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AUTHOR(S): Peter P. Prince and Robert S. Dike

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

DESIGN OF THE ZTH VACUUM LINER*

Peter P. Prince and Robert S. Dike
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

The current status of the ZTH vacuum liner design is covered by this report. ZTH will be the first experiment to be installed in the CPRF (Confinement Physics Research Facility) at the Los Alamos National Laboratory and is scheduled to be operational at the rated current of 4 MA in 1992. The vacuum vessel has a 2.4m major radius and a 40 cm minor radius. Operating parameters which drive the vacuum vessel mechanical design include a 300 C bakeout temperature, an armour support system capable of withstanding 25 kV, a high toroidal resistance, 1250 kPa magnetic loading, a 10 minute cycle time, and high positional accuracy with respect to the conducting shell. The vacuum vessel design features which satisfy the operating parameters are defined. The liner is constructed of Inconel 625 and has a geometry which alternates sections of thin called bellows with rigid ribs. These composite sections span between pairs of the 16 diagnostic stations to complete the torus. The thin bellows sections maximize the liner toroidal resistance and the ribs provide support and positional accuracy for the armour in relation to the conducting shell. Heat transfer from the vessel is controlled by a blanket wrap of ceramic fiber insulation and the heat flux is dissipated to a water cooling jacket in the conducting shell.

Design Requirements

From an engineering design viewpoint the design requirements for ZTH can be separated into two groups. Table 1. The most important group, the primary requirements, determines the nature of the liner geometry. If one of these parameters were to change it is possible that the geometry which satisfied the new parameter would be quite different than that of the original design. For instance, if the required toroidal resistance were to decrease by a factor of two, the liner solution would not be restricted to thin walled bellows configurations but could include double walled or thick walled options. This impact on design is not as strong with the secondary requirements. With the exception of the liner aspect ratio, the ratio of the minor to major radius, the secondary requirements are satisfied by the characteristics of the innerspace between liner and shell. A change in one of these parameters (say an increase in bakeout temperature) would not result in a new liner geometry but could be satisfied by altering the thermal properties (decreasing the thermal conductivity) of the innerspace.

The solutions which satisfy the design requirements become more apparent when each parameter is justified by its impact on the overall mechanical design:

The physics requirement for a high liner toroidal resistance is based on plasma equilibrium calculations which predict that to optimize plasma conditions the magnitude of induced toroidal liner currents should be minimized. This benefits the mechanical design of the

Table 1
DESIGN REQUIREMENTS FOR THE ZTH VACUUM LINER

PRIMARY REQUIREMENTS	SECONDARY REQUIREMENTS
LARGE TOROIDAL ELECTRICAL RESISTANCE	300 °C BAKEOUT
25 KV ISOLATION IN ARMOR SUPPORT	10 MIN REP RATE @ 4 MA
900 KPa MAGNETIC LOADING	PLASMA OFFSET FROM SHELL
HIGH POSITIONAL ACCURACY	2.4 M MAJOR RADIUS
16 AXIS SYMMETRY	40 cm MINOR DIAMETER

vacuum vessel since the anticipated magnetic loading due to plasma termination is also dependant on the magnitude of the toroidal currents. Without the benefit of this relationship the light structure required for the high resistance would not be sufficient to resist the imposed loading. Current calculations for ZTH predict a magnetic loading of 1250 kPa and this in addition to the vacuum loading of 1 ATM is assumed to be the design loading.

It is also desirable to limit the current which develops in the armour since large anticipated currents would require that the armour supports be designed to resist very large magnitudes of magnetic loading. By providing 128 poloidal gaps between toroidal sections and 44 toroidal gaps between poloidal armour sections the resistance of the armour is larger than that of the liner which results in termination currents flowing in the liner and not the armour.

The positional accuracy of the liner with respect to the conductive shell is important because of field error considerations. With some experiment designs this requirement does not merit special attention as the solution is inherant in the designs. However, in ZTH, since the liner geometry is a bellows configuration and since the bellows are nonuniform in shape, special features must be provided to align the liner and armour within the shell. This is done by alternating solid ribs with the bellows sections. The ribs are accurately machined and provide reference surfaces for both the armour and the shell. This ensures repeatable location of the vacuum vessel and greatly reduces the positional requirements for the bellows convolutions while also providing attachment for the armour.

The symmetry of the liner design is truly a case of design by compromise. Although there are many configurations which would satisfy the requirements of the liner alone, only a few can do so and still supply the required diagnostic access and interface with the machine support structure. In brief, the liner was designed to supply 16 stations for diagnostic access and other characteristics were selected in a manner which minimizes conflict with the required access.

The secondary requirements are satisfied by selecting the geometry and thermal characteristics of the interspace based on thermal analysis of the front end. This does not include the aspect ratio of the liner which was selected to meet physics requirements.

* Work done under the auspices of the US Department of Energy.

The secondary requirements are dependant on the geometry of the front end and can only be determined after the configuration that satisfies the primary requirements is known. A large range of thermal conductivity is available with the numerous materials suitable for use in the interspace and this will allow the thermal response of the front end to be tailored to meet varying requirements. The major limitation is the approximately 250°C continuous use temperature limit of available electrical insulators.

The Design

The ZTH liner will be constructed entirely of Inconel 625 and will be composed of 16 equal bellows subassemblies and 16 equal diagnostic sections. Each bellows subassembly consists of 7 equal length bellows sections connected by 8 support rings. Figure 1. With a convolution height of 2.3 cm, a pitch length of 2.3 cm and a skin thickness of 1.6 mm the bellows geometry produces a toroidal resistance of 8.3 milli Ohms and a stiffness equivalent to a 1.2 cm uniform wall thickness pipe. The high resistance is a product of the high resistivity of the Inconel 625 ($\rho = 133 \times 10^{-8}$ m-ohm) and the 3000 cm toroidal path length of the bellows. Analytical calculations indicate that the selected bellows configuration coupled with the 128 support rings has sufficient strength to resist the expected loading, but sufficient uncertainties exist to warrant a detailed finite element analysis. This is particularly true for the diagnostic sections at the tubulation penetrations.

Besides increasing the stiffness of the liner the support rings provide reference surfaces to which the armour can be attached and by which the liner can be located with respect to the conductive shell. Figure 2. In addition at 2 toroidal locations the rings will incorporate a bolt circle and metal O-ring seal to allow access to the vessel interior for repair. The ID of the rings are deeply scalloped to reduce their cross

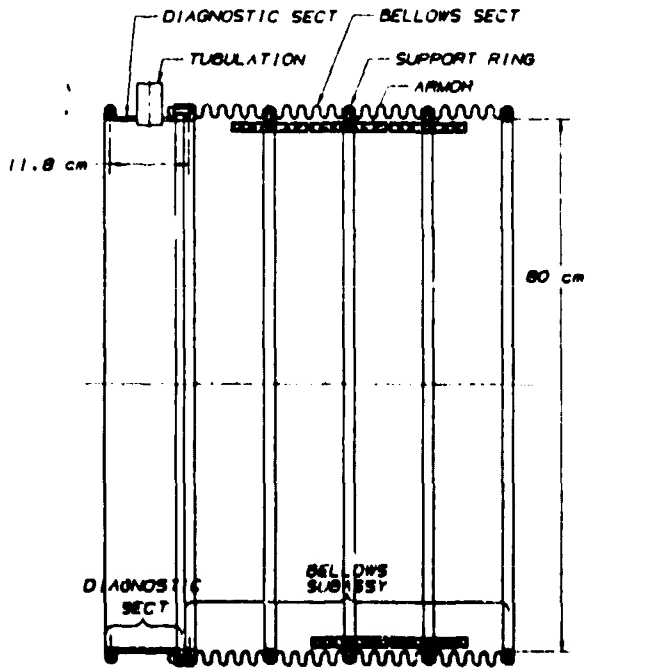

Fig. 1. ZTH liner subassembly non arced, only 4 of 7 bellows sections shown

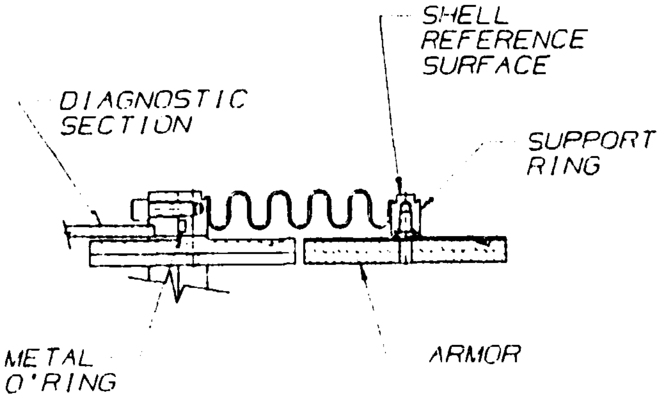

Fig. 2. ZTH Liner Detail, Vacuum Seal Section.

section and minimize toroidal fluctuation in liner resistance.

With 128 support rings and 44 tiles per ring, 5632 tiles are required to protect the liner. Fortunately, only the toroidal length of the tiles varies and that length is constant for a given poloidal position which results in 44 tile sizes.

The overall geometry of the liner and ZTH was set by the decision to have 16 diagnostic stations. To incorporate this in the liner every eighth bellows section was replaced by a 6.4 mm thick, single wall, chord section, diagnostic skin. This skin was chosen because its uniform surface enables the diagnostic tubulations to be attached to the liner using conventional welding techniques. This was an important factor due to the mechanical loading and thermal stresses expected in that location.

Although the liner has 16 axis of symmetry and has 16 diagnostic sections, only 15 of the sections will provide diagnostic access. The other section is located under the gap region of the shell where for structural and electrical insulation reasons no penetrations are allowed through the gap and this precludes diagnostic tubulations at this station. There are 5 different diagnostic tubulation configurations which occupy the 15 available diagnostic stations. Figure 3. All tubulations were designed to minimize the required hole in the conducting shell in an effort to reduce the field errors which occur due to non uniformities in the conductor.

The horizontal tubulations are one piece tubes, 1.8 mm wall, and are welded to the diagnostic skin. They are of sufficient length to penetrate the shell and each tube terminates with a welded on CONFLAT[T] flange which allows interface with the diagnostics. A simple hole is provided in the shell for tubulations which are located on the horizontal centerline while a keyhole and insert plate are required for off axis tubulations. The keyhole is required to enable the shell sections to pass over the liner tubulation during

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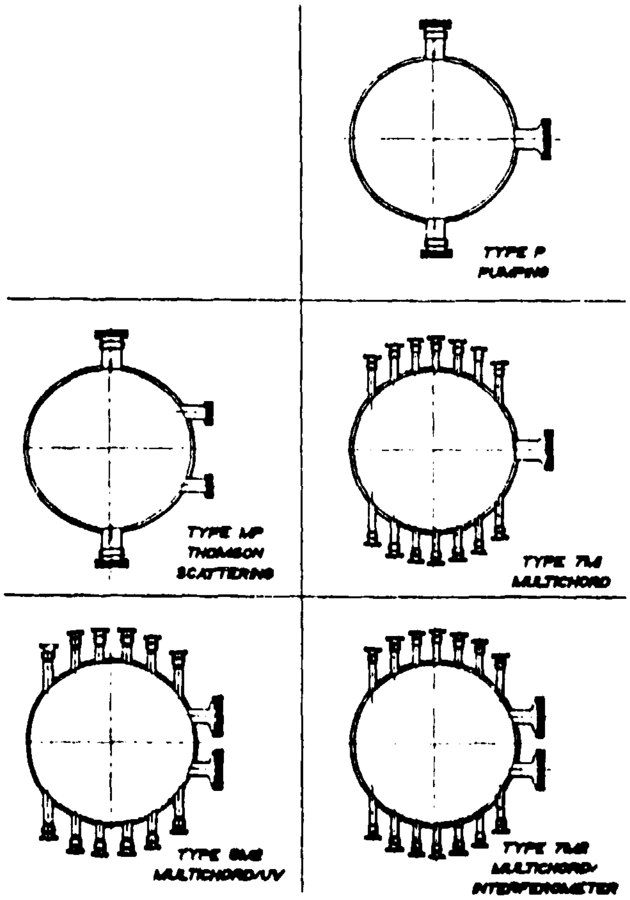

Fig. 3. ZTH Diagnostic Station Configurations

assembly and the insert plate is installed to regain toroidal electrical continuity in the shell across the keyhole.

If the same design were used for the vertical tubulations, the shell would have to pass over the entire tubulation, including the CONFLAT flange and the required shell hole would be too large. Insert plates were considered but were rejected due to structural considerations. As a result a different approach was selected which has the tubulations constructed of two pieces connected with a HELICOFLEX(T) seal. Figure 4. During shell assembly the upper portion of the tubulation which includes the CONFLAT flange is removed. As a result the shell hole only needs to be large enough to clear the male portion of the HELICOFLEX seal. After assembly the upper portion of the tubulation is installed and the shell is now captive. Lacking experience with HELICOFLEX seals the program has opted to build prototypes of these tubulations and test them for reliability. Testing is currently in progress.

The vacuum liner interface with the conducting shell occurs in the innerspace region. The innerspace is the void between the liner OD and the shell ID. In ZTH this space has a nonconstant width as the liner center is offset outboard 12 mm from the shell center. This shift equals the anticipated Shavfranov shift of

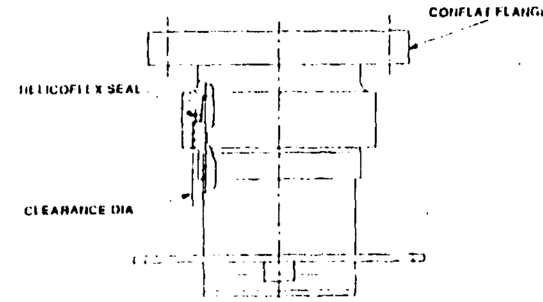

Fig. 4. Helicoflex seal arrangement for ZTH vertical tubulation.

the plasma and results in the innerspace width varying from a minimum of 1.6 cm at the outboard horizontal centerline to a maximum of 4 cm at the inboad midplane.

The innerspace region contains the liner structural supports, the thermal and electrical insulation and some electrical diagnostics. These components must be carefully selected to satisfy the secondary design requirements of Table 1 while still allowing for the following: 25 kV of isolation between shell and liner, a uniform heat flux from the liner to the shell to prevent temperature gradients from thermally stressing the liner, and protection of the electrical insulation from temperatures exceeding 250°C.

To position the liner within the shell crescent shaped standoffs will be attached to the liner. The standoffs will be made from a liquid crystal polymer such as XYDAR(T) by injection molding and will be machined to final shape. Figure 5. Due to the thermal expansion of the minor diameter of the vacuum liner the standoffs cannot fill the innerspace completely, but must be undersized by approximately 3 mm to allow for the expansion. The liner diameter and the thickness of the standoffs have been carefully chosen to position the liner at the proper position at the defined operating temperature of 200°C. At temperatures other than the operating temperature the plasma will have a thermal shift in addition to the desired Shavfranov shift. This also results in all liner loads being reacted to the shell through the inboard and bottom standoffs as the vertical and outboard standoffs are not in contact for temperatures below 300°C.

The electrical insulation will consist of a epoxy based coating on the shell ID to ensure good thermal contact with the cooling capacity of the water jacket and KAPTON(T) inserts providing increased tracking distance at joints between the shell sections. The thermal insulation will be a glass fiber blanket enclosed mat of ceramic fiber and its thermal

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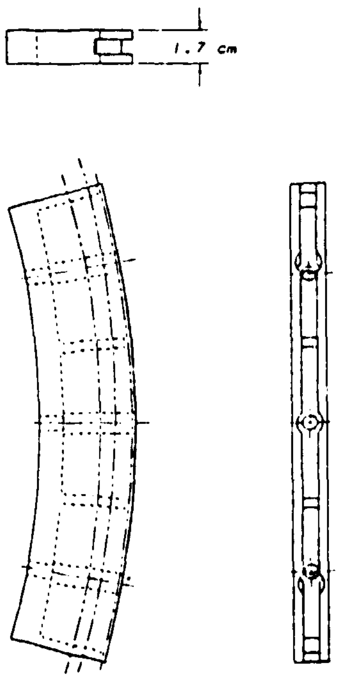

Fig. 5. ZTH Innerspace Spacer,

resistance will not be constant due to the non uniform innerspace width. The primary purpose of the thermal layer is to prevent excessive temperatures at the electrical insulation and to keep the liner at a uniform temperature. Current calculations predict temperatures outside of the thermal blanket as lower than 100°C in a macro view.

Design Uncertainties

The design detailed in this report is still preliminary in some aspects. Still pending are results of a liner FEM stress analysis, a transient heat transfer analysis of the front end cross section, and a vacuum test program for the helicoflex seal. Some areas of the design could change as a result of these studies.