The Theoretical Analysis Of Tritium Containment In Fusion Reactors

by

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Abstract

The concept of fusion reactors as power generating machines was investigated. Specific attention was focused on the problems involved with tritium containment. Several ceramics and metals were compared as possible tritium barriers for future reactors. It was discovered that the future of ceramics for tritium containment is limited due to the problems in generating a continuous layer inside the reactor. However, regenerative oxide layers on the reactor walls may prove to be a possible solution.

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1. Introduction

Fusion reactors may offer mankind an almost limitless supply of electrical power in the future. If this is to become a reality, the major problem of tritium containment must be dealt with. As it is necessary to breed tritium as the reactor operates, tritium inventories on the order of a kilogram (10^7 curies) can be expected for a 1000 MW(thermal) plant[1]. The release of only a small fraction of this tritium would not only pose a serious radiological hazard, but would also reduce the amount of tritium available for the fueling of subsequent fusion reactors.

Metals such as stainless steel, niobium, vanadium, molybedenum, and others are being considered for use as tritium barriers in fusion reactors. Research on the tritium transport properties have shown them to have very high permeablilities to tritium[2]. Oxide layers on these metals have been found to reduce the effective tritium permeabilities[3].

Ceramics have long been considered for use in thermonuclear reactors for their thermal properties and abundant raw material supply[4]. Recent studies [5] have now shown ceramics to also have excellent tritium transport properties.

A general look at ceramics as possible tritium barriers was undertaken. This required a general working knowledge of fusion in a tokamak design reactor, which was obtained through personal conversation and the literature available.

Another objective of the study was to investigate the tritium concentration in the wall of the PLT (Princeton Large Torus) machine. This was attempted as a two region problem with the metal and its oxide comprising the two regions.

The remaining sections of the text discuss the fusion background information, ceramics, and an analysis of the oxide layer on the first wall of the PLT machine.

2. Thermonuclear Fusion

2.1 Lawson Condition

The Lawson Condition is a minimum condition that must be satisfied in order to produce more power from a fusion reaction than it takes to produce the reaction. At 10 kev (approximately 100,000,000 °C), the following equation must be satisfied:

$$n\tau \geq 10^{14} \text{ ion-sec/cm}^3 , \qquad (1)$$

where n is the ion density and τ is the energy confinement time. This condition has yet to be demonstrated by a tokamak fusion reactor.

2.2 Types of Fusion Reactors

There are basically two different concepts for fusion reactors. One is the inertial confinement fusion concept and the other is the magnetic bottle or tokamak idea.

Inertial confinement fusion requires a small fuel pellet to be the focal point of several large laser beams. When the lasers strike the outer surface of the fuel pellet, there is an explosion due to the large amount of energy being deposited in such a short time. As the exploding portion of the fuel accelerates outward from the center of the pellet, there is an equal and opposite force inward due to the conservation of momentum. This inward force is large enough to produce the high density and force required for a fusion reaction. Figure 1 is a diagram of a typical design for the laser fusion reactor concept.

The magnetic bottle or tokamak concept utilizes high powered electromagnets to compress the plasma, a completely ionized, gas fuel mixture, to the required density. To achieve the high temperature required, one or a combination of the following heating methods may be implemented: passing an electric current through the plasma, injecting fuel particles, or transmitting radiowaves through the plasma. Figures 2 and 3 illustrate two typical tokamak designs.

Figure 3 is an illustration of the Doublet III reactor which will be the first fusion reactor to satisfy the Lawson Condition.

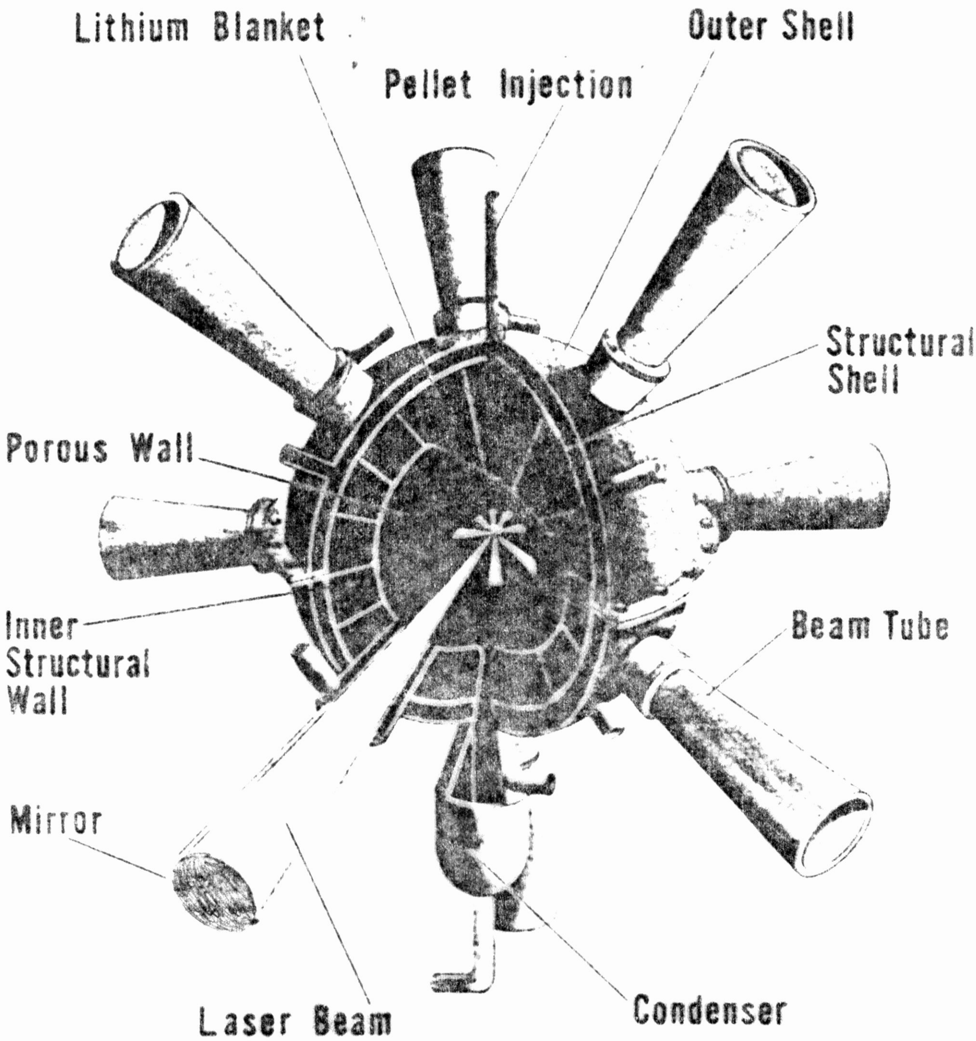

Figure 1

Laser Fusion Reactor

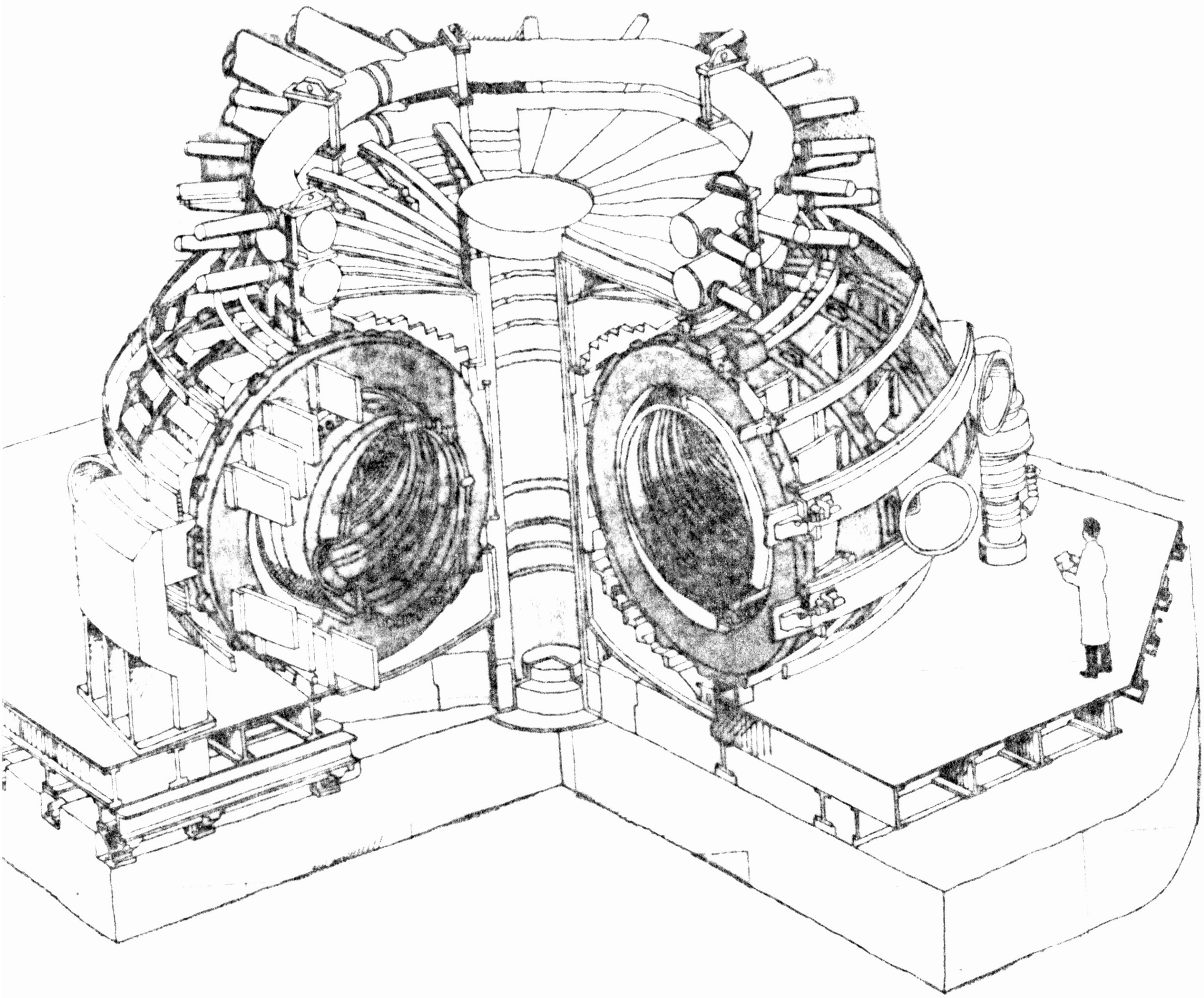

Figure 2

Typical Tokamak Reactor

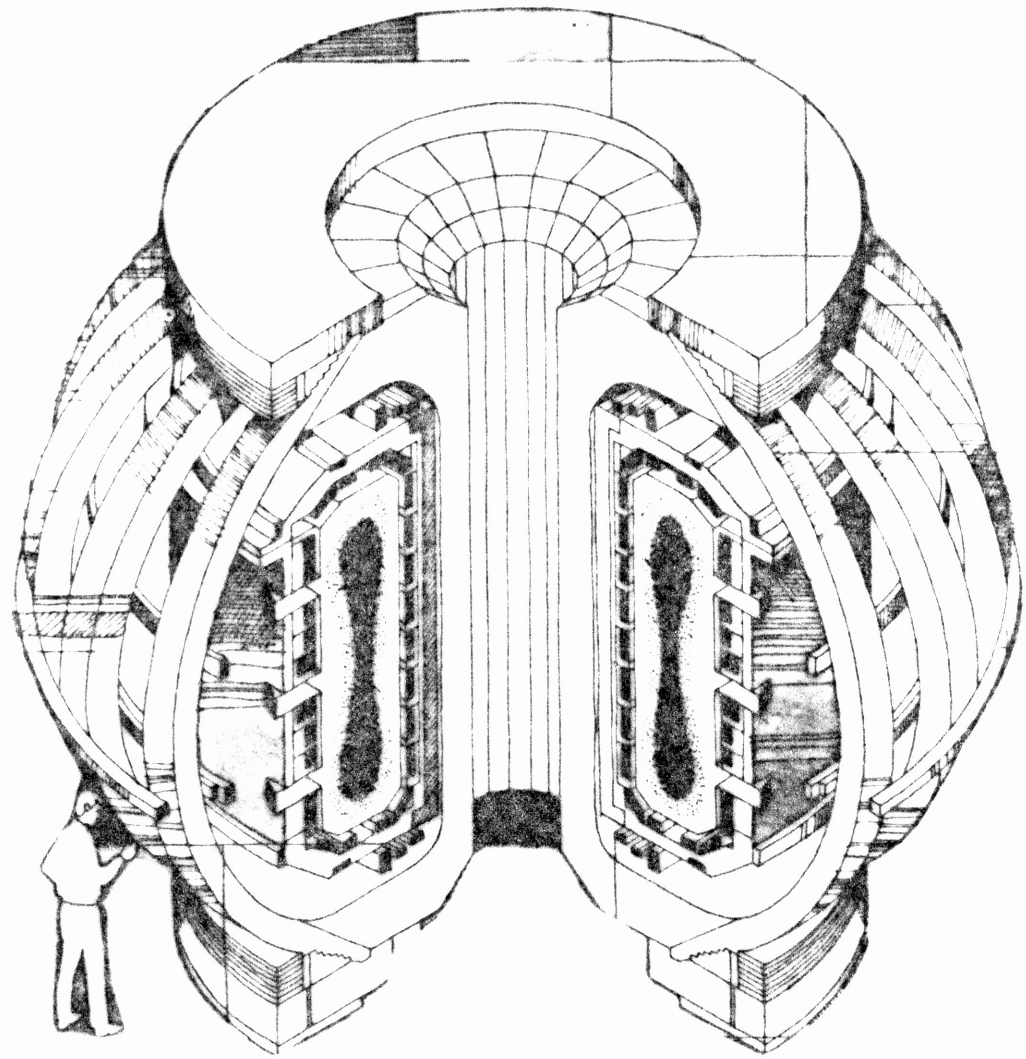

Figure 3

Doublet III fusion Reactor

2.3 Fusion Reactions

The abundance of the proposed fuels for fusion reactors (deuterium and tritium) is one of the many advantages for fusion as an electrical power source. Deuterium may be obtained from ocean water and tritium can be bred from lithium , which is a mineable element.

Equations 2 through 7 summarize several possible fusion reactions.

D-T

$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He\ (3.5\ Mev) + ^{1}_{0}n\ (14.1\ Mev) \qquad (2)$$

D-D

$$^{2}_{1}H + ^{2}_{1}H \longrightarrow ^{3}_{2}He\ (18.2\ Mev) + ^{1}_{0}n\ (2.45\ Mev) \qquad (3)$$

$$^{2}_{1}H + ^{2}_{1}H \longrightarrow ^{3}_{1}H\ (1.01\ Mev) + ^{1}_{1}H\ (3.02\ Mev) \qquad (4)$$

D-He 3

$$^{2}_{1}H + ^{3}_{2}He \longrightarrow ^{4}_{2}He\ (3.6\ Mev) + ^{1}_{1}H\ (1.47\ Mev) \qquad (5)$$

P-Li 6

$$^{1}_{1}H + ^{6}_{3}Li \longrightarrow ^{4}_{2}He\ (1.7\ Mev) + ^{3}_{2}He\ (2.3\ Mev) \qquad (6)$$

P-B 11

$$^{1}_{1}H + ^{11}_{5}B \longrightarrow 3\ (^{4}_{2}He)\ (8.7\ Mev) \qquad (7)$$

The deuterium-deuterium fusion reaction yields the most energy of any of the reactions, but requires a higher temperature than the deuterium-tritium reaction.Therefore , the D-T reaction is being considered for the first generation fusion reactors.

2.4 Tritium Breeding

In order to use the D-T reaction as a source of energy, tritium must be bred from lithium. Equations 8 and 9 describe the breeding reactions.

$$ {}^{6}_{3}Li + {}^{1}_{0}n \text{ (thermal)} \longrightarrow {}^{4}_{2}He \text{ (2.1 Mev)} + {}^{3}_{1}H \text{ (2.7 Mev)} \quad (8) $$

$$ {}^{7}_{3}Li + {}^{1}_{0}n \text{ (fast)} \longrightarrow {}^{3}_{1}H + {}^{4}_{2}He + {}^{1}_{0}n \quad \text{(-2.74 Mev)} \quad (9) $$

(Natural Lithium is 7.5% ${}^{6}_{3}Li$, and 92.5% ${}^{7}_{3}Li$) .

The tritium breeding is easily accomplished in the fusion reactor due to the high number of neutrons being emmitted from the fusion reactions in the plasma.

3. Ceramics As Tritium Barriers

Good tritium barriers are characterized by their low diffusion coefficients for tritium. Ceramics have low diffusion coeficients especially in comparison to metals. Table 1 summarizes the diffusion coefficients of several ceramics and metals proposed in future fusion reactors.

Presently there are two possible methods of applying ceramics to the walls of a fusion reactor. One method involves plating the insides of the metal walls with a ceramic layer. This method allows tritium leakage in between

Material	D - Diffusion Coefficient (cm^2 / sec)
Tungsten	1.17×10^{-4} (6)
Molybdemum	5.99×10^{-5}
Niobium	3.45×10^{-4}
BeO	1.07×10^{-11} (7)
Laminar PyC	4.24×10^{-15}
Vapor Deposited Si C	3.69×10^{-13}
Boron Carbide	1.44×10^{-9}

Table 1

the plates. The other method involves plasma spraying of the walls , but this produces large grains which allow the tritium to diffuse in between grains.

The problems with ceramics could possibly be solved with a concept similar to that utilized in the pebble bed reactors. The lithium would be encased in pyrolytic carbon balls that would be circulated around the vacuum chamber of the reactor. The fusions in the plasma would provide the necessary neutrons to breed the tritium from lithium. Because pyrolytic carbon has a very low diffusion coefficient , the tritium would be trapped inside the ball. The balls would then be processed onsite to acquire the tritium fuel.

This concept was discovered to be inadequate for tokamak reactors due to the continuous divertor surrounding the vacuum chamber (see Figure 4). However, this idea would be feasible for the inertial confinement fusion reactors. Due to the long period of time before laser fusion can be effectively demonstrated , work on the concept of breeding tritium in pyrolytic carbon balls must be delayed.

4. Oxide Layers

There have been no developments in the applications of ceramics in recent years, but the oxide layers that

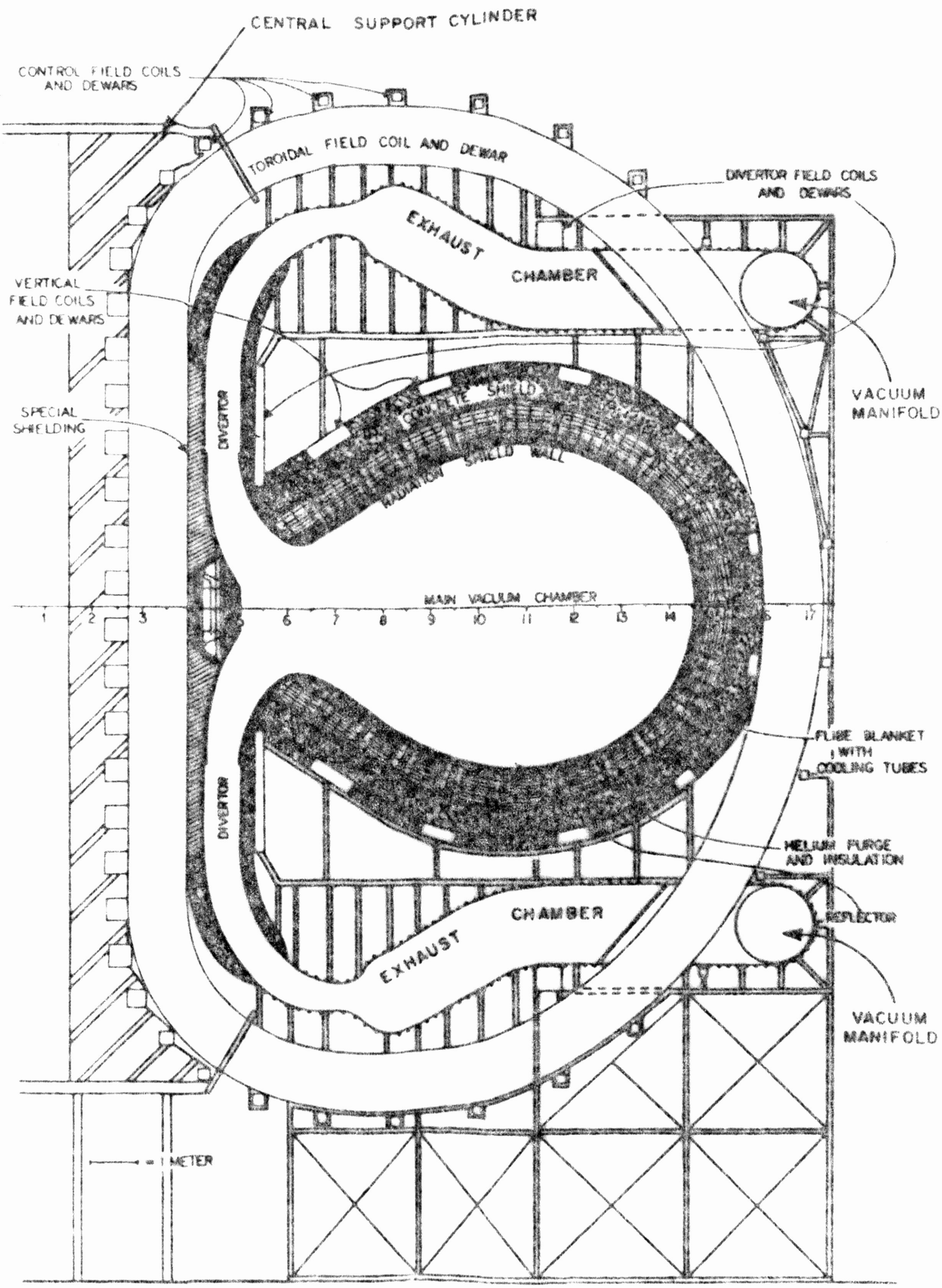

Figure 4

Nuclear Island

form on the reactors' metal walls have been found to possess low diffusion coeffecients.

These oxide layers are generated by passing steam or oxygen over the walls. The ease in generating these oxide layers makes the problems with cracking and chipping easy to remedy.

A section of the project involved the calculation of the tritium concentration in the wall of the PLT (Princeton Large Torus) machine (see Figure 5). This problem was approached as two regions, one region being the stainless steel wall and the other region consisting of the oxide layer.

Finite differences techniques were initially implemented, but were abandoned due to the extreme difference in the thicknesses of the two regions. The increments that were to be used in the seperate regions must be approximately the same to allow for the application of the boundary conditions at the two regions' interface.

The problem was then approached from an analytical point of view with laplace transforms. The coefficients that were developed proved to be too complicated to invert in the time remaining. This problem may be approached in the future with one region and strange boundary conditions.

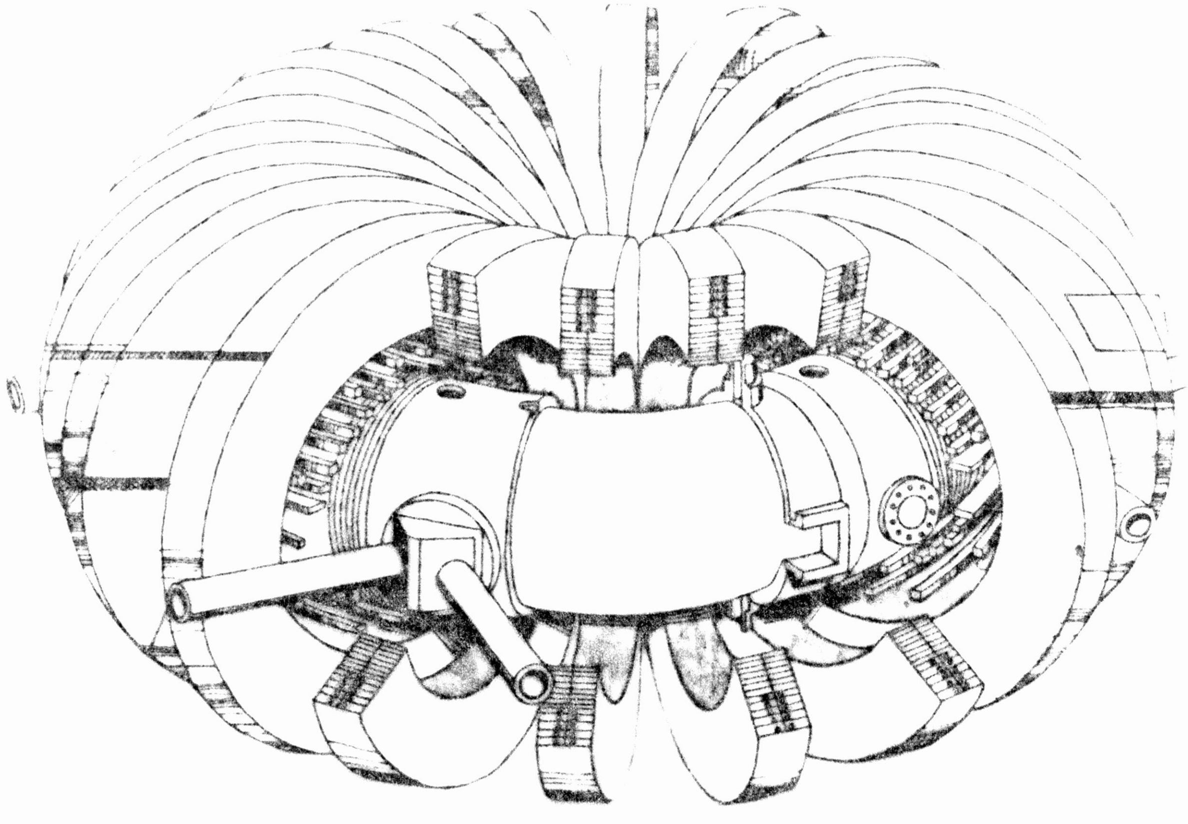

Figure 5

Princeton Large Torus Machine

5. Experimental Work

There was no experimental work involved with the ceramic's ability to contain tritium, but there was some experimental work done on a stainless steel sample from the PLT machine. Electrolysis in acid was done on the sample and the water and acid mixture was boiled to distill the water. The distillate was then counted by a liquid scintillation detector to determine the number of tritium atoms in the sample. The assay yielded less than 10^9 atoms of tritium. This work had little significance to the study of ceramics, but provided invaluable experience with laboratory facilities.

6. Conclusion

Because of the low diffusion coefficients exhibited by ceramics, they may be considered for application in fusion reactors. However, advances must be made in the implementation of these materials. New methods of coating the reactor walls must be discovered in order to prevent any tritium leakage.

Until advances are made for the application of ceramics, the oxide layer on the metallic first wall of the tokamak reactors will serve as a much needed addition to the tritium barrier that the metal wall provides.

The oxide layer is not only advantageous because of its low diffusion properties, but also its ability to regenerate itself. The oxide layer will crack and chip as the reactor operates, but will regenerate because of the oxygen present in the system. With these facts in mind, it can be concluded that regenerative oxide layers on the metal walls of fusion reactors will serve as adequate substitutes for ceramic liners until new advances in ceramic applications can be discovered.

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