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THE TOKAMAK FUSION TEST REACTOR NEUTRAL BEAM INJECTION SYSTEM VACUUM CHAMBER*

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Summary

Most of the components of the Neutral Beam Lines of the Tokamak Fusion Test Reactor (TFTR) will be enclosed in a 50 cubic metre box-shaped vacuum chamber. The chamber will have a number of unorthodox features to accomodate both neutral beam and TFTR requirements. This paper presents the design constraints, and the resulting chamber design.

Introduction

The Tokamak Fusion Test Reactor located at Princeton University Plasma Physics Laboratory will need at least twelve neutral beams to inject the required energy into the Tokamak plasma. These twelve will be arranged into four groups of three, known as the Neutral Beam Line (NBL). The injection systems will be placed at four locations around the torus as shown in Figure 1.

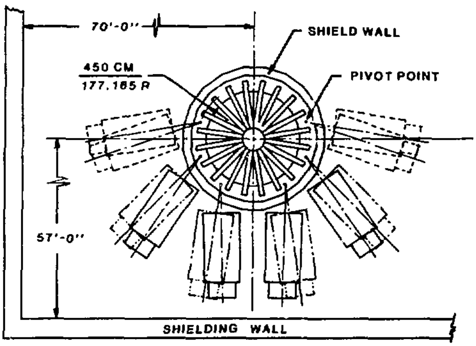

Figure 1. TFTR Neutral Beam Line Locations.

Each NBL will contain three sources and neutralizers along with a common magnet, ion dumps and a calorimeter. The relative locations of these components are shown in Figure 3. The system will be enclosed by a vacuum chamber which will be evacuated by cryogenic and mechanical pumping. The cryopumping system will keep the pressure in the range of 1 mPa (10^{-5} torr) during operation. For more information on the NBL see references 1, 2 and 3.

Vacuum Chamber Design Criteria

The primary purpose of the chamber is to provide a leak-free boundary to maintain the vacuum. The chamber will also be the main structure of the NBL; providing support and mounting surfaces for many of the components.

The chamber must provide vacuum integrity and structural stability within constraints imposed by the TFTR environment and the neutral beam components. In many cases, accomodating these restrictions overshadowed ordinary vacuum vessel considerations.

TFTR Requirements

There are two main reasons for the limitations which the TFTR places on the NBL vessel design. First, space near the NBL positions is restricted and second, the entire TFTR Test Cell will be radioactive during TFTR operation.

At the TFTR site, the reactor will be located in the Tokamak Test Cell. The floor of the cell measures 45.7 m (150') x 38.9 m (114'). It is 18.3 m (70') high. In the area of the neutral beams there is a potential space conflict. The conflict arises because the TFTR requires the shortest possible pivoting beam line; but the torus magnetic field coils and shielding require room in the same area. The problem was resolved by limiting the NBL to the space envelope shown in Figure 2 and 3.

The NBL will be moved to and from the test cell by a 100 Mg (110 ton) overhead crane[4]. The chamber must support the component loads during movement of the 63 Mg (70 ton) system.

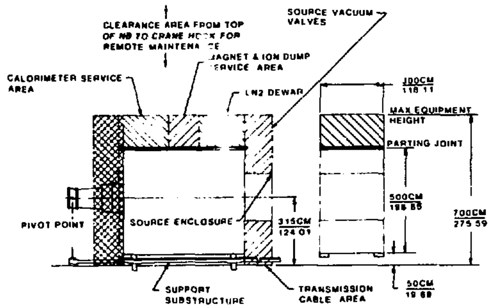

Figure 2. NBL Space Envelope Elevation View.

At the NBL positions on the torus, each system will be lowered onto its pivoting substructure. The chamber will then be connected to its mechanical vacuum pumping system. After this, the substructure will then move the entire NBL forward so the vessel can be mated with the torus vacuum vessel.

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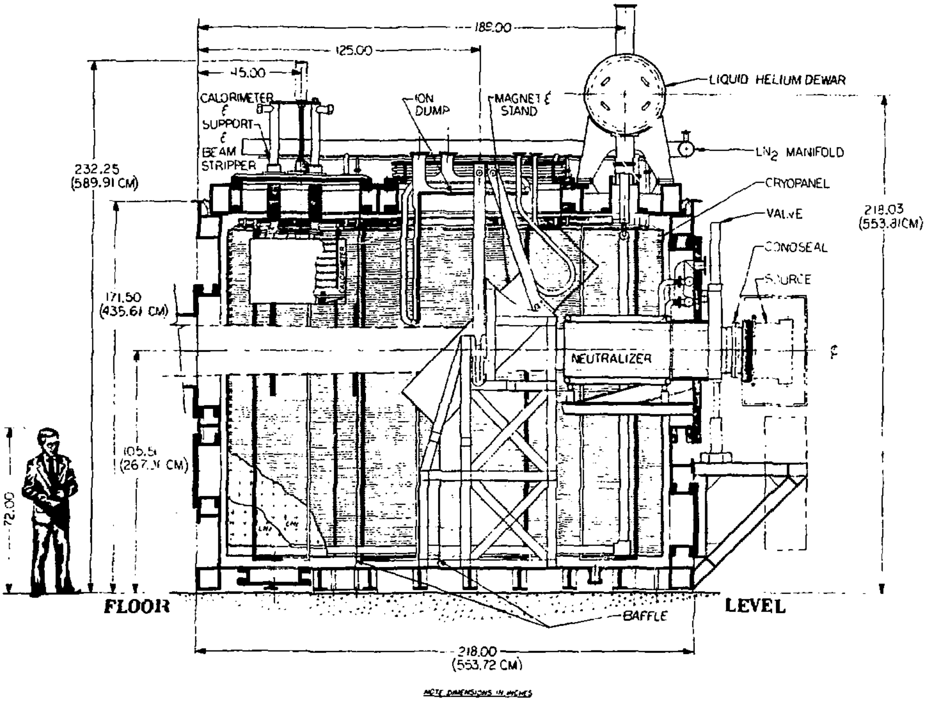

Figure 3. NBL Component Location

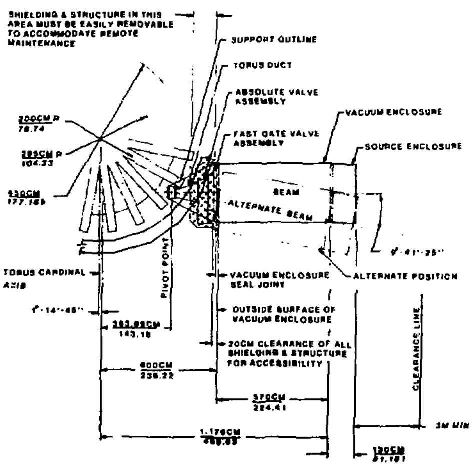

Figure 4. NBL Space Envelope Elevation View.

In addition to the space restrictions, the TFTR placed some constraints on the material used to fabricate the vessel. The TFTR plasma will be very sensitive to magnetic field disturbances. Therefore, the disturbance to the TFTR fields by each chamber is limited to less than five gauss within a cylinder seven meters in diameter concentric with the Tokamak. This placed limitations on the electrical resistivity and magnetic permeability of the chamber material because it is located within strong and rapidly fluctuating TFTR magnetic fields.

Within the Test Cell the TFTR will be generating significant amounts of 14.1 MeV neutrons. Although precise fluences are not known at this time, it is expected that shortly after the beginning of deuterium-tritium operation, the activation of the TFTR components will be too high for direct handling. Thus, all TFTR components must be designed to be handled using remote-handling equipment and procedures.

Compatibility with remote handling equipment affected the design of all NBL components. Each sub-system must be as simple as possible, preferably designed as an easily replaceable module which can be removed without disturbing other systems. It also required vessel penetrations for each component be available so that each can be removed easily. The use of a manipulator for maintenance, assembly and disassembly made it necessary to consider visual cues and accessibility; and self alignment features and manipulator clearances for any planned service. Special consideration was given to this requirement in the whole system. For information on the TFTR remote maintenance system see References 5 and 6.

The high neutron fluence placed one other restriction on the design of the NBL vacuum chamber. The seals used on the vessel must be resistant to radioactive degradation. Therefore, only metal gasketed or welded seals were considered.

NBL Requirements

Subsystems of the NBL are also reponsible for design constraints. The three considerations which had the most important impact on the design are: (1) that the vessel be a right parallelepiped in outline; (2) that it maintain dimensional stability and vacuum integrity while supporting a full vacuum load and; (3) that it resist hydrogen embrittlement.

The first of these requirements, came from a potential space conflict between the NBL space envelope and the need for large cryopumping surfaces. The NBL requires approximately 2,500 cubic meters per second of deuterium pumping speed. About 25 square meters of surface area is required to provide this pumping. The only way to obtain this amount of cryopumping within the given exterior envelope was to make the panels the largest flat slabs possible. The vessel was required to be a box design to enclose this large pumping surface within the given envelope.

The second important consideration, that this box-shaped vessel support a vacuum of about 1 mPa (10^{-5} torr) with 100k Pa (14.7 psia) external pressure dictated that the vessel must be designed in accordance with high vacuum practice. In addition the 100k Pa external load on the large sides called for heavy reinforcement to keep deflections to a tolerable level.

The third important consideration, that the chamber material resist hydrogen embrittlement, is due to the fact that the vessel walls will be in contact with low pressure deuterium gas for years during TFTR operation. The loss of ductility among steels in the presence of hydrogen is well known. In particular, the heat affected zones of the corner welds of this box shape will be more susceptible to embrittlement because of the likelihood of local plastic strain in these areas.

Chamber Design

Material

Aluminum, mild steel and stainless steel were the only materials considered for the vessel. All grades of aluminum were eliminated because the electrical resistivity is too low. All magnetic steels including the 400 series stainless grades were eliminated because of their high magnetic permeability. The 300 and 200 series stainless steels were the only remaining candidates.

A 300 series stainless, AISI type 304, was initially thought to have ideal properties for this application. It combine proven vacuum compatibility and fabrication ease with adequate strength and stiffness; it also has good ductility and toughness, and the proper magnetic and electric properties. And while it is certainly not inexpensive at \$1.90 kg^{-1}, it is one of the least expensive 300 series steels.

Type 304 will be used for the external stiffeners but it will not be used as the vacuum boundary material because there is a reasonable chance that areas of a type 304 vessel might embrittle in the deuterium atmosphere.

This conclusion is certainly not obvious. Type 304 is commonly used in many applications to resist hydrogen embrittlement. But evidence exists that shows type 300 series stainless steels, by tradition thought to be embrittlement resistant, can hydrogen embrittle, depending on the metallurgy[7]. In addition, hydrogen embrittlement of type 304L has been shown to occur at nearly the same rate at atmospheric pressure as at high pressures[7].

The ductility losses in these cases are not trivial. Decreases in ductility to less than 1% elongation due to hydrogen embrittlement have been observed in the type 304 composition range[7].

Both the martensitic and ferritic phases of stainless steels have been shown to embrittle[8,9]. However, the austenitic phases seem to resist embrittlement.[10, 11] In particular, type 316 seems especially resistant to embrittlement[11].

Material within the 304 composition range is metastable austenite, that is, it is susceptible to strain-induced transformation to martensite even at room temperature. The heat affected zones of welds where stabilizing carbon has precipitated are especially susceptible to transformation. It is the martensite phase of these materials which embrittles when exposed to hydrogen.

Within the standard composition range of type 316 however, grades can be obtained which are stable austenite even in the heat affected zones of welds. This type of material is much more resistant to embrittlement though at a 40% price premium.

It should be noted that while experimental evidence shows that a vessel constructed of type 304 might hydrogen embrittle, it is not certain. The most persuasive evidence, duplicating the NBL operating conditions, is lacking. To this date, research has not been conducted on the embrittlement of stainless steels exposed to deuterium in a high vacuum.

Nevertheless, the precaution of purchasing a stable type 316 composition is necessary, because the repair of a crack in an embrittled vessel, when using remote maintenance equipment would be very expensive, if not impossible[12].

Design Description

The chamber will be a box shaped vessel, with a volume of 50 cubic metres, weighing about 35 Mg (38 tons). It features reinforced flat plate welded construction. The flat plate vacuum boundary will be constructed from the largest 20 mm (.75") type 316 standard plate available, 2.43 m (96") x 7.62 m (300"), to reduce the number of vacuum boundary welds.

These plates will be reinforced on the ends by fabricated box beams and midspan by fabricated tee beams. These beams must be fabricated because type 304 beams are not available. These beams will be constructed from 20 mm (.75") plate.

The large openings are designed to conform to Section VIII, Division 1 of the ASME Boiler and Pressure Vessel Code. They will protrude beyond the corner box beams to allow easy access to the flange bolt circles. They will include twin differentially pumped "O" rings to ease leak checking and also to reduce the leak rate. During the initial system shakedown elastomer seals will be used. Metal gaskets will be installed for operation at the TFTR site before tritium is used.

One of the handling requirements is the ability to remove all components from the system. In the case of the cryopanels this means that a removable cover will be necessry. The planned seal between the cover weldment and the bottom weldment is shown in Figure 5. It may either be welded shut or sealed with differentially pumped double 'O' rings for convenience during the prototype operation. This large rectangular 'O' ring seal will not be bolted or clamped but will rely on the weight of the cover to begin the seal. Once a slight vacuum is drawn, the sealing force will increase with the differential pressure, giving a vacuum tight joint.

Relief valves will be provided in the vessel to prevent internal pressure. Large pins will be installed at four locations on the lower weldment to guide the cover weldment on during assembly. Mating surfaces at four locations on the cover will ride along the pins to center the cover. In addition to the guide pins, eight shims will be installed on the cover. These shims will be fitted at assembly to make up the manufacturing tolerances. They limit the deflection of the sides of the bottom weldment to less than 1.25 mm x (0.050").

The use of internal compression members was eliminated in all but one case. Removable beams were ruled out as beyond the ability of the provided remote maintenance equipment. The large cryopumps prevent the use of fixed beams from side to side. The single exception is the magnet stand, which will act as a compression member between the bottom and the cover, supporting both the magnet weight and the atmospheric load on the top cover during operating conditions. All of the other load had to be supported by external beams.

Structural Criteria

This vacuum vessel must operate safely and reliably over the eight year life of the TFTR. During this period it is expected to be cycled from atmospheric pressure to 1 mPa (10^{-5} torr) less than one thousand times. With the exception of leak checking at the fabricator's shop and a prototype shakedown at the Lawrence Berkeley Laboratory, all of these cycles will occur in the controlled environment of the Test Cell.

To insure the safe operation of this vessel structural criteria were developed based in part upon Section VIII, Division 1, of the 1977 ASME Boiler and Pressure Vessel Code. Although specifically excluded, the areas which are similar to ordinary cylindrical pressure vessels, such as the openings are designed to the code[13]. However, many areas are not covered by this code. In these cases, additional criteria were developed for strength, stability and deflection.

The criteria can be summarized as follows:

1. Each area of the vessel must show a combined stress less than the allowable stress shown for that material in the 1977 Pressure Vessel Code. The efficiency of the welds is the same as is given in the code.

2. The deflection of large spans is limited to changes undetected by the human eye according to the American Institute of Steel Construction practice.[14]

3. In areas where buckling had to be considered two criteria were applied.
   a. The actual axial load must be less than the Euler column buckling load.
   b. The interaction between bending and axial loads must be less than the American Institute of Steel Construction allowable for interaction on beam-columns.[15]

Using handbook formulas and engineering judgement, these rules were applied to all areas of the vessel under all anticipated load cases. The single exception to this approach is the cover; which is so unorthodox that a handbook model was not deemed accurate enough. The deflection of the cover is the subject of an ongoing finite element analysis.

In all areas, the worst case conditions governed the design.

Vacuum Considerations

The vacuum integrity of the vessel is essential to the operation of the NBL. Special care was taken in the design to insure high vacuum integrity.

The design features welded construction wherever possible and 'O' ring seals on all demountable joints. The demountable joints larger than 0.5 m (20") in diameter feature a double 'O' ring seal with a guard vacuum.

The interior surface behind each opening will be ground to a three micron (125 μ inch) surface finish for a few inches beyond the inside diameter to allow the placement of a gasketed cover plate for the leak checking of individual openings.

The interior surface finish of the vacuum boundary will be a simulated #1 mill finish. No other surface preparations, other than a thorough cleaning, are planned.

Vacuum compatible welding practices are essential to the success of the design. The welds are designed to be done from within and the MIG process is recommended. This process has been the most successful in producing leak free welds. However, the fabricator will be allowed to use any process which will insure the same weld quality.

The chamber has some other features consistent with high vacuum design practices. The opening for the mechanical pumping system is a large diameter high conductance opening. Also the interior of the vessel is the minimum surface area because the beams are external. Any welds which could potentially hide a vacuum weld are made intermittent

Much of the success of this vessel depends upon the fabricator. In this case, an experienced vacuum vessel fabricator should be able to achieve a helium gas leak rate of less than 0.01m Pa · liter · sec^{-1} (10^{-7} torr · liters · sec^{-1}) at a base pressure of 0.1m Pa (10^{-6} torr) when evacuated with a 3.5 m^3 sec^{-1} vacuum pump.

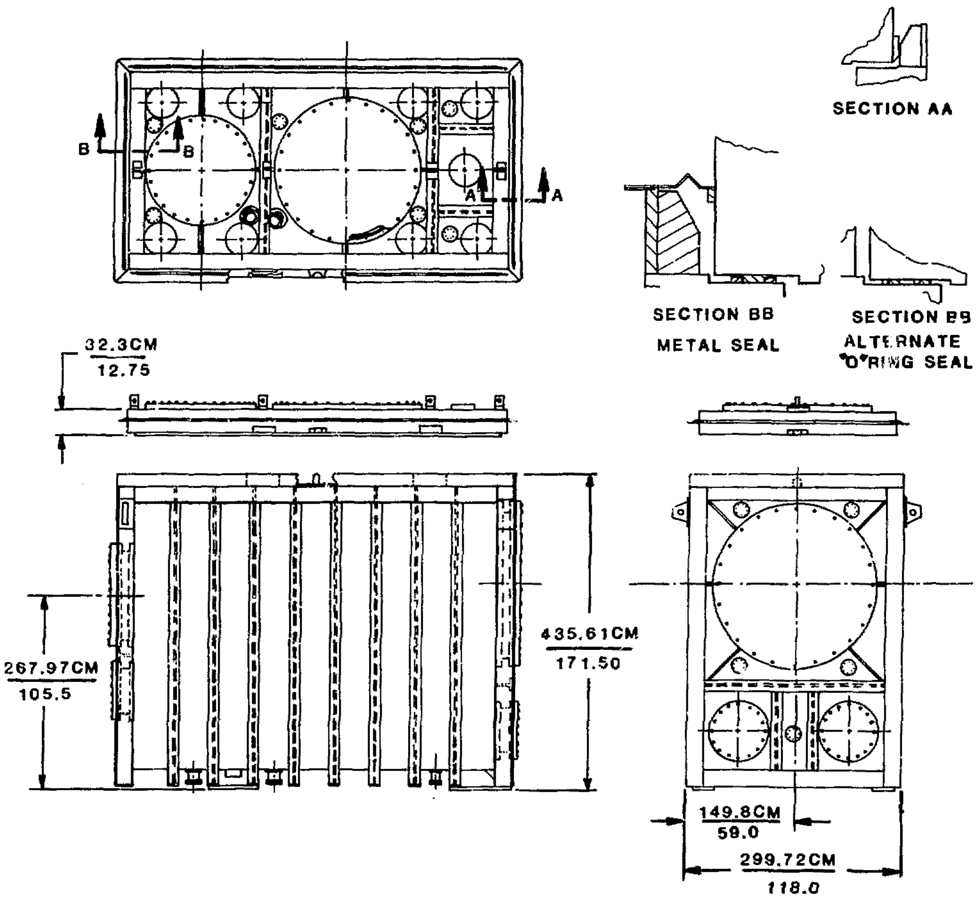

Figure 5.TFTR - NEUTRAL BEAM LINE VACUUM VESSEL

The acceptance leak test consists of enclosing the entire chamber in polyethylene sheeting and flooding the plastic enclosure with helium gas. The output of the vacuum pumping system will be run through a calibrated helium mass spectrometer of 100 μPa • liter • sec^{-1} (10^{-10} torr • liter • sec^{-1}) sensitivity. The leak rate measured by the device will be compared to the specified leak rate.

The cleanliness level will be checked by testing the base pressure for the given vacuum pumping system.

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