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G.H. Rappé. The J.E.T. (Joint European Torus) vacuum vessel. *Revue de Physique Appliquée*, 1977, 12 (10), pp.1735-1741. 10.1051/rphysap:0197700120100173500 . jpa-00244395

HAL Id: jpa-00244395

<https://hal.science/jpa-00244395>

Submitted on 4 Feb 2008

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Classification
 Physics Abstracts
 52.75 — 28.50R

THE J.E.T. (JOINT EUROPEAN TORUS) VACUUM VESSEL

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(Reçu le 30 décembre 1976, révisé le 27 juin 1977, accepté le 8 juillet 1977)

Résumé. — La chambre à vide du JET (Joint European Torus) machine de grandes dimensions a été conçue en forme de tore à section non circulaire et entièrement métallique. Pour répondre aux conditions de stabilité mécanique et aux exigences de l'ultra vide l'ensemble est complètement soudé.

Le tore est composé de 32 secteurs rigides (correspondant au nombre de bobines de champs toroïdal) reliés entre eux par des soufflets à bords parallèles.

Les secteurs rigides sont à doubles parois solidement entretoisées de manière à former un caisson résistant aux efforts extérieurs. Les soufflets assurant la liaison entre ceux-ci déterminent la résistance électrique autour du tore, le courant induit dans la chambre à vide en parallèle avec celui du plasma devant être aussi faible que possible. Tous les efforts appliqués sur la chambre à vide sont pris par les secteurs rigides qui comportent en outre toutes les ouvertures sur l'intérieur de la machine, telles que queusots pour le pompage, diagnostics, chauffage additionnel du plasma...

Cette chambre à vide toroïdale a été conçue à doubles parois pour les secteurs rigides ainsi que pour les soufflets qui les lient et il est proposé de faire circuler un gaz inerte chaud dans cet intervalle afin d'étuver le tore complet à 500 °C, procédure qui, facilitant le dégazage intérieur, permettra d'atteindre la pression de base requise de 10^{-10} torr.

Afin de protéger l'extérieur de l'appareil de cette haute température la chambre à vide sera isolée thermiquement.

Beaucoup de précautions ont été prises dans le choix des matériaux constituant cette chambre. Résistance des matériaux à haute température et caractéristiques électriques ont indiqué que les alliages à haute teneur en nickel seraient les mieux appropriés. Le choix final s'est porté sur l'INCONEL 600 (nom de fabrique de chez Huntington, USA) ou NICROFER 7216 (nom de Vereinigte Deutsche Metallwerke, F.R.G.) pour les secteurs rigides, et l'INCONEL 625 (NICROFER 6020) pour les soufflets, ce dernier matériau ayant la résistivité électrique requise.

Les queusots horizontaux soudés dans le plan équatorial sont à leur tour soudés aux chambres de pompage qui comportent les pompes turbomoléculaires et les cryopompes, tout en conservant le maximum d'accès sur l'intérieur pour les faisceaux de particules énergétiques neutres : système proposé pour le chauffage additionnel du plasma.

La chambre à vide a été étudiée de façon à ce que tous les efforts soient pris par les secteurs rigides. Les efforts dirigés radialement de l'extérieur vers l'intérieur sont transmis et tenus par des modules placés entre secteurs rigides adjacents. L'ensemble travaille comme une structure en forme de voute comprimée avec 100 tonnes.

Les forces appliquées sur la chambre à vide sont dues : à la pression atmosphérique, en opération normale et pendant l'étuvage à 500 °C, aux forces électromagnétiques dues aux courants de Foucault induits dans cette structure métallique par les variations de flux magnétique dans le temps, et aux contraintes thermiques, la chambre se dilatant pendant l'étuvage et durant les opérations expérimentales.

Abstract. — The large vacuum vessel of the J.E.T. (Joint European Torus) experiment has been designed as an all metal composite torus of non-circular cross-section. To comply with mechanical stability and ultra high vacuum requirements it has been designed as a completely welded fabrication. The metal structure consists of 32 rigid and wedge-shaped sections (equal in number to the B_{TOR} field coils) which in turn are joined together by parallel bellows to form a torus. The rigid sectors are of box type construction suitably ribbed to withstand the stresses imposed upon them by the external forces. The bellows linking these rigid sectors determine the electrical resistance of the metallic vacuum vessel the long way around the torus, since currents which are induced in parallel with the plasma current should be kept as low as possible. All forces acting on the vacuum vessel are absorbed by the rigid sectors which also incorporate the openings to the interior of the machine, such as ports for pumping, diagnostics, auxiliary plasma heating, etc...

This toroidal vacuum vessel has been designed as a double walled structure with the bellows linking the rigid sectors being fitted as pairs, and it is proposed to circulate hot inert gas through out this interspace in order to raise the temperature of the whole vacuum vessel to 500 °C to achieve bakeout conditions which will assist in reaching the required base pressure of 10^{-10} torr. In order to protect external apparatus from this bakeout temperature the outside of the vacuum vessel will be thermally insulated.

Much consideration has been given to the choice of materials from which to construct this vacuum vessel. Stress conditions at elevated temperatures and electrical requirements indicate that one of the most suitable materials would be in the high content nickel alloy range. The final choice was to use Inconel 600 (a trade name of Huntington Alloys, USA) or Nicrofer 7216 (a trade name of Vereinigte Deutsche Metallwerke FRG) for the rigid sectors and Inconel 625 (Nicrofer 6020) for the bellows, the latter material having the required electrical resistivity.

The horizontal ports lying on the equatorial plane are connected to pumping boxes which in turn form locations for the turbo molecular and cryopumps. They also provide maximum access to the interior of the vacuum vessel for the beams of energetic neutral particles proposed for additional plasma heating.

The vacuum vessel has been so designed that all the stresses are taken by the rigid sectors, whilst the radial inward directed forces are transmitted to and supported by a modular restraint ring which acts as an arch type of structure transmitting pressure forces of 100 tons between adjacent rigid sectors.

The forces acting on the vacuum vessel are due to the atmospheric pressure during normal operation and during bakeout operations at 500 °C, the electro magnetic forces due to eddy currents which are induced in the metallic structure when the magnetic fluxes linking the vacuum vessel change with time, and the thermal stresses arising for expansion of the vacuum vessel during the baking and during experimental operation.

1. Introduction. — J.E.T. (Joint European Torus) is an experiment in a programme which has the ultimate aim of using a new source of energy, this energy is that released by the fusion of the nuclei of light atoms. The essential objective of this experiment is to obtain and study a plasma in conditions and dimensions approaching those needed in a thermonuclear reactor.

The J.E.T. apparatus is composed of approximately seven major components: toroidal field coils, poloidal field coils, diagnostics, iron core, power supplies, control systems and the vacuum vessel. The main parameters of the vacuum vessel are shown in the following table:

Diameter in horizontal direction:	2.63 m
Diameter in vertical direction:	4.18 m
Wall thickness on R_i and R_a :	12 cm
Maximum wall thickness:	18 mm
Total weight:	68 t
Weight of one octant:	8.5 t
Volume:	$\approx 190 \text{ m}^3$
Internal wall area of the equivalent torus with smooth surface:	$\approx 220 \text{ m}^2$
Internal wall area taking into account the convolutions of the bellows:	$\approx 450 \text{ m}^2$
Internal wall area including the protection screening of the bellows and the ports:	$\approx 780 \text{ m}^2$
Electrical resistance in toroidal direction:	0.52 m Ω
Electrical resistance in poloidal direction (all rigid sectors in parallel):	0.03 m Ω
Bellows material:	Inconel 625 or Nicrofer 6020
Rigid sector material:	Inconel 600 or Nicrofer 7216
Thermal insulation to the outer structure:	Triton Kaowool 2.5 cm thick

The forces acting on the vacuum vessel arise from two main sources:

(a) from the atmospheric pressure acting on the outside wall of the vessel and is in the order of 20 tonnes on each of the 32 rigid sectors,

(b) from the electromagnetic forces due to the eddy currents which are induced in the metallic structure when the magnetic fluxes linking the vacuum vessel change with time. These forces put an additional load of 10 tonnes per sector upon the vacuum vessel.

There is also another small force due to thermal expansion which occurs during the bake-out cycle, but this force is not present when the machine is in operation.

This paper will describe the design and manufacturing philosophy of the vacuum vessel.

2. The vacuum vessel. — 2.1. GENERAL DESIGN. — This toroidal vacuum vessel is an all metal completely welded composite structure, designed to ultra high vacuum standards. It is of double walled construction throughout for reasons of reliability, also the inter-space between the inner and outer shells can be used to advantage for heating the vessel to bake out temperature of 500 °C and for cooling should this be found necessary during operation of the apparatus.

Its D shape cross section is determined by the shape of the toroidal field coils and is of maximum size the inside shape of the toroidal coils will permit, after due allowance for assembly, thermal insulation and expansion of the vacuum vessel during the bake out cycle.

The basic structure consists of 32 rigid and wedge shaped sectors, equal in number to the toroidal field coils, which in turn are joined together by parallel bellows to form the torus. All forces acting on the vacuum vessel are absorbed by the rigid sectors which also incorporate openings to the interior of the machine, such as ports for pumping, diagnostics, auxiliary plasma heating by neutral injection and

adjustable limiters. The large horizontal port can also be used for man entry in order to perform work on the interior of the vacuum vessel. An appreciation of scale can be obtained from the photograph at figure 1 which shows a full scale model of the large rigid sector cut about the horizontal plane.



FIG. 1. — Full scale model of the large rigid sector.

The present design of the rigid sectors is one of box type construction suitably ribbed to withstand the external forces (Fig. 2). The bellows sections linking the rigid sectors determine the electrical resistance of the vacuum vessel the long way round the torus, that is for currents which are induced in parallel with the plasma current and which should be kept as low as possible.

The double wall structure of the vacuum vessel serves several purposes:

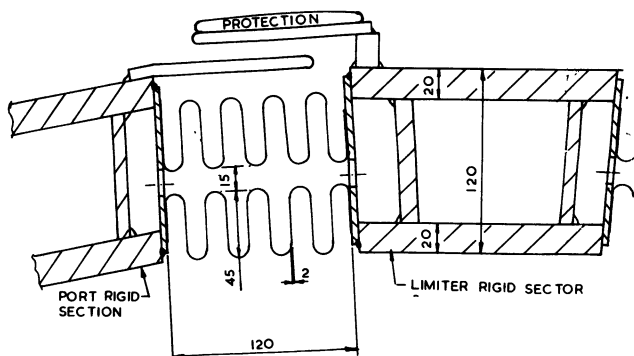


FIG. 2. — Box type construction of the rigid sectors.

1) It is a safeguard should the inner wall develop a leak. Should this happen the experiment could still proceed simply by continually pumping the interspace.

2) During operations with tritium this interspace could again be pumped thus decreasing the tritium partial pressure above the outer bellows hence reducing the tritium permeation to a negligible amount.

3) In order to reach the required base pressure of 10^{-9} torr it is necessary to heat the rigid sectors and bellows to a bake out temperature of 500 °C. To achieve this hot argon gas will be circulated through the interspace. The inlet gas temperature will be carefully controlled in order to limit the thermal gradients in any part of the vacuum vessel to a maximum of 50 °C.

4) Should at a later date it be found necessary to cool the torus, cold gas could again be circulated in this interspace via a heat exchanger, the vacuum vessel being thermally insulated on the outside.

For ease of handling during assembly and subsequent repair, possibly under remotely controlled conditions, the torus is divided into octants, each octant consisting of four wedge shaped rigid sectors, joined by welding to four parallel bellows assemblies (Fig. 3). In order to form a complete torus, the octants

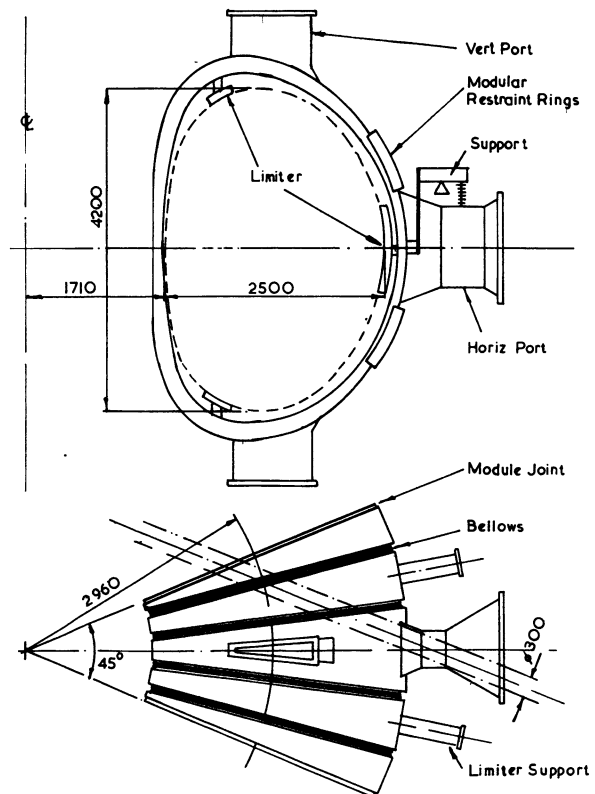


FIG. 3. — General layout of the vacuum vessel octant.

are joined to each other by means of a specially designed reweldable U joint, the edge of one being fillet welded to the face of the other. This weld acts as a vacuum seal weld only, the mechanical stresses

being taken by the bridging plates securely bolted to adjacent rigid sectors (Fig. 4). To maintain the double wall structure an additional plate is welded around the contour of the D shape.

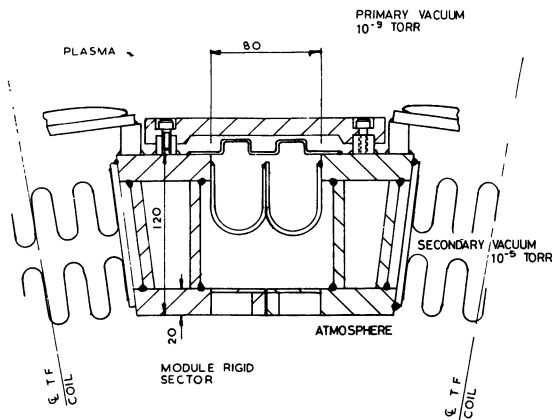


FIG. 4. — Drawing of cross section of the octant joint.

The support system of the vacuum vessel has been designed to minimise the built in stresses in the torus and to accommodate the radial movement which is to be expected during the bake out cycle, any distortion due to mechanical loading and any movement due to electro mechanical stresses. This has been achieved by hanging the torus from the mechanical structure on spring loaded suspension units (Fig. 5).

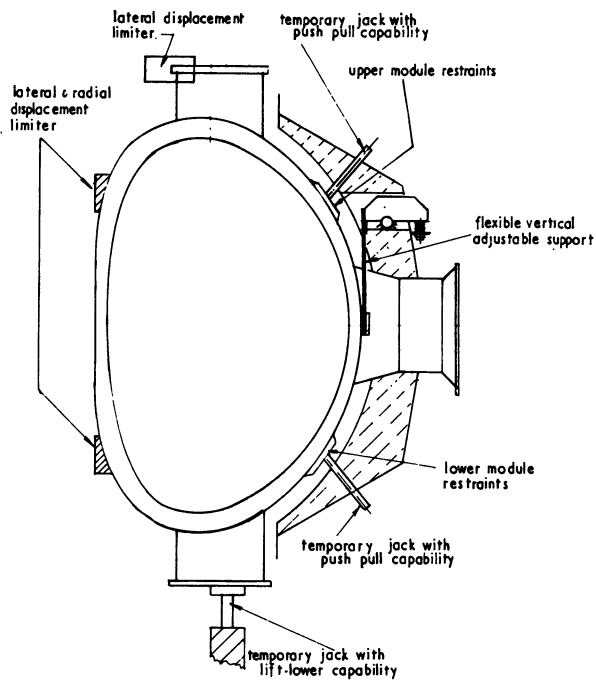


FIG. 5. — Vacuum vessel suspension system.

Many materials in the stainless range were critically examined in order to find one with the required strength characteristics at high temperatures. Of these, the high nickel content alloys such as Inconel and Nicrofer were found to be most suitable, having

the required tensile properties, electrical resistivity and workability.

Inconel 625 (Nicrofer 6020) was finally chosen as the bellow material and Inconel 600 (Nicrofer 7216) as the material from which to manufacture the rigid sectors, where the requirements are not so severe.

A comprehensive test programme was carried out to prove the stress calculations welding design and weldability of the material.

A plane model of the most highly stressed part of the rigid sectors was made with the cross section full scale and of length 1470 mm. It represented two rigid sectors joined by an interlinking bellows section. This flat model was then subjected to cyclic bending and fatigue tests, as well as thermocycling and helium leak tests.

Cross Section of Plane Model

Length, 1470

Supported for Test at 1400 Centres

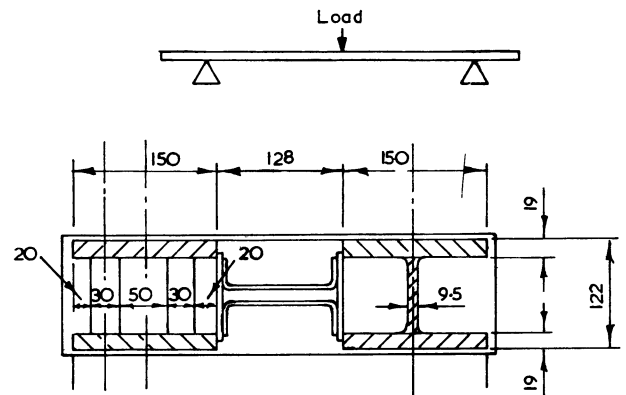


FIG. 6. — Cross section of plane model.

A schematic diagram of this model is shown in figure 6. It was supported on two columns 1400 mm apart and subjected to a static load of 16 tons which induced a stress of 12 kg/mm² in the members and a central deflection of 1.6 mm. The interspace was evacuated to a pressure of 10⁻⁵ torr and cyclic bend tests were made with the 16 ton load at a frequency of 250 deflections per minute up to a total of 5 × 10⁴ cycles. After thermocycling several times between ambient temperature and 500 °C the load was increased to 32 tons and a cyclic bend test of a further 5 × 10⁴ cycles was performed. At the completion of these tests no cracking of welds was observed and no helium leakage could be detected in the vacuum space. Selected areas of this model will now be sectioned, polished and examined metallurgically for any abnormalities of grain structure.

The most important stress situations which arise in the rigid sectors and bellows are those due to:

a) atmospheric pressure due to normal operation and under bake out conditions of 500 °C,

b) electromagnetic forces due to eddy currents which are induced in the metallic structure when the magnetic fluxes linking the vacuum vessel change with time,

c) thermal stresses due to thermal expansion of the torus structure during the bake out operation.

These stress calculations for such complicated fabrications as the rigid sectors can only be done with the help of *finite element* codes on a computer. Using such codes together with certain simplifying procedures large numbers of stress calculations have been carried out and from these the varying wall thicknesses of the torus shells have been established which will permit a vacuum vessel to be made which is both economical in material and of sufficient mechanical strength to perform its required duty.

With regard to the bellows, stress calculations were made using many permutations of material thickness, width to depth ratios of convolutions and shape of convolution. The bellows are most highly stressed in their straight section at the inner region of the torus. Figure 7 shows a typical result of the stress calculations for plane bellows having a wall thickness of 2 mm under air pressure loading. The maximum stress is 24 kg/mm² which gives a safety factor of 1.4 with respect to the yield strength of Inconel 625 at 500 °C. For safety reasons both inner and outer bellows are designed to withstand the air pressure loading.

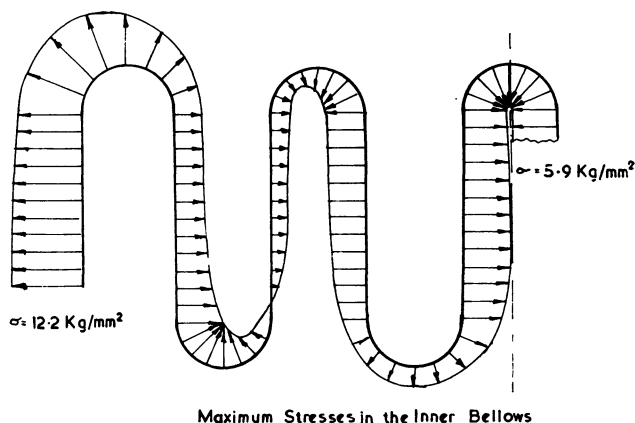


FIG. 7. — Typical result of stress calculation.

The rigid sectors vary slightly with regard to their internal stiffness, also the external forces acting upon them vary due to their different wedge angles. These radially inward-directed forces are transmitted to, and supported by, the modular restraint ring which acts as an arch like structure transmitting pressure forces of 50 tons between adjacent rigid sectors. The location of the support rings was chosen so as to be compatible with the position of the port structure, to cause the minimum possible stresses along the inner straight part of the rigid sector as well as in the outer regions where the ports are attached. The rigid sectors

will fail by buckling rather than by yielding due to excessive membrane stresses. Since the initial failure of such a shell is by bending, the residual stresses are kept relatively low approximately 12 kg/mm² at maximum which gives a factor of safety of 3 with respect to the yield strength of Inconel 600 at ambient temperature. However during the baking operation when the only external force acting is air pressure, the maximum stress is approximately 7 kg/mm² and the safety factor rises to 4 with respect to the yield strength of the material at 500 °C (1).

The pumping system for this vacuum vessel has been designed to meet the following requirements:

a) to achieve a base pressure in the torus via four of the large horizontal port openings of 2×10^9 torr with desorption rates for clean metal surfaces of less than 10^{-12} torr l/s. This necessitates a pumping speed applied to the torus of 4×10^4 l/s,

b) to use a completely oil and contamination-free pumping system, avoiding the use of any organic materials in the construction of the vacuum vessel (a completely all welded vessel),

c) pumping will be by turbo-molecular and cryo-pumps,

d) to achieve in the shell interspace, a base pressure in the order of 10^{-5} torr.

Each octant will have its own interspace pumping system which is connected via two ports to the limiter rigid sector.

The design parameters of the vacuum system are summarized in EUR-JET-R5, Table IV.

The cross section of JET showing the vacuum vessel in position is shown in figure 8.

2.2. MANUFACTURING PHILOSOPHY. — In order to assess the feasibility of manufacturing a vacuum vessel of this shape and size study contracts were placed with various commercial companies for them to study the problems. In the light of their replies some minor design changes were made, but on the whole there appeared to be no constructional difficulties. For fabrication purposes the vacuum vessel divides conveniently into two parts:

1. bellows assemblies
2. rigid sectors and their assembly into octants.

2.3. BELLOWS. — Several different methods of forming the D shaped bellows, such as explosive forming, hydraulic forming and rolling were evaluated and, of these, forming by rolling was considered to be the best, mainly because of the size and non circular shape. Following a call for tender a contract has been placed with Flexider of Turino, Italy, to manufacture these bellows from Inconel 625 of 2 mm thickness.

They will be formed up from a plain blank by rolling in all of the convolutions simultaneously

(1) EUR-JET-R5 The JET Project Design Proposal.

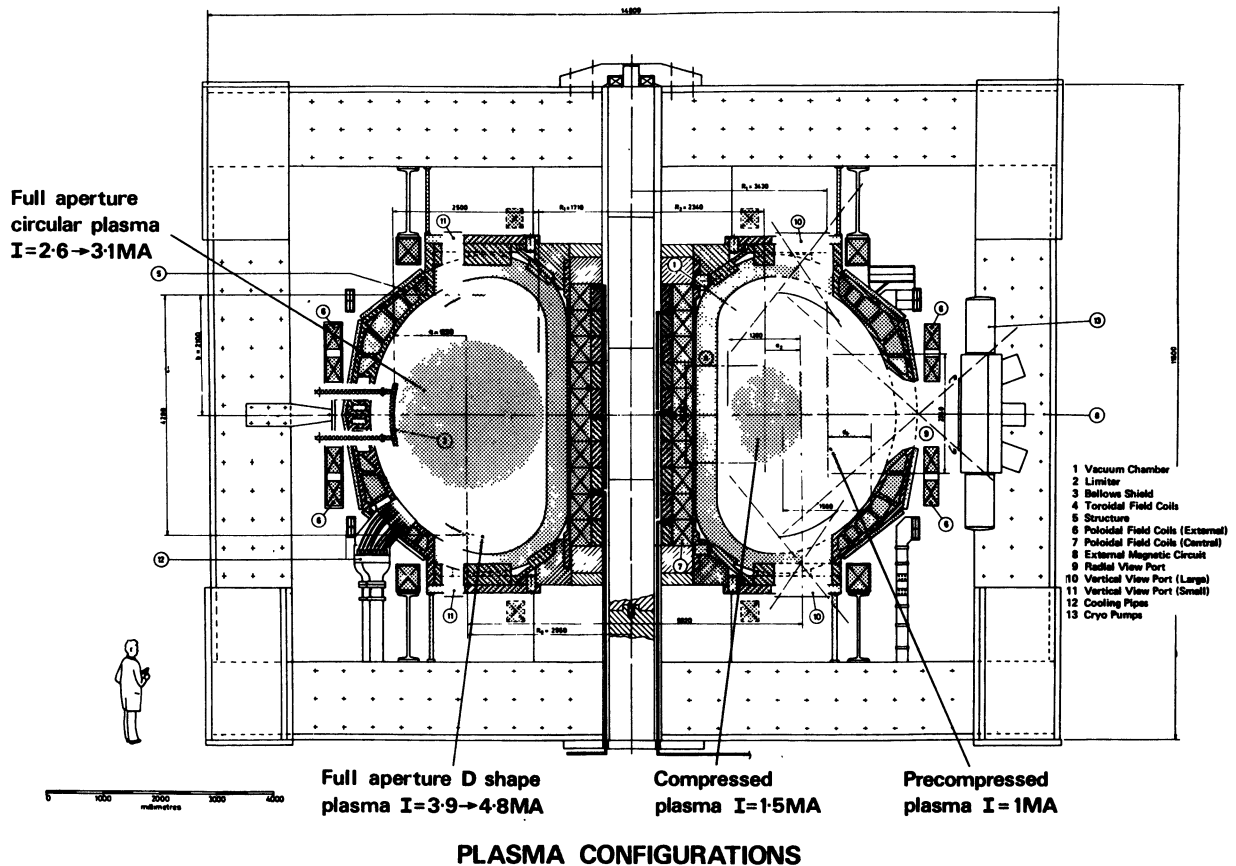


FIG. 8. — Cross section of J.E.T. showing vacuum vessel in position.

whilst at the same time an axial load is applied to the edge of the blank to assist the flow of material around the rollers. Trial rolling of circular bellows of 4 meters diameter have proved that it is possible to produce this convolution shape.

To generate the required contour strong D shaped flanges, of the correct contour of the finished bellows, are welded to either end of the blank. During the convolution rolling process this flange is guided in a true D shaped path by means of adjustable rollers which by movement in or out from the rolling spindle accommodate for the change in radius of curvature of the D shape (Fig. 9).

To maintain the double wall structure of the torus a pair of bellows (one inner and one outer) are placed one inside of the other and flat D shape flange plates of 4 mm thickness are fillet welded to each end forming a bellows assembly. These flange plates are later welded to the edge of the rigid sectors during the assembly into octants (Fig. 10). Each bellow assembly will be vacuum leak tested and to be accepted must have a leak rate not greater than 10^{-9} torr l/s.

2.4. RIGID SECTORS. — As previously stated the rigid sectors are fabricated from Inconel 600 with a plate thickness which varies from 20 mm in the narrow central part to 15 mm on the wide outside face. The fabrication is a box type construction with the inner and outer shells being joined by flat D shaped bulk-

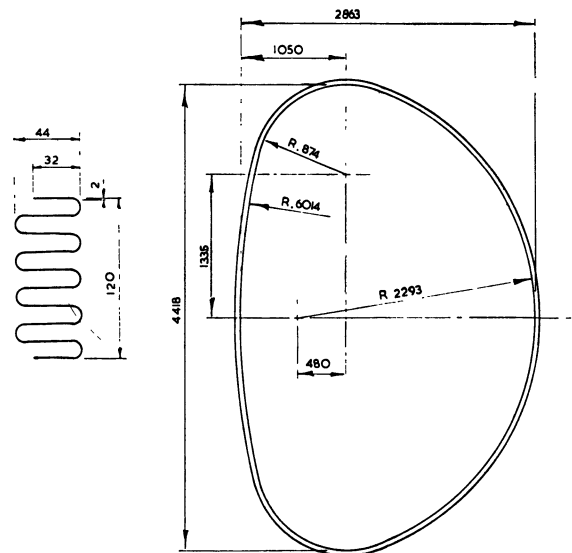


FIG. 9. — D-shaped bellows.

heads or diaphragms. This method of construction is relatively easy to fabricate and provides ample access for welding, which is by the argon arc process throughout (T.I.G. or M.I.G. being specified). The use of flux coated electrodes is not considered to be desirable for welding of ultra high vacuum vessels.

When the material is received from the supplier it will be plasma cut to the required developed shape.

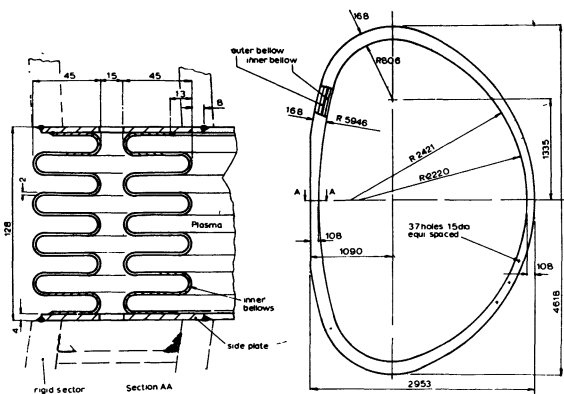


FIG. 10. — D-shaped bellows assembly.

The pieces required for the inner shell will then be surface outgassed by heating in a vacuum furnace to a temperature of between 850° and 900 °C for 2 hours.

The plates will now be formed to the correct contour, and welded to form the inner shell. Stiffening bulkheads will be welded on to this shell and the outer shell will be then welded on to these thus making a rigid sector, which when the horizontal and vertical ports are welded in will be stress relieved in an inert atmosphere. When chemical cleaning to ultra high

vacuum standards is complete the shell interspace will be pumped down and the rigid sector will be subjected to a vacuum leak test.

Rigid sectors and bellows assemblies can now be joined together by welding to form an octant. By means of a special assembly jig it is possible for all of the welding to be performed in the down hand position thus assuming good quality welding throughout. On completion each end of the octant will be blanked off by using large specially designed flanges so that the inner vacuum space can be evacuated in order to carry out a vacuum leak test.

Since the torus is a ultra high vacuum vessel all of the fabrication work, welding, machining, cleaning and vacuum testing must be performed under *clean area* conditions. To do this a separate building will be specially adapted to house the required machinery and to provide changing facilities for the personnel working in the area.

It cannot be emphasized too strongly that the success or failure of making a vacuum vessel of this size and complexity will depend almost entirely upon the degree of quality control which can be operated at the companies works.

- (1) EUR-JET-R5 The JET Project Design proposal.
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