heat load of 100 kW/m$^2$ and a maximum heat load of 200 kW/m$^2$. A typical panel is shown in Fig 1.



Fig. 1: A typical panel shown from the side opposite the plasma with a large cut-out for a port.

Other panel variants with different wall thicknesses and different shapes have also been developed, mainly for port protection, but these are not reported here.

## 3. Design of the panels

The water cooled panels, consist of two stainless steel plates laser welded together in such a way as to produce a cooling channel. After welding of the plates together, the cutting of the plates to shape, bending to the required radius and the insertion of flanges, the plates are inflated to produce the quilted appearance. The panels are shaped to try to match the complex geometry of the inside of the PV. This bending has been simplified as much as possible and the panels have only one bend radius. The gaps between panels provide a potential heating of the PV and are hence kept to a minimum, requiring an accurate outer contour so that the edges of the panels in the machine line up as closely as possible. An example of how the panels fit together is shown in [6].

The outline design of the panels, i.e. outer surface contour, bend radius and the position of the panel fixing points and location and orientation of the flanges were provided by IPP. This information was taken by the manufacturer and a detailed design of the cooling labyrinth of the panels produced. The design was performed in such a way that adequate cooling of the panel was obtained, i.e. a Reynolds number of over 5000, for a pressure drop less than 0.6 MPa at a given flow rate. In addition the panels were so designed that there was sufficient margin for over-pressure conditions, see section 4.3.

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The panels are cooled in a combined series/parallel arrangement and the manufacturer of the panels were required to provide the panels with pressure drop lower than 0.6 MPa and also to have panels of the same type to lie within a narrow range of pressure drop spread. In addition the cooling circuits for the W7X machine have been developed which also places demands on the pressure drop requirements for the panels.

The laser welding technique used for the panels means that there are areas of the panels which are only cooled by lateral conduction, such as between the cooling channels and the edges of the panels. In order to avoid hot spots during operation, there were limits placed on the width of these areas. A particular problem for the panel cooling is in tight corners where it is difficult to get the water to flow.

Calculations were performed to predict the pressure drop in the panels. Correlations were performed based on test panels to ensure that the calculations were correct. However, given the different sizes of the panels, the many different cut-outs and special features and the fact that the cross-section of the channels inside the panel is not constant, it was not possible in the time available to correctly predict the measured pressure drop of the panels based on these calculations.

It was specified that panels of the same type shall also have a measured pressure drop variation of less than +/- 15%. This was to ensure that the balancing of the flow between panels could be achieved. The pressure drop against flow was measured for all of the panels as part of the incoming inspection at IPP. The location of the individual panels in the PV modules is selected according to the result of this measurement.

## 4. Manufacture and testing of the panels

Based on the detailed design, see section 3, of the panels, the manufacturing process started with the laser welding together of the two stainless steel sheets. This was done to form a labyrinth water channel. The panels were then cut to its outer contour using laser cutting. The panels were bent in a jig to obtain the single bend radius, the flanges were then welded into the bent panels, using an automatic process and then the panels were returned to the jig and inflated. The jig served to limit the inflation and to define the height of the water channel after inflation. The outer contour of the panels was then seal welded and the contour brought within the required accuracy.

### 4.1. Leak tests

The panels were leak tested by the supplier by pressurizing the inter-space with He, approx. 1,5 MPa, and by an external sniffing sensor. The panels were then delivered to IPP Garching, no panels were found to be faulty at the manufacturer.

On delivery to IPP Garching the panels were further tested with a combined pressure/leak test where the panel was placed in a vacuum oven and internally pressurised with He. If a leak exists, He is detected in a

leak detection unit attached to the vacuum oven. This vacuum oven system is shown in [6]. Two tests were performed for each panel, a cold leak test at room temperature at 4 MPa and a hot leak test at 150°C at 2.5 MPa. The allowed leak rate is $5 \times 10^{-7}$ Pa.l/s at room temperature and $5 \times 10^{-6}$ Pa.l/s at 150°C. The test is very demanding and replicates the real operating conditions of the panels.

Of the panels which were received 15 leaks were found in total, of these 10 were due to the use of defective flange material, provided by IPP, 3 were due to re-inflation of the panels to obtain better flow characteristics and 2 were found to be due to inadequate welding. Of the 15 panels which were found to have a leak, 14 were re-made and 1 was repaired.

## 4.2. Flow characteristics

The flow characteristics of each delivered panel were measured in a dedicated test stand in IPP over a wide range of water velocities. The panels were checked that they meet the requirements set down above. Fig. 2 shows the flow characteristics of a set of poloidal closure panels of the same type showing a 90% variation in the pressure drop across this range of panels.
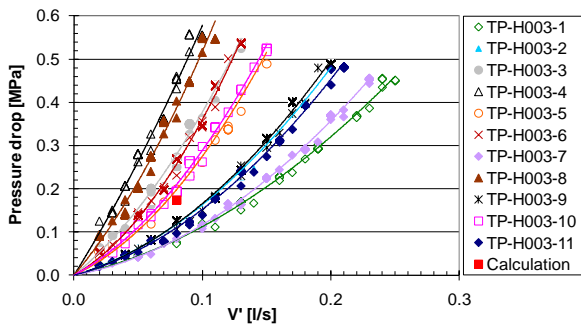


Fig. 2: Pressure drop spread for the panel type TP-H003.

This was the worst example found. In this case a prototype was manufactured and tested before the other remaining panels were released. The spread of pressure drops only became clear when the remaining panels were manufactured and tested.



Fig. 3: Panel of the type TP-H003, after burst test.

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The panel, used for the poloidal closure is shown in Fig.3.

In this case the reason for the spread in the pressure drop was due to a local narrowing of the water channel near a bend in the panel, this narrowing has a large effect on pressure drop.

Table 2 shows an overview of the number of panels that had to be re-worked due to problems with the flow characteristics. The remedial measures available to get the necessary pressure drop spread were the re-inflation of the panel at a higher pressure or the local re-working of the panels to remove blockages.

| Panels | Wall | Pumping gap | Poloidal closure |
|---|---|---|---|
| Acceptance | 170 | 28 | 83 |
| Re-inflation | 30 | 2 | 7 |
| Unsuccessful re-inflation | 5 | 0 | 0 |

Table 2: List of panels re-inflated to achieve the required flow characteristics.

When a panel was returned for re-inflation a higher pressure was necessary for the re-inflation with the consequence that the water channel widened. However, it was noticed that the panel did not have exactly the same geometric shape after the re-inflation as before. This meant that the panel needed to be re-shaped. It was also noticed that under the highest re-inflation pressures there was a chance that a leak could develop at the flange, see section 4.1.

## 4.3. Burst testing

The operational pressure of the panels is 2.5 MPa and the panels are part of the hot liner which means that they must withstand this pressure up to 150°C. Considering accident scenarios and other off-normal events the panels are designed to be able to withstand a much higher pressure. To demonstrate this for major delivery a panel was tested to destruction by filling the panels with water and increasing the pressure until failure of the panel occurred. Fig. 4 shows the result of one such test.



Fig. 4: Failed welding seam at 11 MPa internal pressure

Typically failure occurred in the laser beam welded seams of the panels at a pressure of between 11 and 13 MPa.

### 4.4. Dimensional control

The dimensional control of the panels is important since they must fit together with the water supply pipes, the holding points and with each other. Tolerances were specified of the holding points, the position of the flanges for the water cooling, the shape of the panel, the outer contour and the width of the external seam. The panels generally meet these requirements, however, it was found that because of the welded construction it was not possible to hold all these tolerances all of the time. However, a system was set in place to check any possible deviation outside this tolerance band, where a Non-conformance report (NCR) was written and checked internally within IPP before acceptance or rejection. A total of 131 NCRs for dimensional control were received of which only 2 could not be accepted.

### 4.5. Pressure deformation tests

Tests were also performed on the panels to study the effect of repeated pressurisation and de-pressurisation to the operating pressure. Since the panels consist of large stainless steel plates they can flex under pressurisation. This is shown in fig. 5. The tested panels were constrained in the same way as they will be in the W7X machine and then the panel were pressured to the operating pressure.



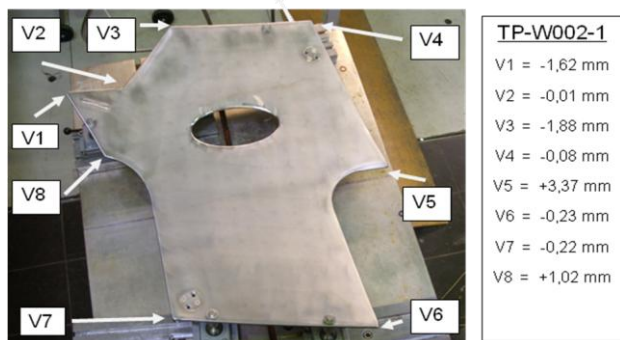| TP-W002-1 | |
| --- | --- |
| V1 = | -1,62 mm |
| V2 = | -0,01 mm |
| V3 = | -1,88 mm |
| V4 = | -0,08 mm |
| V5 = | +3,37 mm |
| V6 = | -0,23 mm |
| V7 = | -0,22 mm |
| V8 = | +1,02 mm |

Fig. 5: Deflection measurements of a panel during a pressure deflection test.

The deflection of the corners was then measured. Typical values are shown in fig. 5. The panel was then cyclically de-pressurised and pressured for up to 1000 cycles. These pressure deformation tests were performed prior to the pressure/leak test to ensure that no damage occurred during this type of testing. This type of testing was performed for each panel type.

### 5. Heat Flux testing

As part of the preparation for the initial phase 1 operation of the machine for high power short pulse

plasma discharges, an un-cooled panel was tested in GLADIS [7]. This test at a time averaged load of $200kW/m^2$ for 10s showed no plastic deformation of the panel. Measurements of the profile of the panel before and after testing showed no change in shape. The temperature of the panel reached a local maximum value of 150°C. Cooling of the panel to 50°C took 30 min under the conditions in GLADIS. This suggests that the panels can be used un-cooled in phase 1 operation as long as adequate consideration is given to the cool down of the panels between pulses.

### 6. Conclusions

The panels used to protect the plasma vessel have been delivered and tested at IPP Garching. The panels have been extensively tested both during manufacture and after delivery to IPP. The results of this testing demonstrate the suitability of the finally delivered panels for their purpose.

Certain problems were encountered during the manufacture of the panels and some of the requirements of the panels have not been easily achieved. This situation was resolved by a combination of repair, re-manufacture and acceptance of out of tolerance panels, where it could be demonstrated the panels can be built into the machine.

The complex geometry of the panels and their cooling circuits were the main reasons for the difficulties experienced, particularly with the use of the welded construction. The importance of the pressure drop in the panels to obtain a balanced flow between neighbouring panels and the difficulties in achieving this within the panels means that measures will probably need to be taken outside the panels to have a balanced flow. The complexity and time taken to obtain defined flow characteristics in the panels suggests that the strategy defined for the cooling control is modified or other solutions to the panels be used for this purpose.

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