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DESIGN OF THE VACUUM LINER FOR THE NATIONAL COMPACT STELLARATOR EXPERIMENT (NCSX)*

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ABSTRACT

The National Compact Stellarator Experiment (NCSX) requires an inner vacuum vessel (liner) which will serve as a structural component, withstanding full atmospheric pressure and magnetic disruption loads. It must also be capable of bake out to 350 C. without imparting excessive thermal loading on saddle coils which reside on an outer shell surrounding the liner.

NCSX will be sited in the Princeton Beta Experiment (PBX) test cell. Many of the existing site assets including the test cell, TF and PF coils, power supplies, neutral beam heating systems, and site utilities will be utilized to minimize the cost of the project.. The conceptual design features a stellarator core that is pre-fabricated and dropped into place on the PBX platform. The existing TF and PF coils are then reassembled around the stellarator core. Trade studies have been conducted to explore different configurations for the liner and the saddle coil structure. These included a design which used a low conductance non vacuum liner assembled within an outer vessel which surrounded the NCSX device, and served as the primary vacuum containment.

The plasma has three periods and is very convoluted, changing in cross section from nearly circular to bean shaped with a very concave contour on the inner surface. The contour repeats twice every period, that is the shape is identical after 60 degrees toroidally, but with the shape inverted 180 degrees. The liner is required to follow the plasma surface very closely and, as result, is complex in shape.

A trade off study has been made to determine the best fabrication technique to produce such a liner. The study included casting, pressing, explosive forming, isostatic pressing, and brake bending from flat developed patterns. The decision on a fabrication method relied heavily on previous experience by other experiments such as HSX, W7-AS, and W7-X which dealt with similar, convoluted shapes. The method picked was the flat pattern technique utilized by Wendelstein W7-AS .

The liner is designed to be built in three sections corresponding to the plasma field periods, and final assembled around an inner shell core. After welding of the liner sections, the outer shell segments will assembled around the liner. Saddle coils will then installed around the shell.

Insulation must be installed between the liner and shell to protect the shell during liner bake out , and to minimize heat transfer from the cooler shell during operation. Because the radial build up is limited and the shell is designed to operate at cryogenic (LN2) temperatures the choice of insulation materials is limited. A trade off study has been performed and extensive thermal analyses have been done to determine an insulation design which can operate in the extreme temperature range from 77 K to 623 K.

The engineering design is being developed by a team from Oak Ridge National Laboratory and Princeton Plasma Physics Laboratory. A Physics Validation Review of NCSX is planned for September, 1999. The Conceptual Design effort will then commence in earnest, culminating in a Conceptual design review in March, 2000. First plasma is planned for September, 2004.

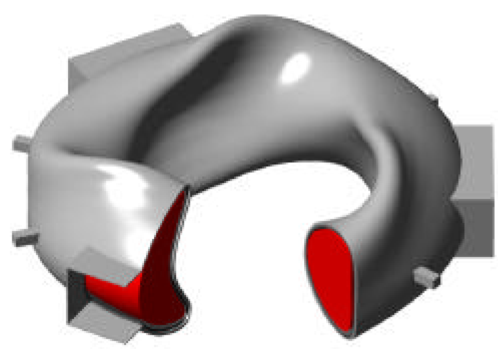

Figure 1. Liner Baseline Geometry

INTRODUCTION

Early studies were done assuming a low conductance liner constructed within the PBX vacuum vessel and Saddle Coil Shell.[Shell] The liner would have been hundreds of individual panels mounted between a series of radial ribs, and vacuum pumped differentially with the vessel. The concept was rejected when analyses proved that the vacuum quality would be unacceptable unless the liner conductance to the outer vessel wall and Shell was kept at such a low level that it would be virtually a continuous liner. The resulting liner had no cost benefits.

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The baseline Liner geometry (figure 1) is driven by the configuration of the plasma and the Shell.[1] Segmentation of the liner is driven by assembly requirements and inherent fabrication limitations (discussed under Fabrication Tradeoff Study). The torus three sub-assemblies, complete with ports, will be assembled and field welded into around a central shell assembly, with the TF coil top and outer legs removed. See figure 2. The field welding must be performed inside and this implies a man access port at each of three locations [maneuvering of a man 180 degrees around the inside of the torus is problematic]. In addition, access must be available for later installation of wall tiles into the liner. Since this must be done without removal of TF legs, the access must lie between TF coils.

To aid in assembly the three torus sections will be provided with machined end flanges (ribs) that provide weld seams and serve to take up any misalignment between sections due to tolerance buildup or distortion in the sections. They also serve as mounting surfaces for the poloidal limiters. The welding of the sections to their respective end flanges will be done with the components all preassembled on a fixture into a complete torus. This will force a good fit during the final field assembly.

PORTS AND ACCESS

Three large, rectangular[cylindrical surfaced] port mounting surfaces extend out from the Liner through the Shell. The surfaces span several TF coils and lie inside their envelope. The surfaces provide consistent interfaces for several sizes of radial ports, including the NB tubes and the removable panels required for man access into the liner.

The ports could be directly mounted to the Liner wall but the interfaces would be complex in shape and differ with every port configuration and location. Using the mount surfaces permits Liner fabrication to proceed at the subcontractor before the final port configuration is finalized and is not sensitive to changes occurring late in the design cycle. The surfaces may be bored for ports after fabrication of the liner segments is complete. The offset in the mounting surface also improves the access view factor of each port.

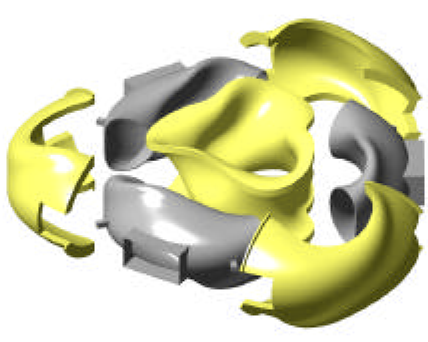


Figure 2. Liner assembled into Central Shell

PLASMA FACING COMPONENTS

Initial operation will be with three poloidal limiters and neutral beam armor protection at three location with no additional wall protection. Provisions will be provided for later [upgrade] installation of wall tiles as required. The limiters are carbon-carbon tiles, inertially cooled during operation and cooled between shots by conduction to the liner wall. Attachment is accomplished via ribs which are located at the field joints of the liner. See figure 3

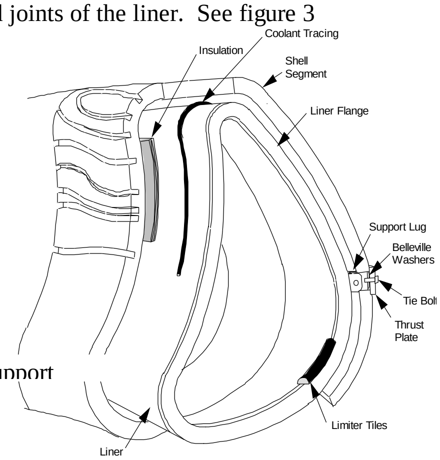


Figure 3. Liner Support

LINER STATISTICS

BASELINE MATERIAL	Inconel 625
NOMINAL OUTER RADIUS	1.8 m
INNER R. VARIES BETWEEN	1.05 m - 1.46 m
APPROX. OUTER PERIMETER	11.31 m
MAX HEIGHT	1.28 m
THICKNESS	9.53 mm
INSIDE SURFACE AREA WITH PORTS	37.5 m^2
ENCLOSED VOLUME	6.2 m^3
WEIGHT WITHOUT PFC'S	3770 Kg

OPERATING PARAMETERS

UPGRADE OPERATION HEATING	12 Mw
AVERAGE PLASMA FLUX	32 w/cm^2
BAKE OUT TEMPERATURE	350 C
OPERATING TEMPERATURE	38 C
TEMPERATURE RISE, OPERATION	21 C/sec
THERMAL GROWTH, BAKE OUT	1 cm radial
PULSE DURATION	3 seconds flat top
COOL DOWN BETWEEN SHOTS	10 minutes

STRUCTURAL ANALYSIS

Analyses have been performed to determine the required thickness of the liner based on atmospheric vacuum load and disruption predictions. The results are shown in figure 4. Failure criteria is based on a large buckling allowance rather than deflection or stress. This is done because there are large uncertainties in the disruption loads and also to offset any errors in the analysis which assumes a simplified contoured model rather than the actual faceted surface. Further structural analysis is planned later in the program.

SUPPORT STRUCTURE

The Liner is supported at its nominal[dimensional] inner and outer midplane so that vertical thermal growth will be as nearly symmetric as possible. A support scheme is shown in figure 3 which utilizes lugs supported off the shell. The lugs are mounted radially to the Liner centroid and are free to slide. They are preloaded by belleville washers to maintain concentricity
to the device center.

LINER FABRICATION TRADEOFF STUDY

Two broad options are being considered for fabrication of the liner; one with a contour closely conforming to the plasma and the other with a faceted (developed) shape to approximate the plasma contour. A contoured liner could be formed by pressing or explosive forming sections of the liner and welding them together to form the finish shape. A developed liner could be flat

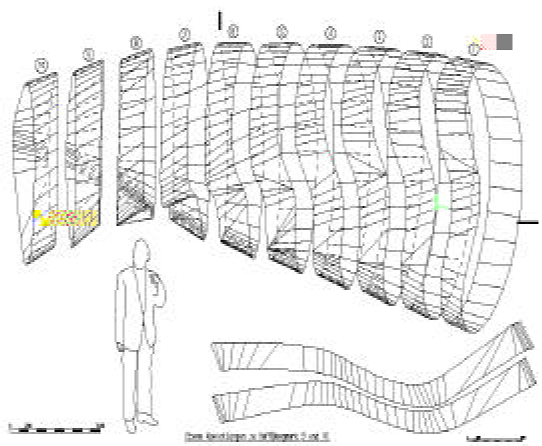


Figure 5. Developed Liner

patterned in segments and brake bent into shape directly from sheet stock. 48 or more segments (16 in each period) would be welded into the final shape. Such a developed liner would be of a series of trapezoids or triangles which approximate the plasma shape.

Contoured Liner

Contact was made with the HSX and WENDLESTEIN [2] projects during a fabrication tradeoff study to determine which options might be viable choices for the liner fabrication. It was determined that commercial procurement using the explosive forming or pressing method would be prohibitively expensive. The dies required in explosive forming are very massive and the forming has to be done in two or more progressive shots with stress relieving of the parts between shots. HSX was able to utilize University

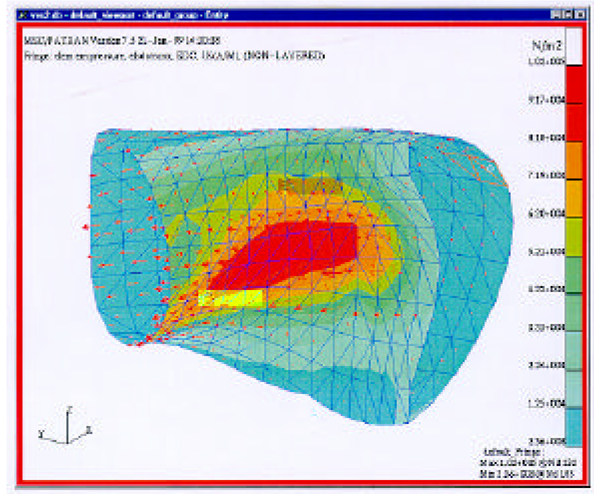


Figure 4. Shell loading during disruption.

personnel to perform the operation in-house and keep costs down; not an option for NCSX. Pressing produces very esthetic, precision, contoured shapes, parts have high rigidity and there would likely be fewer piece parts and seams to deal with.
Unfortunately large panels of such heavy gauge require very high forces, ranging up into hundreds and even thousands of tons, limiting the operation to a few industries such as automotive plants and aircraft manufacturers. The present

estimated costs presently far exceed the estimate for a developed liner and vendor contacts are being made to substantiate the estimates. Over seas sources such as the Russian Republic are also being investigated.

Developed Liner

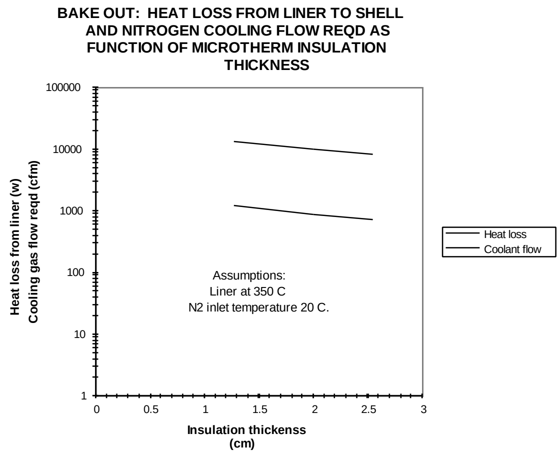
The developed liner is the baseline for the NCSX liner. It is relatively low tech and can be fabricated with equipment found in many manufacturing facilities. A fairly simple brake bend machine is sufficient to form the segments once the shape has been patterned. The method has precedence with WENDELSTEIN W VII & AS. See figure 5. A US supplier has been identified to do prototype sections for the NCSX liner.

THERMAL ANALYSIS

Bake out of the liner and cooldown between shots is provided by Dowtherm A [3] flow through tracing attached to the Liner wall. A nominal flow of water must be circulated in the Saddle Coils during bakeout to maintain them near room temperature. Another solution would be to circulate nitrogen in the annulus between the Shell and outer cryostat insulation. The heat loss and gas flow as a function of insulation thickness is shown in figure 6.

CONCLUSIONS/CONCERNS

No serious technical problems have been identified which would preclude fabrication of the NCSX Liner in its present configuration. There are concerns with fabrication



of a developed liner since it entails a large number of seams and has the potential for weld distortion and vacuum integrity problems. This presently seems like an acceptable tradeoff in NCSX which is constructed of heavy gauge material which makes it very costly, perhaps impractical, to press. Further vendor contacts and an R&D program are planned to resolve these issues.

REFERENCES

1. D. Williamson et al.,"Design Description of the Saddle Coils for the National Compact Stellarator Experiment (NCSX)", (Proceedings of the 18th Symposium on Fusion Engineering (Albuquerque, USA, October 1999)

2. Conversation with Joerg Sapper, WENDELSTEIN7-X, 4/27/99 and follow up letter 5/19/99.

3. Dowtherm is a trademark of Dow Chemical Corp.