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AN ALUMINUM VACUUM VESSEL/FIRST
WALL CONCEPT FOR THE CTHR

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FOREWORD

The Westinghouse Fusion Power Systems Department, under contract to the Department of Energy, Office of Fusion Energy, has been examining the technical and economic feasibility of fusion-fission hybrid reactors based on the tokamak concept since 1977. An important element of this work was the development of a reference first-generation Commercial Tokamak Hybrid Reactor (CTHR) design. The purpose of this reference design is to permit the identification of the technical features of such a system in sufficient detail to support an assessment of the potential availability of solutions to major design problems and to provide a benchmark estimate of economic feasibility. The work reported herein was performed as part of this overall effort. A summary of the CTHR plant point design is presented in the CTHR Final Report⁽¹⁾.

1.0 INTRODUCTION

In the development of a first wall vacuum chamber for the Commercial Tokamak Hybrid Reactor (CTHR) , it is essential that the performance of this system permit the reactor to achieve the sustained burn time necessary for economic operation. The purpose of this investigation was to develop an initial design concept for a CTHR vacuum vessel/first wall system which could satisfy engineering and operating requirements for a commercial environment.

To date, nearly all commercial conceptual designs for tokamak fusion reactors are based on stainless steel as the construction material for the vacuum chamber/first wall. Unfortunately stainless steel is restrictive with regards to thermal-mechanical performance as well as impurity release and plasma contamination characteristics. The hybrid reactor offers the unique condition that energy extraction from the first wall is not critical from the point of view of system economics. In view of this, consideration of a low Z structural material operated at a low temperature for first wall application becomes an attractive proposition. The use of aluminum in such an application has a number of attractive and unique features. The features embodied in the design of the CTHR aluminum vacuum vessel/ first wall system lends technical and economic feasibility to magnetic tokamak confinement commercial energy generation.

The purpose of this report is to define the aluminum vacuum vessel concept developed using the CTHR baseline parameters⁽¹⁾ and provide some of the cursory analyses supporting the concept selection. The comparison of this concept versus a similar stainless steel concept and the performance trade-offs are discussed in the CTHR final report⁽¹⁾. This report also provides a brief review of first wall surface low Z coatings and discusses plasma disruptions anticipated for a commercial size plasma, as they relate to the aluminum vessel concept development.

2.0 SUMMARY

The purpose of this investigation was to develop a design concept for a commercial tokamak hybrid reactor (CTHR) vacuum vessel/ first wall system which satisfies the engineering requirements for a commercial environment. The hybrid reactor offers the unique condition that energy extraction from the first wall is not critical from the point of view of system economics. This allows the consideration of low temperature structural material for first wall application. Therefore, the CTHR aluminum vacuum vessel/first wall design philosophy was to utilize a low temperature design, thus minimizing the severe material and thermal stress problems associated with high temperature systems.

The mechanical arrangement consists of a series of internally finned aluminum tubes fabricated into 30 sections and assembled around the torus as shown in Figure 1. The coolant manifolds are at the top and bottom of the torus. The vessel sector length depends on the spacing between TF coils. Each sector is mounted on a rail system that permits translation for assembly or removal. The tubes in each sector are welded to tube sheets which are in turn welded to semi-cylindrical manifolds which distribute the coolant uniformly to the tubes. The tubes, which are approximately 2.5 cm in diameter at the manifold location, traverse the torus poloidal periphery and change from a circular cross section to a 2:1 elliptical cross section at the horizontal midplane. The arched tube is designed to be self-supporting between the manifold locations.

One of the common concerns with first wall designs is to assure that coolant materials do not reach the plasma through faulty containment structures. Cracks in the coolant tubes would permit plasma contamination or even quench. The water cooled aluminum concept developed during this study has two important features which minimize the leakage potential. First, the coolant

Figure 1. Mechanical Arrangement of the Reference Design

is low pressure which minimizes stresses in the containment structure. Second, a surface coating is applied to the plasma side of the tubes to serve as a sacrificial first surface.

The first surface of the vacuum vessel will be plasma flame sprayed aluminum applied to the tubular wall. The relatively low Z material aluminum coating maintains the vacuum integrity of the system and allows the penetration of high energy neutrons. The aluminum coating will be eroded from the first surface by various processes. The surface erosion rate should not be of sufficient magnitude to have a significant effect on the operation of a self-sustaining fusion reactor. The ability to refurbish the coating in situ routinely was an important consideration in material selection. The process by which the first surface can be renewed would be by vapor deposition using a maintenance plasma fueled with aluminum pellets. A flame sprayed aluminum surface offers structural survivability against repeated plasma disruptions. In order to determine the consequences to the aluminum first surface, it was necessary to estimate the plasma disruption time, stored energy in the plasma and the uniformity of this energy deposition on the first surface.

Utilizing the scaling law developed by Carreras⁽²⁾ to estimate the disruption time, it becomes evident that the disruption time is a function of plasma edge temperature. CTHR has a potential plasma edge temperature range from 1 keV to 1 eV. The corresponding disruption time varies from 50 μ s to 10 ms. Such a wide range of disruption times can have various consequences to the first surface. In general, the damage done to the first surface decreases as the disruption time increases. As the disruption time increases, the possibility of detecting and controlling a disruption also improves.

The uniformity of the energy deposition on the first surface is needed to determine material damage since any large scale dumping of kinetic energy into localized areas could lead to intolerable structural damage. It was assumed that during hard plasma disruptions, the thermal flux to the first surface was uniform, based on Sestoro's⁽³⁾ virtual limiter postulate.

The CTHR reactor will have approximately 0.6 GJ of stored energy in the plasma during the burn pulse. Half of this stored energy is in the form of magnetic energy with the remaining half being kinetic thermal energy.

Transient heat conduction and hydraulic calculations were performed for the water cooled aluminum vacuum vessel using a general purpose thermal/hydraulic computer code to determine the first surface, coolant tube and coolant temperatures along the tube channel during a burn pulse. In order to keep the structural tube material temperature below 100°C during a normal operating cycle, the water flow rate required is about 0.9 l/s per tube. This flow rate necessitates pumping power of the order of 1.0 MW for the first wall system. Due to the high thermal conductivity of aluminum, the temperature gradient across the tube thickness is minimal; however, there is a diametric temperature gradient across the tube which induces a membrane stress across the tube. The equivalent stress at the highest stressed region is below the elastic limit of the structural material. In analyzing fault conditions the following results summarize the consequences.

- For a uniform plasma disruption, the surface coating approaches melting temperature, which provides a thermally softened condition to attenuate the thermal surface stress wave and avoid surface crack growth.
- For highly localized fault conditions, the associated high surface flux ablates some of the aluminum coating material which in turn avoids structural damage to the vessel.
- For uniform and localized fault conditions, the tube and flange structural material remains well below the melting temperature due to its high thermal conductivity.

Fabrication of the vacuum vessel modules will be an important consideration. A manufacturing technique for the dual tubes with spiralling fins is presently available. This procedure can be modified to achieve the elliptical cross section and the "D" shape curvature. The prebent, reconfigured cross section tubes will be assembled together in a special fixture which will hold them

throughout the fabrication procedure. The tube sheet manifolds will then be welded to the tubes and then to the semicylindrical manifolds. The assembled module will then undergo a heat treatment to retemper the aluminum structure. The inside of the vessel module will be flame sprayed with aluminum. This process will affect only the tempered properties of the tube surface and will not alter the overall temper properties. After final fabrication, each module can be leak checked and subsequently hydrostatically and performance tested at pressures and temperatures simulating operating conditions.

In general the outstanding features of the aluminum vacuum vessel/first wall system are the following:

- Minimal potential for coolant leakage into plasma
- Insitu renewable protective first surface
- First surface integral with vacuum vessel
- Effective use of a low Z first surface material
- Low stresses due to the thermal properties of the structural material and low pressure coolant
- No welds exposed to plasma environment
- Available technologies for manufacturing, fabrication and testing
- Potential for low radiation activation during operations
- Relatively easy volume compaction for waste disposal after useful lifetime (crushable compaction)

Sufficient analyses have been performed to indicate that this first wall system conceptual design meets the specified functional requirements and design criteria of Section 3.0. A summary of the first wall design and operating parameters are given in Table 2.1.

The main problem with the aluminum vacuum vessel concept is that its effective wall thickness is about three times thicker than a stainless steel tubular wall concept (1.5 cm vs. 0.5 cm). This reduces the number of fast neutrons reaching the fertile blanket as does the water coolant in the aluminum tubes. The net result can be a reduction in fissile fuel production of approximately

TABLE 2-1

ALUMINUM VACUUM VESSEL/FIRST WALL DESIGN AND OPERATING PARAMETERS

DESIGN PARAMETERS

● Plasma β (percent)	6.0
● Plasma Z Effective	1.5
● Plasma Operating Period, (s)	1268
● Burn Time, (s)	1200
● Exhaust and Replenish Time, (s)	68
● Peak Neutron Wall Loading, (MW/m ²)	3
● Surface Flux, Radiation-Convection (MW/m ²)	0.6
● Average Neutron Power Density (MW/m ³)	46
● Vacuum Pumping Rate Based on Allocated Pumping Port Area (ℓ/s)	200,000
● Allowable Plasma Impurity influx for reference plasma operation (T ℓ/sec)(argon)	0.042
● Operating Vacuum Chamber Pressure (torr)	10 ⁻⁷

MATERIALS

● Low Z Coating Material	Aluminum
● Specified Thickness (cm)	0.5
● Preparation	Plasma Flame Sprayed
● Structural Material	Aluminum 6061 T-6
● Coolant	Pressurized Water

OPERATING PARAMETERS

Vacuum Vessel

● Maximum Temperature (°C)	118
● Maximum Annual Fluence (n/m ²)	6.25 x 10 ²¹
● Maximum Stress (MPa)	105

Water Coolant

● Operating Pressure (MPa)	0.69
● Flow Rate (m/s per tube)	7.25
● Inlet Temperature (°C)	37
● Exit Temperature (°C)	93
● Total Pumping Power (MW)	1.0

16 percent, which is only partially offset by the increase in thermal power (10 percent), based on the reference CTHR concept⁽¹⁾ (UC fertile fuel, Li_2O tritium breeding compound). This ultimately results in an increase in the cost of electricity for a Hybrid/Light Water Reactor symbiotic system using the U-Pu fuel cycle. The aluminum vacuum vessel concept may be better adapted to the Th-U fuel cycle with a fission suppressed thorium fueled concept utilizing an initial zone of lithium for tritium production.

3.0 SYSTEM REQUIREMENTS AND DESIGN CRITERIA

The Commercial Tokamak Hybrid Reactor has been conceived to be an early 21st century, moderately long pulse, ignition reactor. The principal function of the vacuum vessel structure is to provide a vacuum containment within which a plasma can be generated and controlled. The vessel must be designed to suitably confine the plasma during all modes of operation and to provide structural integrity for the severe radiation, thermal and mechanical stresses imposed upon the structure. The principal loads on the vessel induced thermally are those from the plasma particle and radiation fluxes, and the neutron and alpha heating. The other principal loads come from the coolant pressure. The reactor chamber vacuum boundary removes the atmospheric load from the vacuum chamber, and thus only a small partial vacuum pressure differential exists across the vessel structures.

The achievement of a satisfactory tokamak system design is dependent upon the successful design of the first wall system. The primary functional requirements and design criteria of the first wall system are listed as follows:

- To meet the design requirements imposed by plasma impurity control, materials integrity, fabrication and assembly, and thermal-hydraulic performance.
- To contain and isolate tritium fuel gas
- To be equipped with electrically insulated flanges that serve as breakers for the currents induced in the vacuum wall, yet provide a shunted discharge path of high resistance for plasma disruptions.
- To have all extensions of the vacuum boundary, i.e., ducts, drift tubes, and other integral vessel extensions, conform to the overall structural, material and vacuum integrity requirements imposed on the vacuum vessel.

- To enclose the appropriate volume (associate with a plasma having a 6 meter major radius) in which satisfactory plasma burn can occur.

The first surface operating environment limits the lifetime of the vacuum chamber primarily by high helium generation from n, α reactions causing displacement damage and loss of ductility. The first surface is also susceptible to dimensional instabilities resulting from radiation-induced swelling and thermal-radiation creep. Accompanying the radiation induced damage is a high surface erosion rate caused by two different mechanisms. These erosion processes are sputtering (ions and neutrals interacting with the first surface), and blistering (high surface strains produced by surface heat flux causing surface spallation). Surface mass loss has two deleterious effects on the operation of a fusion reactor. One is that the mass loss will contaminate the plasma with impurities, thereby cooling the plasma by radiation losses making it impossible to maintain a self-sustaining fusion reaction. The second is that the mass loss of the first surface reduces the structural integrity of the vacuum chamber limiting the overall useful lifetime of the vacuum chamber. Any first surface material under consideration should be able to accommodate these first surface interactions with minimal impact on reactor operations and economics. Operation of the tokamak is cyclic, thus subjecting the vacuum chamber to a cyclic thermal environment inducing severe thermal fatigue, which poses a major limitation to the lifetime of the vacuum chamber. The impact on the overall operation is design dependent and trade-off studies are needed to optimize the vacuum chamber system to determine the interplay between the individual components. However, the preliminary objective is to identify a material that has the physical properties and characteristics to meet the previously set forth operating requirements.

4.0 VACUUM VESSEL

4.1 MATERIAL SELECTION

First wall materials must maintain the vacuum integrity of the plasma chamber in order to achieve a sustained fusion reaction. However, the choice of such a material to effect such an environment is limited. To date, nearly all the vacuum chamber design studies are based on stainless steel as the structural material. Stainless steel offers a data base that is extensive in regards to radiation response (fission spectrum) which allows in-depth analysis in evaluating its potential use. It will be necessary for the material identified to have a full data base available for design purposes. However, since nickel and iron base alloys are the only materials that have any respectable irradiation data (fission spectrum), any other material identified as a leading candidate will have to undergo an extensive material development program. This lack of adequate design data does not inhibit the investigator from scoping studies utilizing the available data base.

In selecting the structural material for the vacuum vessel, the operating environment of a fusion reactor must be considered. The first wall lifetimes will be limited by the radiation damage and severity and frequency of major plasma disruptions. Loss of ductility and swelling are the primary effects of radiation damage on the first wall material. In addition to the radiation effects on the vacuum vessel lifetime, the relative operating temperature and stress levels will determine the lifetime of the vacuum vessel.

The hybrid reactor can be used to produce both fissile fuel and electricity. This dual product feature enables the vacuum chamber to operate at relatively low temperatures without jeopardizing the economics of a commercial reactor. This is due to the operating characteristics of a hybrid reactor where the neutron energy is multiplied in the blanket zone beyond the first wall, providing sufficient power density for power generation without using the

first wall heat generation. To optimize the thermal performance of the reactor, the vacuum chamber's thermal energy can be used as a pre-heat source for higher temperature operating systems throughout the reactor.

The list of candidate materials for vacuum chamber application are as follows:

- Austenitic Stainless Steel
- Aluminum Alloys
- Refractory Metals

Each material offers advantages for particular design aspects and with proper design, any one of these materials can probably provide a viable first wall design. The selection method utilized in this design study is based on consideration of a number of desirable characteristics, such as:

- The commercial availability of the material.
- The technology base for fabrication and joinability
- Compatibility with high vacuum systems
- Available material design data
- Previous use in analogous systems (fission reactors, high vacuum systems, etc)
- The ability of the material to accommodate the base operating environment and also survive abnormal operating conditions.

On the basis of this qualitative assessment and the unique operating conditions associated with a hybrid reactor, commercial aluminum alloys were selected as the initial CTHR vacuum chamber material. The other candidate materials all show promise as a structural material. Aluminum appears to have the superior thermal/physical properties amenable to a commercial tokamak hybrid reactor design for the following reasons:

- Austenitic stainless steels have extensive commercial experience in the nuclear fission industry. As a result of this use, a vast data base has been compiled for irradiation effects (fission spectrum) on stainless steel. This data is useful initially, however, the design data necessary for first wall application must be obtained in a fusion

reactor spectrum. In view of this, there is an extensive material irradiation testing program required to verify austenitic stainless steel's viability as a first wall structural material. A low thermal conductivity is the major disadvantage to the use of austenitic stainless steels. The high erosion of the first wall due to charge exchange neutrals and surface vaporization from plasma disruptions necessitate a relatively thick first surface, or an in situ renewable surface, to withstand the relatively high material loss. Stainless steel's low thermal conductivity may yield unacceptable temperature gradients and subsequent thermal stresses for the operating environment of a Commercial Tokamak Hybrid Reactor. Also, stainless steel, being a relatively high Z material, does not show favorable surface properties in regards to the influx of high Z impurities into the plasma causing a quenching of the plasma.

- The major drawbacks of molybdenum alloys are lack of weldability and fabricability, which are necessary characteristics for the first wall material due to the intricate tube assemblies that make up the structure. Molybdenum alloys also have low ductility at room temperature. The ductility of molybdenum alloys continually degrades as the material becomes irradiated and, accordingly, the ductile brittle transition temperature continually increases from room temperature. Thus, during maintenance periods, it may be necessary to keep the first wall component heated to a temperature above the ductile brittle transition temperature. The high temperature strength properties of molybdenum make it a likely candidate for limiters and beam dumps. Similar problems are associated with niobium alloys in regards to joinability which makes them unattractive as primary structural materials for the vacuum chamber. The high temperature strength of niobium allows its possible use as limiters, divertor target beam dumps, etc.

Due to the fact that a hybrid reactor can tolerate a relatively cold first wall, aluminum alloys appear to be the most promising choice for use in a commercial hybrid reactor. The choice of aluminum alloys is due to its high

thermal conductivity (approximately a factor twenty higher than stainless steel) which allows the alpha energy escaping from the plasma to be transported through the wall. The fabricability of aluminum allows it to be manufactured in a wide range of structural assemblies. Aluminum, being a low activation material, minimizes the storage period for decommissioned first wall components. Another attractive feature is aluminum being a low Z material minimizing the plasma contamination.

A significant characteristic of a candidate first wall material would be the ability of the material to withstand surface heating without melting. Evaluation of transient surface temperatures resulting from the absorption of radiation allows prediction of surface behavior during plasma disruptions. A general method for predicting the transient surface temperature behavior for a semi-infinite medium⁽⁴⁾ not actively cooled is as follows:

$$(1) f_m = \frac{KT_m}{2} \left(\frac{\pi}{DT} \right)^{\frac{1}{2}}$$

where f_m is power per unit area, D is the material's thermal diffusivity, K being the material's thermal conductivity, T_m is equal to the melting temperature minus the initial temperature and T being the time interval that surface flux at a constant rate impinges on the semi-infinite medium that is not actively cooled. Figure 2 illustrates how various metals can withstand surface heating.

Plasma dump energy, which is addressed in a later section along with disruption times, generates extremely high energy fluxes at the surface. These loads can cause severe material losses along with thermal shocks affecting the structural integrity of the vacuum chamber. The overall affect of plasma disruptions is addressed in a later section.

4.2 MECHANICAL DESIGN AND GENERAL ARRANGEMENT

The vacuum chamber is constructed from thirty segmented free standing D shaped segments where twenty six of the segments form 12.75° increments of the 12 meter diameter torus. The remaining four segments are 7.125° increments where

Figure 2. Material Thermal Response Due to a Concentrated Surface Flux Impinging Normal to its Surface

two are combined between toroidal field coils which will be the initial segments to be removed to provide the void for the other first wall segments to be rotated to and removed. The vacuum chamber/first wall is fabricated from varying diameter tubes which are cylindrical and 2.5 cm in diameter at the manifold locations, traversing the vertical periphery changing from a circular cross section to a 2:1 elliptical cross section at the horizontal midplane. Figure 3 illustrates the mechanical design and general arrangement of the analyzed concept. The 0.32 cm thick 6061 aluminum tube is an internally finned duplex tube which offers a number of unique benefits such as:

- Substantial gains in heat transfer.
- Inner-fins increase the overall tube stiffness allowing the structure to become self supportive.
- The inner tube filled with an inert gas reduces the cooling water (hydrogen inventory) in the first wall.
- 6061 Aluminum Alloy has excellent corrosion resistance properties
- Alloy 6061 T-6 can be hot worked and subsequently heat treated to achieve the final mechanical properties

The tubes in each sector are welded to each other axially using the MIG welding process. These tubes are then welded to a tube sheet at the top and bottom, which are in turn welded to semi-cylindrical manifolds which orifice and distribute the coolant uniformly to the tubes.

The vacuum chamber is designed to support its weight when suspended from continuous rails attached to the inlet/outlet coolant manifolds. The roller slide suspension system allows the vacuum chamber to freely expand to accommodate the thermal growth during heatup from ambient to operating temperature. However, the thermal growth of the vacuum chamber is minimal due to the relatively low operating temperature of the vessel. The vacuum chamber will have approximately 1 cm of growth associated with the temperature rise.

Right angle flanges are attached to the end sections of each segment forming the means by which the segments are joined together. Since only a partial

Figure 3. First Wall Design

vacuum will exist across the flange, it does not require a high integrity vacuum seal to achieve the desired plasma environment in the chamber. The vacuum vessel's first surface will be plasma flamed sprayed aluminum applied to the tubular wall.

The vacuum chamber is cooled by circulating relatively cool, low pressure water through the annulus of the aluminum duplex tube. The pressurized water is supplied to each segment separately through manifold piping.

Consideration was given to the location of the boundary within which the high vacuum necessary for the plasma to be maintained. The following locations were considered as a primary, as well as secondary, vacuum boundary;

- The containment building
- On the outer surface of the shield
- Between the shield and the blanket
- On the outer surface of the first surface/vacuum chamber

The pumping volume associated with a reactor containment building for a commercial tokamak would present additional operating cost. Also, designing all the supporting components that need to be located within the containment building to operate in a relatively high vacuum environment would be an unwarranted constraint. A high vacuum containment building would also give rise to problems of achieving vacuum tight seals at the large number of penetrations for coolant pipes, electrical leads, etc. through the thick, concrete walls. To locate the primary or secondary vacuum seal between the shield and the blanket requires a separately cooled, rather massive structure to withstand the atmospheric load. Therefore, valuable blanket and shield space would be lost. This structure would also inhibit blanket refueling. Utilizing the vacuum chamber as the only vacuum region puts prohibitive loads on a free standing chamber which requires additional structure to achieve stability against the external pressure. Also, the neutronic performance in the outer blanket would be degraded due to the increased first wall material which would shield neutrons from the outer blanket. Due to these limitations in locating the primary vacuum seal at the various locations listed, it was

decided that the optimum location would be to locate a secondary seal at the outer surface of the shield or in the inner reactor chamber area. Then the secondary vacuum boundary greatly relieves the sealing requirement at the first wall. The shield is a massive structure which is designed to withstand loads due to its own weight, and a number of other loads supported from the structure. To design the shield to withstand atmospheric pressure on its outer surface with little or no extra material is a reasonable design modification. For the CTHR concept, the inner reactor chamber provides an excellent choice for the secondary seal. This portion of the reactor building can more easily be sealed and this also permits control of the tritium release since it can be removed from the inert gas as it is pumped down to a partial vacuum. Vacuum pumping is discussed in Section 4.5

4.3 THERMAL AND STRESS ANALYSIS FOR THE FIRST WALL

Scoping thermal calculations were performed to assess the structural life of the first wall structure. The water flow rate in the aluminum duplex tube is adjusted to maintain the tube temperature below 120°C for strength purposes. The spiral duplex tube promotes a high film coefficient necessary to dissipate the intense incident heat flux.

The power cycle for the CTHR is 1,268 seconds with a 95 percent duty cycle; thus the "on" cycle is 1200 seconds. A 70 percent plant availability was assumed for CTHR and thus, the total number of cycles is approximately 17,400 per year.

For CTHR operating conditions, the average neutron wall loading is 2 MW/m^2 . For the vacuum vessel design, the maximum neutron current, which occurs near the horizontal midplane, was taken to be 3 MW/m^2 . The associated gamma and incident flux is 0.6 MW/m^2 with an accompanying neutron power deposition density throughout the first wall structure of 46 MW/m^3 .

The pressurized coolant water inlet temperature is 37°C and an outlet temperature of 93°C has an associated heat transfer coefficient of $4.37 \text{ W/cm}^2\text{°C}$ which corresponds to a 7.25 m/sec flow velocity. The worst case

first wall tube mechanical load comes from the 0.69 MPa coolant pressure. Also, the G forces must be considered in the analysis. Swelling loads associated with neutron irradiation are assumed to be negligible. Thermal loads corresponding to plasma-on conditions cause a through-the-coolant-tube wall temperature difference of 2°C. The temperature difference through the first wall plasma flame sprayed aluminum coating is 25°C with a peak outside coating temperature of 118°C assuming conductivity properties for the coating to be similar to aluminum 6061 alloy.

The stress analysis is directed to the first wall tube over the worst loading conditions under normal operating conditions. The stresses are computed by linear elastic methods. This is justified by the fact that the maximum equivalent stress is less than the 0.2 percent yield strength for aluminum alloy 6061-T6. At an operating temperature of 150°C, the allowable stress for the structural tube is 200 MPa.

The tubular module primary membrane stress in the first wall, induced under a sustained coolant pressure of 0.69 MPa, is maximum in the hoop direction at the horizontal midplane and is given by:

$$\sigma_{pm} = \frac{PR}{\delta} = 2.86 \text{ MPa}$$

The longitudinal membrane stress due to the coolant pressure is given by:

$$\sigma_{pm} = PR/2\delta = 1.43 \text{ MPa}$$

where P, R and δ are the coolant pressure (0.69 MPa), the major radius of the elliptical tube (1.33 cm), and tube thickness (0.32 cm), respectively.

The mechanical bending stress is due to the gravitational forces acting on the structure and the internal coolant pressure acting on the elliptical cross section. The maximum bending due to the coolant pressure occurs at the point of maximum radius of the ellipse and is given by:

$$\sigma_{pb} = \frac{6M(1 - \nu^2)}{\delta^2} = 14 \text{ MPa}$$

When M and ν are the bending moment⁽³⁾ and the Poisson's ratio for aluminum 6061-T6. The maximum bending fiber stress due to the gravitational force is located at the manifold and is given by:

$$\sigma_{Gb} = \frac{Mc}{I} = 109.3 \text{ MPa}$$

The bending stress at the horizontal midplane due to the gravitational force is 76.6 MPa where M , c and I are the maximum moment in the tubular wall, the maximum distance from the neutral axis and moment of inertia, respectively. The duplex tube was treated as a single tube. The increased stiffness from the inner tubes was not taken into account, thus making the stress analysis conservative.

The thermal stress induced in the tubular wall in the hoop direction is given by the following relation:

$$\sigma_T = \frac{E\alpha(\Delta T)}{2(1 - \nu)} = 30.4 \text{ MPa} \quad (\text{hoop and longitudinal midplane})$$

where E , α and ΔT are elastic modulus, coefficient of thermal expansion and through-the-wall temperature difference.

In addition, the across the diameter temperature difference induces a uniform through-the-wall longitudinal bending stress given by:

$$\sigma_T = \frac{E\alpha \Delta T_o}{2(1 - \nu)} = 12.4 \text{ MPa} \quad (\text{longitudinal bending stress midplane})$$

The equivalent stress σ_{eq} is derived from the principal stresses σ_1 , σ_2 and σ_3 . The σ_{eq} is given by:

$$\sigma_{eq} = \frac{1}{\sqrt{2}} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{\frac{1}{2}} = 110 \text{ MPa}$$

where: $\sigma_1 = 47 \text{ MPa}$ (longitudinal stress)
 $\sigma_2 = 126 \text{ MPa}$ (hoop stress)
 $\sigma_3 = 0.7 \text{ MPa}$ (pressure stress)

The pulsed operation of the tokamak reactor has the consequence of cyclic thermal loading on the first wall and adjoining components. This thermal load induces a self limiting secondary stress that can promote creep-fatigue failure. Thus, the creep fatigue must be accommodated in the material selection, operating temperature and first wall design.

In determining cyclic lifetime for creep-fatigue interaction there is a fatigue property data curve at room temperature shown in Figure 4 for aluminum 6061-T6 alloy. For a five year lifetime, there is approximately 87,000 cycles. For that lifetime, the allowable peak stress (with a factor of two stress safety factor) is approximately 120 MPa, which is above the calculated equivalent stress.

Using elastic analysis, the ASME Code Case 1592 provides criteria to prevent failure from short-term ratcheting or long-term creep-ratcheting. The Bree diagram shown in Figure 5 represents ratcheting information. The ordinate is the secondary stress ratio σ_T/S_y and the abscissa is the primary stress ratio σ_p/S_y . The stress plane is divided into six regions. The elastic region which corresponds to purely elastic behavior. The shakedown regions, S_1 and S_2 , where the structure shakedown to elastic behavior occurs in the first few cycles. In the plastic region cyclic plastic strain occurs and the design must be checked for fatigue failure.

The ratcheting regions R_1 and R_2 have stress states that produce incremental plastic growth for each cycle leading to short-term failure. The corresponding point for the present design falls within the elastic region thus additional analysis is not warranted at this time. The preliminary analysis indicates elastic behavior. However, the radiation effects, such as radiation-induced creep or swelling should be considered in more detail to fully evaluate the viability of the present design.

Figure 4. Fatigue Properties of Aluminum 6061-T6

Figure 5. Modified Shakedown Boundary for Primary Plus Secondary Stress Intensity Limit

4.4 FLANGE AND CURRENT BREAKER SYSTEM

The plasma vacuum boundary is formed by sealing between the thirty movable first wall sectors. Beyond the high vacuum region is a secondary vacuum boundary which is located at the outer surface of the shield or the reactor chamber. This outer vacuum provides a means for scavenging tritium and greatly simplifies the seal between sectors and at penetrations. Small leak paths that would have contaminated the plasma with atmospheric pressure being the driving force, are now acceptable at a pressure of 1 torr.

Figure 3 illustrated several views of the first wall details and flange segment. The thirty sectors make up the torus by being inserted between the toroidal field coils and rotated circumferentially around the torus. When all sectors are in place, the inner leg of the vacuum chamber is inaccessible for manual operations. An automatic seal welder, which has been successfully used for remote applications, would be difficult to use due to the limited

clearance in the center leg of the reactor. However, there are commercially available seals which provide the quality of sealing necessary. The main requirement for the successful application of this seal is that the seal must be uniformly loaded at about 36 kg per cm and the flange surface finish along with the seals surface finish must be kept protected from surface damage. Thus the seal must be compressed by a force normal to the seal. Clamping screw actuators are used to pull the flanges together and to develop the necessary compression pressure to activate the "Helicoflex"[†] seals. The sealing principle of the Helicoflex seal is based on the plastic deformation of a helical or coiled spring liner which is of greater ductility than the material surrounding the liner. Permanent contact between the seal and sealing faces is ensured because the compressive stress on the lining is reacted by the radial elasticity of the spring. Each flange has a common gearmotor that drives a flexible shaft connecting the actuators. As the actuator is engaged, a screw advances out of the actuator, crossing the gap between the flanges and engaging in a nut mounted on the other flange.

The first wall design utilizes electrical insulator coatings on the flanges and "Helicoflex" seals at two locations to provide the required current breaker in the first wall. There are a number of commercially available ceramic insulator materials that have favorable electrical characteristics that can be bonded to the metallic gasket surfaces to form a reliable, leak-tight vacuum seal. To fully assess the reliability and operating limitations for this proposed current breaker system it will be necessary to gather experimental data.

4.5 VACUUM PUMPDOWN CONSIDERATIONS

The vacuum pumping for the main toroidal plasma chamber must provide high vacuum conditions (approximately 10^{-8} torr) prior to plasma operation. The outgassing of the first surface walls and leakage into the plasma cavity

[†]Tradename for a high grade vacuum seal developed by Cefilac in conjunction with the French Atomic Energy Commission.

through the seals must be taken into account to determine the required pumping speed. The first wall torus structure is made up from thirty sectors. This arrangement yields approximately 7.5×10^4 cm of seal surface. The surface finish on the flange and deformable seal is assumed to be polished with the associated contact surfaces having a finish where the peak to valley height is $(5 \text{ to } 1) \times 10^{-4}$ cm. The plasma is assumed to operate with a Z effective of 1.5 and the throughput due to outgassing and seal leakage not exceeding 20 percent of the assumed impurity influx for these plasma conditions. The reference case assumes argon to be the inert gas between the blanket and first wall at 1 torr pressure. The allowable throughput for the seal criteria is calculated to be 0.042 Tℓ/s. The throughput calculation for a metallic gasket seal, which is believed to be conservative compared to the sealing characteristics of a helicoflex seal, is as follows:

$$Q(\text{T-ℓ/sec}) = \Delta P = 4 \left(\frac{T}{M} \right)^{\frac{1}{2}} A^2 \frac{1}{W} \exp\left(\frac{-3P}{R}\right) \text{p torr}$$

where L is total seal length, W seal width, A surface roughness, M molecular weight of leaking gas, T temperature of gas, R being the sealing factor associated with the metallic gasket and P being the sealing pressure (seal force/LW). The pressure difference between the secondary vacuum and operating vacuum is effectively 1 torr since the plasma chamber is essentially zero (10^{-8} torr).

The previous equation is plotted in Figure 6 where the surface roughness versus the sealing pressure are the varying parameters with the throughput being held constant. This figure illustrates that the surface roughness and sealant pressure are not that sensitive in the range that is being considered, i.e., seal pressure 0.069 to 0.69 MPa and surface finish $(5 \text{ to } 1) \times 10^{-4}$ cm. In assuming a sealant pressure of 0.55 MPa with an associated aluminum clamping bolt having a 1.25 cm diameter necessitates that the flange bolts be spaced approximately 1.25 m. Approximately 10 bolts per flange would be used to load the helicoflex seal between flanges to give the necessary flow impedance to effect the high vacuum inside the torus chamber.

Figure 6. Seal Surface Roughness Versus Sealant Pressure with Gas Throughput Being Constant

In addition to the leakage between flanges there is continuous mass loss due to vaporization of the first surface material. The mass loss rate attributed to vaporization in a vacuum can be calculated by using the following relation:

$$Q = 583 \left(\frac{T}{M} \right)^{\frac{1}{2}} P R a$$

where Q is mass loss in Tl/s, M is the molecular weight of the material, P being the vapor pressure at the temperature of operation T, R being the gas constant with a being the surface area of the vacuum chamber.

Numerically, for an aluminum first surface at 500°C, the following values are used to calculate the mass loss due to vaporization:

$$P = 1.2 \times 10^{-10} \text{ torr}$$

$$T = 773 \text{ K}$$

$$R = 62.364 \text{ T l/K}$$

$$a = 500 \text{ m}^2$$

$$M = 27$$

Thus, Q is equal to $1.167 \times 10^{-2} \text{ T l/s}$. In assuming a plasma Z effective of 1.5 and pumping speed of 200,000 l/s, the allowable impurity influx concentration of aluminum atoms would be 0.38 Tl/s. The actual value is approximately a factor of thirty below the allowable value.

5.0 FIRST SURFACE LOW Z COATINGS

Coating the first wall of a fusion reactor with a renewable low Z material should provide a solution to a number of the problems associated with a first surface. The first surface and vacuum chamber maintain the vacuum integrity of the system while allowing the penetration of the high energy neutrons. The first surface is subjected to neutron, D, T, and alpha particle bombardment which induce a number of erosion processes. These include blistering, sputtering, vaporization and unipolar arcing.

Operating conditions for a commercial tokamak reactor are not well defined at this time. However, it appears that a candidate low Z coating material must have the following characteristics to provide the performance necessary for first wall protection:

- Low vapor pressure at operating temperature
- Acceptable sputtering and erosion yields
- Good adherence and thermal shock resistance properties
- In situ coating capability is highly desirable

These requirements identify the following materials as potential low Z first surface coatings: beryllium, carbon and aluminum.

The use of carbon as a first surface material may lead to intolerable levels of impurity production via chemical sputtering. There is experimental evidence that chemical interactions of hydrogen with carbon at relatively low temperatures yields a principal product of methane. When CH_4 is formed, it readily desorbs due to its low binding energy. Carbon would also be suspect to coating adhesion failure due to fracture in the interface region from high interfacial stresses caused by the differences in the physical properties of the base and coating material. The carbon would also act as a moderator of the fast neutrons.

The low ductility and non-isotropic behavior of beryllium may affect the integrity of the surface coating. Also, there is a significant difference in physical properties between the beryllium and the base metal aluminum. Due to these material characteristics, the behavior of beryllium as a first surface coating on an aluminum tube wall does not appear to be optimum in choice.

Aluminum coating on a base aluminum metal appears at this time to be an attractive combination. The aluminum coating could be applied in situ by injecting aluminum pellets into the discharge. However, the proposed coating method may yield porous surface structures which tend to absorb gases and may inhibit the vacuum pumpdown system. The surface binding energy of aluminum is in the range of other first surface candidate materials such as Fe, Mo, W, etc. Thus, the impurity atoms entering the plasma from sputtering would be of the same order of magnitude regardless of material. However, due to the lower Z number for aluminum, the tolerable impurity concentration is greater. Another attractive feature aluminum has as a first surface coating is its high conductivity and rather low melting temperature. The relatively low melting temperature yields thermally softened surface conditions, which attenuates surface crack growth and stress concentrations at relatively low temperatures. The high conductivity permits the surface temperature to operate at moderate temperatures. With aluminum being the substrate material there is good compatibility between the base and coating material, thus minimizing the interfacial problems that exist between two different materials bonded together.

The most threatening surface phenomena that would restrict the use of aluminum as a first surface material would be surface blistering due to the high helium generation, retention and immobility in aluminum. The mechanism of blistering would have to be evaluated in detail to assess the physical erosion rate and the overall effect of first surface impurities on commercial reactor operations. Thus, while aluminum was chosen as the reference coating material for this study, it is clear that evaluation (particularly on the experimental level) of all candidate coating materials must continue to assure a viable combination of materials and processes are ultimately developed for commercial applications.

6.0 PLASMA DISRUPTIONS

It is assumed that in the operation of the CTHR, plasma disruptions will be a potential consequence of plasma instabilities. A major disruption is an intense flow of inductive and kinetic energy out of the plasma into the surrounding first surface/vacuum chamber components in a very short time. An estimation of damage to the first wall must be made to assess survivability under such severe loading conditions. The consequences of a disruption to the first wall are determined by two parameters which can only be estimated at this time; the disruption time T_D , and the uniformity of the energy deposition on the first surface. It is recognized that much attention is being given to modes of tokamak operation which would minimize or eliminate disruptions of the type considered here. In view of the speculative nature of this work, the approach taken in the present study is to assume a reasonable disruption scenario and examine the consequences on the vacuum vessel design.

The plasma parameters that determine the stored energy in a tokamak plasma and were used in this analysis are listed in the following table.

Plasma Inductance, L	12 μH
Steady State Plasma Current, I	6.8 MA
Electron and Ion Density, n_e, n_i	$1 \times 10^{20}/\text{m}^3$
Average Ion-Electron Temperature, kT_e	17 keV
Plasma Volume, V	370 m^3
Major Radius, R_0	6.0 m
Minor Radius, a	1.4 m
Magnetic Field on Axis, $B\phi_0$	5.2 T
First Wall Area, A	430 m^2
Approximate First Wall Thickness, δ	0.016 m
Aluminum Density at 200°C, ρ	2.77 g/cm^3
Aluminum Specific Heat at 200°C, C	0.963 J/g °C

The magnetic energy stored in the plasma can be calculated as follows assuming constant plasma inductance:

$$\text{Plasma stored magnetic energy} = 1/2 LI^2 = 0.277 \text{ GJ}$$

Approximately 30 percent⁽⁶⁾ of the stored magnetic energy goes into joule heating (I^2R) with the remaining magnetic energy being distributed to other ancillary components in the vacuum chamber region. This is eventually felt as joule heat. The volumetric heat generation is induced from eddy currents which are assumed uniform throughout the vacuum chamber. The volume associated with the first wall takes into account the first surface coating as well as all the tube metal. It is assumed that the heating is adiabatic with a uniform temperature in the wall. The temperature rise attributed to the magnetic stored energy is calculated as follows:

$$\Delta T_{\text{wall}} = \frac{(0.5 LI^2)(0.3)}{C_p \rho A \delta} = 4.5^\circ\text{C}$$

It is obvious that the assumptions and sophistication of calculation provides only an approximate value for the temperature rise associated with the stored magnetic energy dumping into the vacuum chamber. However, it does illustrate that the calculated temperature rise is reasonable and well within tolerable limits.

In addition to the inductive energy, there is a large amount of kinetic energy associated with the plasma. The kinetic energy can be estimated as follows:

$$\frac{3}{2} [n_e kT_e + n_i kT_i] V = 0.302 \text{ GJ}$$

The kinetic energy is dissipated as an energy flux to the first wall surface. The uniformity and energy deposition time are the two parameters that need to be determined to evaluate the severity of the disruption.

Sestero⁽³⁾ ensures that a virtual limiter, a thick cloud of high-Z impurity ions encompassing the plasma absorbs the escaping particles and converts them into a soft spectrum X-ray radiation which is distributed more uniformly throughout the vacuum chamber.

A scaling law developed by Carreras⁽²⁾, graphically illustrated Figure 7, can be used to estimate disruption time for CTHR;

$$T_D = C[R_0^2 m_i n_i \beta \phi_0 a^6 V^{-3}]^{\frac{1}{5}}$$

where m_i is the average ion mass (2.5) and V is the voltage at the limiter before disruption. The sheath potential on an isolated plate is defined by McCracken and Scott⁽⁷⁾ as follows:

$$V = \frac{kT_e}{2e} \ln\left(\frac{m_i}{2\pi m_e}\right)$$

where e is the electron charge. For a hydrogen plasma, $V \sim 3.3 T_e$, where T_e is the estimated plasma edge temperature.

Figure 8 illustrates the plasma disruption time versus a range of plasma edge temperatures for Commercial Tokamak Hybrid Reactor parameters. It is reasonable to assume that plasma edge temperatures range from ten to hundreds of eV in temperature. This temperature range associates to disruption times in the order of fractions of milliseconds. This estimation of plasma disruption time for a Commercial Tokamak Hybrid Reactor illustrates how difficult a disruption would be to control via sensors, feedback mechanisms, etc., due to the very short time sequence associated with a hard disruption. Under the circumstances considered, the virtual limiter becomes ideal protection in minimizing the consequences due to hard disruptions.

Sestero shows that only a relatively small amount of vaporized material is needed to trap most of the particles coming from the plasma. The required virtual limiter density to stop the escaping plasma particles can be calculated as follows:

$$n_e \ln\left(\frac{\Lambda E_0}{kT_e}\right) + n_e^\alpha \ln\left(\frac{E_0}{I}\right) \geq \frac{E_0^2}{4\pi e^4 n_S}$$

Assuming a pure vapor $n_e = 0$. Thus,

$$n_e^\alpha \ln\left(\frac{E_0}{I}\right) \geq \frac{E_0^2}{4\pi e^4 n_S}$$

Figure 7. Disruption Times in Tokamaks Versus Physical Operating Parameters (Ref. ORNL/DWG/FED-78-1206R)

Figure 8. Plasma Disruption Time Versus Plasma Edge Temperatures for CTHR Parameters

Where n_e^α is the number density of bound electrons, E_0 is the initial energy of the particle, I_0 being the ionization potential for hydrogen, with $I \approx Z I_0$, s is the virtual limiter thickness in the radial direction, and η having a reference value of 3×10^4 .

Assuming a plasma temperature of 10 keV and a limiter material of molybdenum (which provides the mass to effect the virtual limiter), a molybdenum vapor thickness of approximately 44 cm would be required to trap most of the energetic particles coming from the plasma. The mass associated with this vapor layer is calculated as follows:

$$g = \frac{E_0^2 \pi M R_a}{e^4 \eta \ln\left(\frac{E_0}{I_0 Z}\right) Z N A} = 55.3 \text{ mg for CTHR plasma parameters.}$$

The plasma energy will heat the limiter to high temperature (dependant upon disruption time T_D) and vaporize the surface layer which will spread out into a cloud which prevents additional localized energy deposition. The amount of localized energy necessary to vaporize 55.3 mg of molybdenum is calculated as follows:

$$E = \Delta h_T m = 45 \text{ kJ}$$

This assumes an adiabatic process where Δh_T is the change in enthalpy from the initial (steady state temperatures) to the boiling point temperature. Also, the time deposition is a fraction of milliseconds with localized heating. It requires very little of the plasma energy to initiate a virtual limiter, however the time sequence of the vaporization, the formation of the cloud and transient behavior of the plasma certainly has to be investigated to ensure that sequentially the proper order of events occur.

The first wall surface response is dependent upon the disruption time in regards to treating the thermal problem as a classical heat conduction, or as a shock phenomenon with associated evaporative recoil loads. If the disruption time is greater than the ratio of the wall thickness to sonic velocity ($2\mu\text{ s}$), a thermal shock phenomenon will not occur.

Wall ablation due to the kinetic plasma energy dumping onto the surface is a primary concern during hard disruptions. However, the accountability of plasma energy during disruptions is unpredictable. Treating surface ablation requires a highly sophisticated thermal code that accounts for material state transitions and transient boundary conditions. Such calculations are not warranted at this time and simple, conservative calculations where the assumption is made that the total plasma energy goes into the surface instantaneously is misleading. Consequences from wall ablation are severe, with the need to fully assess such potential loading conditions after more is known in regards to plasma disruptions modes.

6.1 LIMITER DESIGN

The Commercial Tokamak Hybrid Reactor vacuum vessel design provides for poloidal rail limiters that are adjusted to the scrape off depth. The limiters are segmented poloidally into four locations. These limiters shape the plasma and protect the wall from an expanding and/or disruptive plasma which would strike the wall and deposit high surface fluxes of localized energy on the wall. Actual optimum limiter geometry will depend on the loading profile which is associated with scrape-off width. It will be necessary to design the scrape off width so the peak surface flux is within reasonable limits for short pulse heating inertially cooled, and for steady state actively cooled surfaces. The limiters will resemble curved rails that will be supported by insulated hangers or posts attached to the vacuum vessel which will give adequate support and freedom for thermal expansion.

When the energy of the plasma is deposited on the limiter, it leads to surface heating resulting both in thermal shock and surface evaporation. Evaporation inhibits continued plasma operation due to increased impurity concentrations along with mass loss that can weaken the structural integrity of the limiter. However, a more severe effect from rapid surface heating would be the material response during such transient loading conditions. Stresses resulting from such loads give rise to surface spalling and cracking which can cause component failure. To date molybdenum has been extensively used in a number of experiments and has had favorable results for withstanding large thermal

fluxes without melting or cracking. Most of the information available in regards to limiter loading conditions and experimental performance is largely qualitative. The actual loading conditions for limiters are not known, thus the limiter design for CTHR is extremely conceptual.

7.0 CONCLUSIONS

In this investigation, a low Z vacuum vessel design concept was analyzed to determine its viability as a commercial hybrid reactor vacuum chamber. There are a number of performance improvements that can be attributed to an aluminum first surface/vacuum chamber. Hybrid reactor economics does not necessitate that the first wall thermal energy be utilized directly in a power conversion cycle. This is due to the fact that high energy multiplication occurs beyond the first wall. To consider the use of aluminum above 150°C would be impractical based on stress to rupture and creep time strengths of aluminum at higher temperatures.

The vacuum boundary of the first wall structure was identified as a primary vacuum boundary, while the reactor chamber was selected to maintain the secondary vacuum. A free-standing vacuum chamber between the blanket and plasma having atmospheric pressure on its outer surface would have to be a more massive structure in order to withstand the external pressures. This massive structure would impede the neutronic performance in the blanket region and also give rise to high thermal stresses. Achieving vacuum-tight seals in a highly irradiated location would present additional problems with only a primary vacuum boundary. Utilizing a secondary vacuum region eliminates or mitigates a number of the more severe problems associated with a vacuum chamber. The vacuum chamber has to be designed to withstand loads only due to its own weight. Primary vacuum seal designs are highly simplified since the driving pressure has been reduced to 1 torr. On the basis of plant availability it was decided that a segmented vacuum vessel that could be rotated about the torus and removed between the toroidal field coils would minimize maintenance downtime.

The use of aluminum as a first surface/vacuum chamber material has a number of attractive material characteristics and properties as follows:

- Favorable joinability and fabrication properties
- Good adhesion qualities at the aluminum first surface to aluminum tube interface due to the similar thermal-mechanical properties
- Acceptable desorption characteristics for a high vacuum system
- Excellant tritium permeation barrier
- In Situ surface application/preparation
- Relatively low radioactive half-life presents minimum activation

The preliminary investigation into plasma disruption and the consequences to first wall was encouraging. However, more analysis is necessary in this area before the design and protection scheme could be regarded as established.

Considerable uncertainty exists in regards to the impact the associated high helium production in aluminum will have on design lifetime performance. Operating temperature of the vessel will be a determining factor in regards to the effect of this radiation by product. Swelling, void formation, embrittlement, and blistering will all have to be investigated in detail to determine how severe a problem helium generation and entrapment is with regard to the use of aluminum as a first wall material.

It is important to realize that this investigation has provided insight into first surface/vacuum vessel design and performance behavior. However, there are a number of factors that add to considerable uncertainty in designing a viable system. These include:

- Experimental results from current devices do not define plasma edge conditions whereby first surface loading conditions are well defined for reactors.
- The operating efficiency and capability of the divertor, limiter and virtual limiter are not known.
- Quantifying the behavior of plasma disruptions (such as energy deposition time, area, magnitude and frequency of occurrence) remains to be achieved.

- Transient effects during disruptions to the first surface, such as vaporization and or melting erosion, must be defined.
- Material response from high levels of irradiation must be tested.

On these bases it is apparant that the viability of any first surface/vacuum vessel design hinges on the results from ongoing development work in this area. It would be too ambitious at this time to carry any design beyond the conceptual level until the operating conditions are more fully recognized and defined.

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