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THE CASSETTE BLANKET AND VACUUM BUILDING: KEY ELEMENTS IN FUSION REACTOR MAINTENANCE

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THE CASSETTE BLANKET AND VACUUM BUILDING: KEY ELEMENTS IN FUSION REACTOR MAINTENANCE*

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Summary

The integration of two concepts important to fusion power reactors is discussed. The first concept is the vacuum building, which improves upon the current fusion reactor designs. Tokamak reactors are complicated, may frequently need repair and are virtually inaccessible for some repairs. A part of the complication arises because the closed surface separating the "hard" vacuum of the plasma zone from atmospheric pressure is located either at the first wall or between the blanket and shield. This surface is subject to radiation damage, cyclic fatigue and loss of function and in situ repair is extremely difficult. Enclosing the entire reactor in a vacuum building simplifies and changes the character of this closed surface.

The second concept, the use of the cassette blanket within the vacuum building environment, introduces four major improvements in blanket design:

- Cassette blanket module. The key unit for simplification of blanket replacement and maintenance. It also isolates the lithium from the plasma by enveloping it in the coolant.

- Zoning concept. Because radiation damage to a structure decreases exponentially with distance, the use of cassettes in series requires only the front fraction of the blanket, the first cassette, be changed as a result of damage during the plant life.

- Rectangular blanket concept. Using this geometry, cassettes may be installed or removed by simple linear motion, between toroidal and poloidal coils.

- Internal tritium recovery. A favorable temperature gradient is used to diffuse tritium out of the cassette.

Introduction

The study of fusion reactors has progressed from the somewhat naive designs of 1969, when they were first introduced, to the fairly sophisticated concepts of 1977. During this time many salient findings and discoveries have come to light. These latter designs have in turn produced some rather complex assemblies. As an example we can select the ORNL experimental power reactor (Fig. 1).[1] The selection of this particular Tokamak model is not intended to put the ORNL design in a poor light, but to use it to represent in general a class of machines. The designs of Culham, Julich, Princeton, Wisconsin, General Atomic and Argonne are equally as complicated. Indeed, Tokamaks are more complicated than the usual illustrative figures and artistic rendering included in the reports would suggest, because they generally do not include necessary additions such as divertors, fuel injectors, neutral

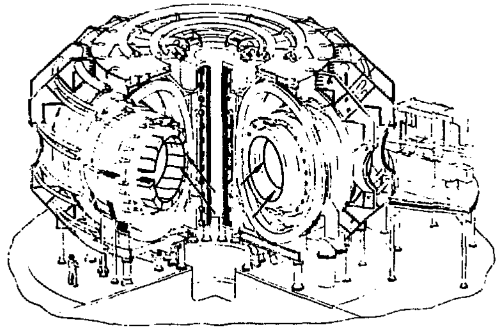

Fig. 1. Tokamak reactor (Oak Ridge EPR reference design). Arrows have been added to show where typical vacuum seals must be made when the reactor is housed in a conventional atmospheric pressure building.

beam injectors, vacuum pumps, cryogenic pumps, diagnostic devices, control systems and other ancillary equipment.

Some basic design features of the Tokamak with which we are concerned and relevant to this paper include:

- Machine Complexity. The basic Tokamak machine with its necessary adjuncts of injectors, poloidal coils, blanket, shield, coolant manifolds, tritium recovery system, divertor, structural frame, among other parts, is an extremely complicated assembly.

- Blanket Access. Next to the plasma heart of this complicated assembly is the "blanket" used to moderate the neutrons. It is the most inaccessible unit of the entire Tokamak. As luck would have it, it is also the part most susceptible to neutron damage and other deleterious effects from the plasma. Planned periodic replacement at intervals of two-three years is virtually certain and emergency repairs are not unlikely.

- Remote Maintenance. The induced activity in the reactor parts, particularly the blanket surrounding the plasma and the injector and divertor where neutron streaming effects will be noticed, all require remote assembly, disassembly, and maintenance.

These areas produce what we can call "the dilemma of the complicated machine." In this paper we examine the use of a vacuum building coupled with the concept of the cassette blanket. We hope to illustrate that this particular combination yields an attractive arrangement that reduces the complexity of the Tokamak significantly.

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Vacuum Building

A part of "the dilemma of the complicated machine," that we hope to improve and simplify, originates from the closed surface separating the "hard" vacuum of the plasma zone from atmospheric pressure. This closed surface is located either at the inaccessible first wall or between the blanket and the shield (see arrows in Fig. 1). The closed surface contains from hundreds to thousands of lineal meters of welds or mechanical seals that are subject to radiation damage, cyclic fatigue or other adverse effects causing loss of function. The vacuum integrity of this closed surface has to be unbelievably high. A practical size reactor (say 2000 MW th), has a fuel injection rate of 0.1 g/s when the burn fraction is 4 percent. An equivalent air leak rate would occur when a fault (a hole in the wall) was only 0.06 cm in diam — (a size about as big as the period at the end of this sentence). Whether this air leak would quench the plasma or whether the intruding gas would be pumped out before this happens is conjectural but it would seem reasonable that leaks, however small, should be avoided.

Our method of using a vacuum building changes the character of the first wall closed surface from one requiring absolute vacuum integrity to one of high pumping impedance. By a vacuum building we mean, in general terms, a spherical or elliptical shell capable of being maintained at a pressure of about 10^{-6} Torr and divided into two principal vacuum zones: the building proper and the plasma zone. These zones would be differentially pumped, and the separation between the two would be one of high pumping impedance. The conservation of the character of each zone would be conserved. The building would be large enough to enclose the total nuclear island.

The vacuum building concept was an important part of the Frascati FINTOR conceptual design.[2] In this Italian version, the main containment vessel was an ellipsoid with a major and minor diameter of 60 and 26 m. It was made of concrete to provide biological shielding and lined with steel for vacuum integrity. The steel also served as a tritium barrier. Vessels of this size and larger have been made by NASA at Plum Brook. Incidentally, the biological shielding required for a fusion reactor must consist of a 1-2-m-thick concrete barrier that fortuitously is thick enough to support the atmospheric structural load. Therefore, additional structural costs for a vacuum building are not significant.

Vacuum Building Advantages

Some of the advantages gained in the use of a vacuum containment vessel are:

• Elimination of all remote field welding in reactor region. The primary vacuum in many of the present reactor concepts is established by peripheral seam welds, generally made between adjacent blanket modules. The total length of these welds that must have 100% integrity against leakage can be thousands of meters. In the event of a leak, it must first be found (no small task) and repaired. In the event of blanket replacement, the entire weld must first be cut and then rewelded after reassembly. All the operations (leak hunting, repair, cutting, replacement, rewelding), must certainly be done remotely, making it an incredibly difficult task. Furthermore, these weld zones are subject to both thermal stress and thermal cycling and, with time, almost certain leakage will occur. These welds are not necessary and can be eliminated by moving the primary vacuum to the room temperature enclosure.

• Ease of blanket module replacement. With the blanket modules assembled as a nested set (packed side by side), and with few mechanical connections and no welded connections, it is possible to visualize remote module replacement accomplished with minimum difficulty. The optimum replacement technique can be one using simple linear translation of first blanket zone modules or secondary zone modules (the cassettes) exiting between coils. This will be discussed later.

• Remote handling. In addition to the blanket cassette modules, remote handling is necessary for a significant number of other reactor components, such as injectors, which must be directly coupled to the plasma. They can probably be repaired or replaced easier in a vacuum enclosure than in one where the vacuum is only on the plasma side. Also, pressure transducers, temperature transducers, plasma diagnostic probes and other items that penetrate into the plasma zone are more easily replaced when they do not have to pass through a vacuum-tight intervening wall.

• Reduction of physical size. The elimination of welds needed to establish the vacuum in the plasma zone if a vacuum building was used eliminates the need to provide space and access to these welds. This can reduce the total reactor diameter as much as 2-3 m.

• More effective control of heat transfer. The proximity of 4 K toroidal field coils and divertor coils to 1000 K blankets, 500 K shields, room temperature vertical field coils and other items, creates a heat transfer problem that absolutely must be minimized. The penalty paid because of energy transfer into cryogenic, superconducting toroidal field coils as a result of the subsequent refrigeration load is approximately 500 W/W. An effective solution for decoupling the energy exchange is to reduce it to a problem of radiation heat transfer and use multiple, thin foil radiation shields.

• Operation time. The effective on-line time of the reactor should improve with the use of a vacuum enclosure because the need to let the plasma zone up to air or up to argon is eliminated. This decreases the "bake in" or outgassing times.

• Tritium release control. The use of a vacuum vessel operating at room temperature creates a highly effective diffusion barrier against tritium release.

• Environmental protection for refractories. The refractory metals (niobium, vanadium, molybdenum, tungsten, titanium, tantalum) are candidates for blanket zone materials and cannot be run at elevated temperatures without a protective atmosphere. Cover gases such as argon may be acceptable, but a vacuum background is a better solution.

• Relaxation of pressure loads. Welding the blanket modules, one to the next, creates an externally loaded pressure vessel. This high temperature vessel may be subject to creep buckling. If the walls are made thin for good neutronics, good tritium breeding, and minimum neutron heating, the structure may fail by buckling. If the walls are made thick enough to resist buckling at a specified temperature, T, then the additional neutron heating of the thicker material causes the wall temperature to rise to $T + \Delta T$, lowering the creep buckling resistance. A series of blanket modules mechanically assembled with vacuum enclosures on all sides circumvents this potential problem.

• Hands on the remote handling compatibility. The concern of experimentalists that a vacuum enclosure is inhibiting and causes unreasonable difficulty for some experiments is resolved because pumpdown time from atmospheric pressure to 10^{-6} Torr can be approximately 10 h. Thus, work or experiments requiring "hands on" operation could be done within a 24-h period. For the remainder of the work the vacuum could be retained. Bear in mind, however, that a fusion reactor, prototype or commercial, is no longer a physics experiment and hands on access is not inherent in the design.

Disadvantages of a Vacuum Building

There are lesser advantages and some disadvantages in using a vacuum building as part of a fusion complex. Some disadvantages are cited below:

- Large surface areas and the problem of continuous outgassing. The differential pumping of the plasma zone and the volume outside of the plasma helps minimize the outgassing problem. Simple, easily placed or removed high impedance closures can be made between these zones so that the plasma zone, where outgassing would be a problem, would have about the same surface area as if it were welded.

- Vacuum abhorring components. Some components function more effectively in other than high vacuum pressure environments; those parts with low vapor pressure such as lubricated bearings and also certain sections of injectors that may arc or have corona discharge. Because these parts are outside of the blanket zone they can be individually pressurized.

- Vacuum welding. Within the blanket area there is the problem that adjacent parts operating at high temperature may vacuum-fuse together if they are initially in physical contact. Therefore, the simple mechanical closures used in the high impedance barriers must have a coating or a treatment that prevents welding. This problem needs further study.

- The vacuum building structure. The building of a large vacuum enclosure is not trivial. However, the biological shielding required (about 2 m of concrete) can certainly be used as a structure. Some NASA space program experience would be helpful here.

Figure 2 shows a view of the NASA Plum Brook facility at Sandusky, Ohio.[3] It was built in 1963 as a space simulation cell and is nuclear rated. Figure 3 shows the floor plan of the facility. The cost in 1963 was \$29M. In 1977 dollars at an inflation rate of 7.5% the cost would be \$80M. As the two figures suggest the facility has essentially all the features required for a reactor site. As we will show subsequently, the test cell is large enough to house a Tokamak reactor.

Fusion Reactor Blankets

Having set the stage by describing the enclosure of the reactor (basically a vacuum everywhere within the nuclear island), the design contraints on the blanket, one of the principal reactor components, are considerably modified. There is no longer a need to rely on the blanket modules themselves to form an impenetrable barrier protecting the plasma from ambient pressure and gas intrusion. Nor is there a need to design a near perfect enclosure and immediately surround it with shields, coils and other reactor components, making it nearly inaccessible. As it is, the blanket has many prime functions to perform and if we are able to eliminate extraneous functions the task of blanket design becomes easier.

The blanket of a fusion reactor is a complicated, multifunctional unit enveloping the reacting plasma. In a deuterium-tritium (D-T) system it must:

- moderate the 14-MeV neutrons to thermal energy levels.

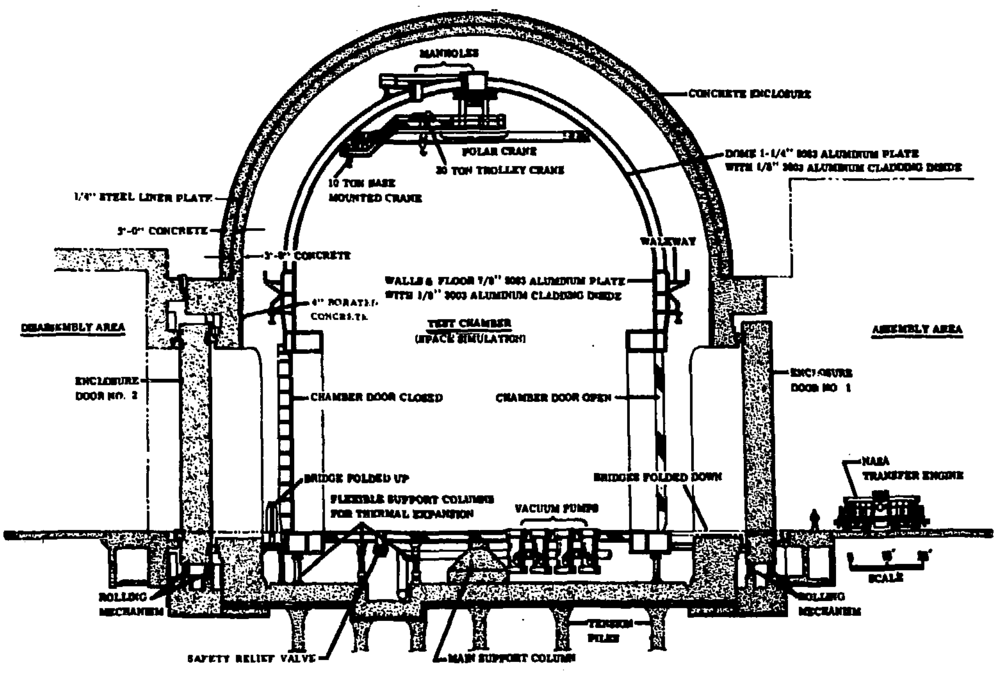

Fig. 2. Cross section view of the test chamber of the NASA Plum Brook facility at Sandusky, Ohio.

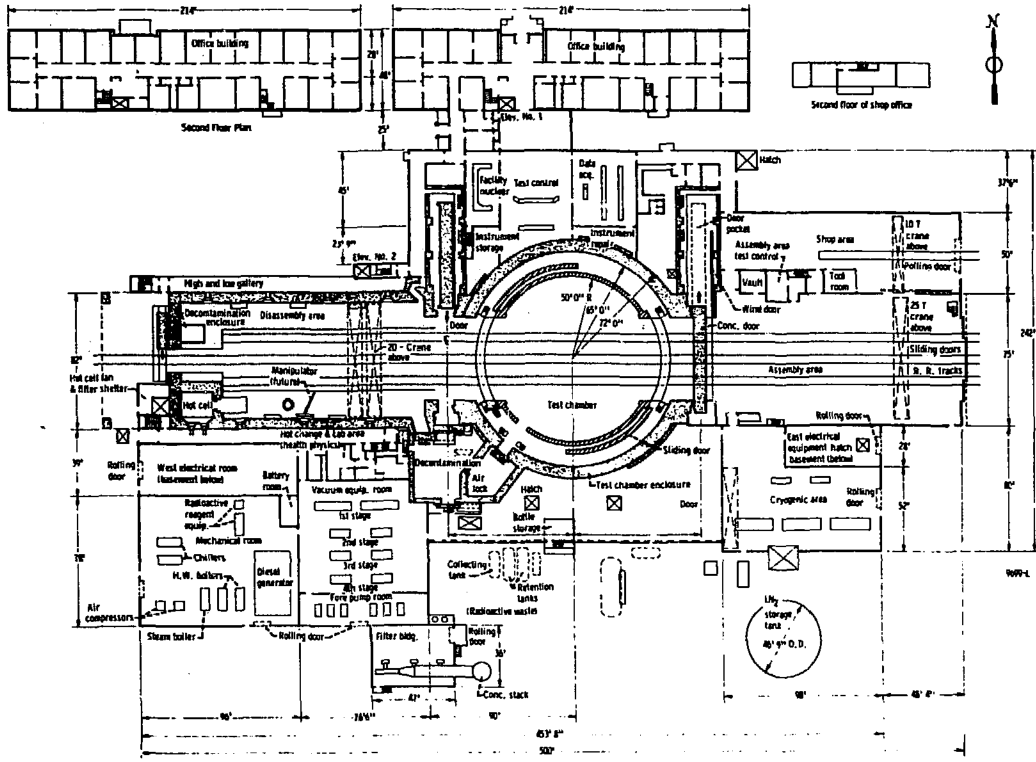

Fig. 3. Floor plan of the NASA Plum Brook facility.

- breed the required tritium fuel via neutron reactions with lithium or lithium compounds.

- provide for thermal energy transfer to an external turbogenerator so that useful electrical power is produced.

- envelop the plasma and yet allow flux penetration so that current may be induced in the plasma.

These tasks must be accomplished in a relatively flimsy structure. The flimsiness is necessary to ensure adequate tritium breeding. The ratio of reacting volume to structural volume is approximately 15:1.

Because of its thermodynamic function as an energy store, the blanket is quite hot. A representative temperature could be between 400-500°C. It is, after all, the heat source of a power plant. It is also subjected to the effects of a fusion environment, such as: radiation, atomic displacements, helium-induced swelling, sputtering, spalling, cyclic fatigue, and thermal stress. Consequently, the life expectancy of a blanket may be less than that of the total plant. The blanket should be designed in small units for easier assembly. Using a single homogeneous unit impairs flux penetration to the plasma.

The blanket is disagreeably located, situated immediately next to the plasma and surrounded by shields, poloidal coils, vertical field coils, toroidal coils, injectors, coolant piping, divertors, structure, and instrumentation, among other items. Yet access is necessary because the blanket (at least the first 12-25 cm) is likely to be the shortest-lived reactor component, requiring periodic replacement. A 5-year lifetime projection is probably optimistic. Some faults in the blanket modules are almost inevitable during their life span, and replacement of single blanket modules, rather than _in situ_ repair, would have to be planned.

The blanket must also be economical to fabricate and maintain, and, of prime importance, be as fault-free and fail-safe as possible. Simplicity must be strived for both in method of manufacture and in the use of contemporary structural materials. Above all, there must exist a credible method of blanket module assembly, disassembly, and maintenance under remote operating conditions.

Cassette Blanket

The idea of the cassette blanket is not a singular one but incorporates a number of innovative features that were developed in an attempt to satisfy criteria of assembly, disassembly, use of current technology materials, and tritium breeding integrated with plasma physics. This design introduces and combines beneficially four major new features:

- _Cassette blanket module_. This is an elementary, relatively simple structure designed to simplify blanket replacement and maintenance. It also isolates the lithium moderator from the plasma by enveloping it in the coolant.

• <u>Blanket zoning</u>. The concept of blanket zoning is based on the fact that radiation damage to a structure decreases exponentially with distance. With the use of cassettes in series, only the front fraction of the blanket, the first cassette, will need to be changed (because of radiation damage) during the life of the plant.

• <u>Rectangular blanket</u>. Because blankets must envelop the plasma but need not conform to plasma shape, the rectangular blanket design uses a straight line geometry, where cassettes may be installed or removed by simple linear motion between toroidal and poloidal coils.

• <u>Internal tritium recovery</u>. This method of internal tritium recovery utilizes a favorable temperature gradient and "MHD-frozen" lithium to diffuse tritium out of the cassette.

The combination of these features produces a blanket assembly that eases the total design problem, is relatively simple, and can be serviced and maintained without undue difficulty.

Cassette Module

A typical cassette has the general characteristics given in Table 1. Figure 4 illustrates the general design features of a cassette blanket module. The cassette's assembly of individual coolant tubes completely encapsulates the lithium moderator, providing good isolation of the lithium from the plasma.

The cassette is relatively slender to facilitate assembly and disassembly. Its thickness is determined by the desired decrease in radiation damage from front to back, usually about 25 cm for a damage reduction of five to ten, and by the temperature profile within the module. The module is about 4 m long and less than 1 m wide. The module assembly includes supply and return headers for the coolant which flows into the parallel tubes that form the cassette. Within the U-shaped tube assembly there is a noncirculating lithium moderator. An expansion plenum accommodates the volumetric change of the lithium during the operating cycle. This bellows-type expansion plenum also acts as a pressure transducer or stress transducer that senses pressure changes in the event of a leak between coolant and moderator. The cassette also incorporates a method for tritium recovery.

Zoning

In the cassette design, we use to our advantage the fact that radiation damage decreases as a function of depth into the blanket. For example, a spatial distribution of damage characterized by atomic displacement rate and by helium generation rate is illustrated in Fig. 5. It can be observed from this figure that in a distance of about 25 cm, the atomic displacement rate decreases by a factor of five and the helium generation rate decreases by a factor of seven. We define this region, that represents volumetrically about 25% of the total blanket, as the first blanket zone (FBZ). The FBZ filled with cassette modules would be changed routinely when radiation effects dictated, or when surface effects such as sputtering erosion required it. All other things being equal, the second blanket zone (the remaining 75% of the blanket) would last 5-10 times longer, or near the approximate 30-year life of the plant.

The coolant circuit for the cassettes in the FBZ may be one that is completely independent of the remainder of the blanket, or the outlet duct may feed to the second blanket zone. Piping connections for the coolant in either case would be outside the shield where access is relatively simple. The shield is integrated with the cassette. There is no lithium flow. The cassettes used within the FBZ may be single or double units as suggested in Fig. 4. The

Table 1. Cassette characteristics

Structural material	316 stainless steel, 20% cold worked
Coolant	Helium at 60 atm
Coolant temperature	T_{in} = 550 K; T_{out} = 750 K
Maximum material temperature in high radiation zone	700 K
Wall loading capability	~4.5 MW/m^2
Probable lifetime	~2 years
Moderator	Noncirculating lithium sealed in place
Tritium recovery	Niobium or vanadium window
Cassette thickness	~0.14 m
Cassette length	~4.0 m
Cassette width	~1 m
Coolant disconnect location	Outside shield
Removal method	Linear motion
Tritium partial pressure	~10^{-6} Torr
HeLi leak detection	Pressure sensor in plenum
Fail-safe feature	Helium-encapsulated lithium
Cost	Appears reasonable; not calculated
Changing time	Appears short; not analyzed
In situ repairs	Not necessary; cassette would be replaced
Compatibility with plasma	Wall of front cassette may be treated with low Z coating
Resistance to magnetic field forces	Not calculated

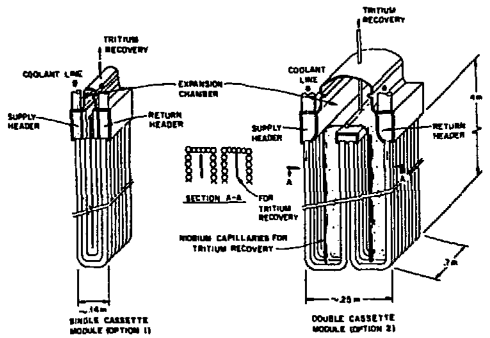

Fig. 4. General design features of a cassette module for a fusion reactor blanket.

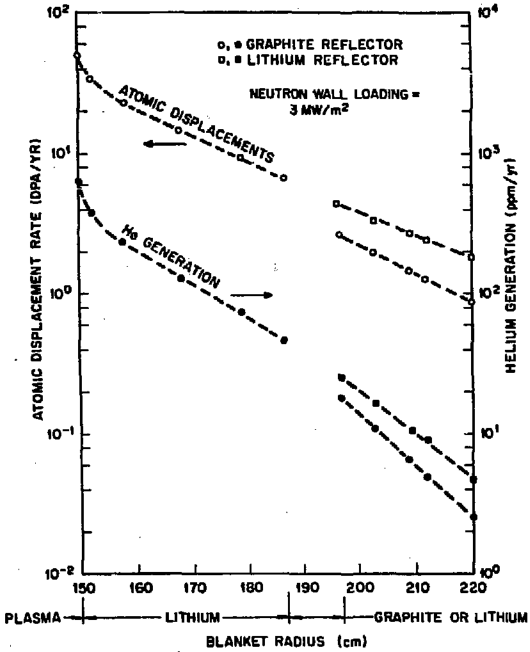

Fig. 5. Spatial distribution of radiation damage versus blanket thickness.

choice of a single or double unit is dictated by: temperature profiles and temperature limits on structural materials of the cassette; adequate temperatures at the niobium capillaries which provide tritium recovery; the level of wall loading; and requirements for assembly and ease of replacement.

Rectangular Blanket

Tokamak plasmas were initially developed or created in structural toroidal shells with circular cross sections creating a circular plasma. With the increasing knowledge of plasmas, physics calculations are now used to decide the basic plasma shape to improve, enhance, and optimize its performance. Plasma shape is now frequently elliptical or elongated, with the major axis in the vertical plane, and is no longer dictated by the surrounding walls.

It should follow that, freed from the task of shaping the plasmas, the shape of the blanket can be dictated by engineering requirements, including fabricability, ease of maintenance, economy, and dependability, but particularly assembly and disassembly. The rectangular blanket using cassette modules is a step in this direction.

The cassette modules that make up the blanket (as previously indicated), are long, relatively thin, box-like volumes. The walls of these volumes are a series of U-shaped tubes containing the coolant which completely envelops the lithium-moderating fluid contained within. The cassettes are removed and replaced remotely using linear motion, passing the cassettes between the vertical field and toroidal field coils and other obstructions. Figure 6 is an illustration of two cassette module subassemblies side by side. The number of subassemblies is equal to the number of toroidal field (TF) coils. Each subassembly is divided radially into

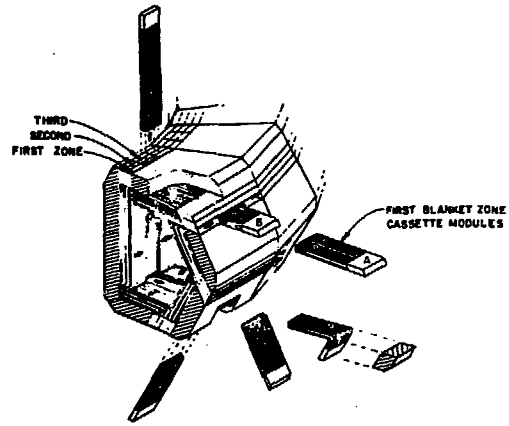

Fig. 6. Cassette module subassemblies. The zoning approach to blanket design using replaceable cassettes. This figure illustrates the removal of cassettes in the first zone damaged by radiation. With this arrangement, there would be a five-step sequence to remove the middle cassettes (A) of the first zone, and the outer cassettes (B) would then be removed to the free space and the sequence repeated.

three "slices." A removal sequence for the cassettes in the FBZ is suggested in the figure.

Figure 7 shows the cross section of a completed tokamak reactor equipped with the cassette blanket. As shown, simple linear motions will permit the removal of the cassettes through the space between VF coils without interference.

Tritium Recovery

The lithium volume contained in the U-shaped envelope of the cassette module (Fig. 8) has roughly centered within it an independent, nonstructural barrier wall that serves a dual role: (1) it acts as an adiabatic, energy-isolating surface between the half of the coolant tubes facing the plasma and the other half of the U-shaped tubes facing the secondary blanket zone, and (2) it is a means of tritium recovery. This barrier wall is made of capillary tubes of niobium or vanadium. Tritium is recovered by diffusion in the lithium and permeation through the niobium. The location of this

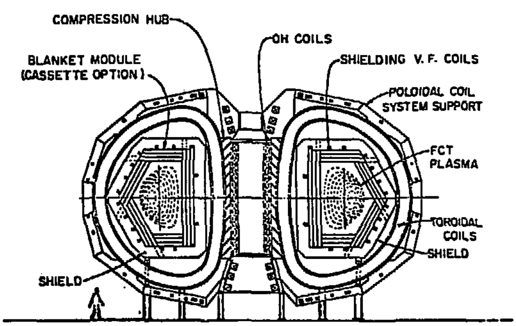

Fig. 7. Cross section of a Tokamak reactor equipped with a cassette blanket.

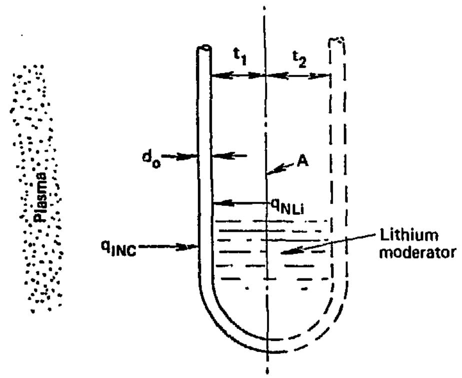

Fig. 8. Tube from the leg of cassette blanket used for heat transfer calculations. Surface A is the adiabatic plane where the niobium capillary tubes, used for tritium recovery, are located.

adiabatic wall A is determined by heat transfer considerations, the desired flux attenuation, the gradient in temperature within the lithium, and the diffusion of tritium in lithium. The lithium is assumed to have zero fluid circulation because of magnetic field effects.

Because the magnetohydrodynamic (MHD) effects strongly inhibit the convective mixing of the lithium, the temperature profile may be determined by simple conduction heat transfer. Thus, we are able to select an appropriate value of t1, and t2, the distances between coolant tubes and the adiabatic surface. To determine an acceptable value of t, we specify that the temperature at the coolant tube wall must be low enough to satisfy radiation damage requirements, while the temperature at the adiabatic surface must be high enough so the tritium will diffuse and permeate through the niobium at an appropriate rate. Once on the downstream side of the niobium tube, the tritium is removed by gas flow. Fortunately, the required temperature profiles occur at a distance that is also appropriate to the idea of zoning for radiation damage.

The Total Concept of The Cassette and The Vacuum Building

The cassette blanket concept appears to fit in well with the idea of housing the entire reactor in a vacuum building. The vacuum building approach liberates the blanket from the requirements of providing absolute vacuum integrity during operation. The building envelops the total blanket in a vacuum. Complex mechanical seals or welds, which almost preclude disassembly and replacement, are no longer required.

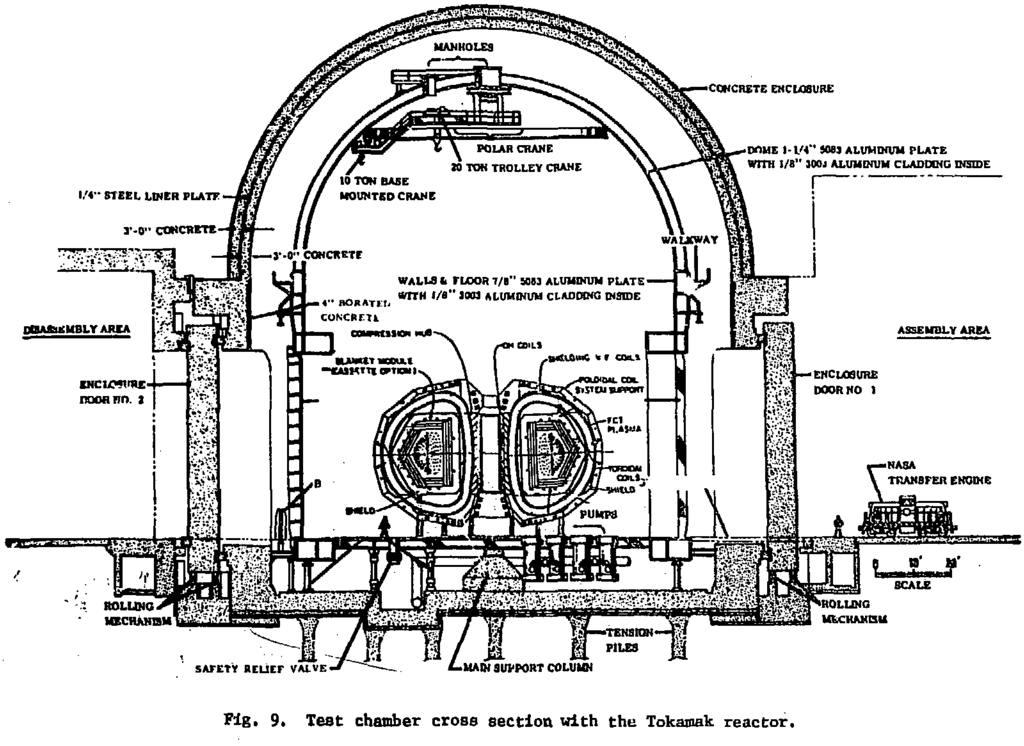

Fig. 9. Test chamber cross section with the Tokamak reactor.

Not only the cassette blanket design but also blanket designs in general should benefit from the vacuum building approach.

We may be able to use existing facilities that are large enough to accommodate a reactor, such as the facility at Plum Brook, Ohio. Figure 9 shows the ORNL experimental power reactor as it might be installed in the facility at Plum Brook. The available volume and dimensions of this existing facility are more than adequate.

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NOTICE

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