

PFC/RR-81-19

DOE/ET/51013-17
UC20A,B

TOWARDS A STRATEGY OF RELIABLE
FUSION FIRST WALL DESIGN

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May 1981

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M.I.T. Plasma Fusion Center Report PFC/RR-81-19
O.R.N.L. Fusion Engineering Design Center
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ABSTRACT

Fusion first walls are subject to a large number of possible failure mechanisms, including erosion due to sputtering, arcing, blistering and vaporization and crack growth due to thermal and magnetic stresses. Each of these failure mechanisms is poorly characterized and has the potential of being severe. A strategy for designing reliably in the face of great uncertainty is discussed. Topological features beneficial to reactor availability are identified. The integration of limiter pumping with rf wave launching is discussed, as a means of simplifying reactor design. The concept of a "sewer" limiter is introduced, as a possible long-life limiter topology. The concept of flexible armor is discussed, as a means of extending maximum life.

Foreword

This metals been of so greet violence,
Oure wallës mowë nat make hem resistence,
But if they weren wroght of lym and stoon,
They percen so, and thurgh the wal they goon;
And somme of hem synken into the ground -
Thus han we lost by tymës many a pound -
And somme are scatered al the floor aboutë,
Sommë lepe into the roof. Withouten doute,
Though that the feend noght in ourë sighte hym shewë,
I trowe he with us be, that ilke shrewë!

- Chaucer

The Canon's Yeoman's Tale

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Introduction

The first wall of any thermonuclear device must survive severe heat, particle and neutron fluxes. In the case of pulsed magnetic devices, such as tokamaks, it is also subjected to pulsed magnetic forces. The term "first wall" is used here to describe those surfaces directly exposed to ion flux; not those surfaces, sometimes called first walls, which are subjected only to heat and neutron fluxes and magnetic forces. The difference is fundamental, since these "second walls" are destroyed by crack growth only, while first walls can be destroyed by either crack growth or erosion, with the two mechanisms interacting strongly. We will focus on the tokamak, because it has probably the most complex first wall design problem, and because it is the reference reactor topology being considered for the Fusion Engineering Device (FED) [FL81].

The Futility of Specifying the First Wall Load

Reactor first-wall studies usually specify the time history and spatial distribution of particle, thermal and magnetic loads on the first wall of a magnetic fusion reactor, in order to analyze and evaluate the structural integrity of the first wall design in question. This process is valid for studies of hypothetical reactors in the distant future, using "best-guess" assumptions about reactor behavior. As a method for next-step reactor design, the process is flawed, because the specifications of plasma-wall interaction have little credibility as a basis for design. The lack of credibility stems from the complexity of the problem, the paucity of direct measurements of the parameters of interest, and the consequent inability of theory to predict plasma-wall interactions.

In order to specify the loads on a first-wall surface, several erosion and crack-growth phenomena must be predicted. Erosion is caused by physical and chemical sputtering of the wall by ions, vaporization, arcing, blistering and spalling by helium, and ejection of molten droplets. Crack growth can be caused by pulsed thermal loads, pulsed induced magnetic loads, and steady-state magnetic loads from particle flux currents and particle loads. The time history of the loads requires knowledge of the physical requirements of plasma initiation, start-up, and shutdown, and the frequency of off-normal conditions such as disruptions, electron runaway and positioning errors, particularly during heating. (The above conditions can only be considered off-normal as a statement of design goals, since any one of them may occur on every pulse of a thermonuclear plasma.) A specification of the detailed poloidal and toroidal spatial distributions requires knowledge of the poloidal distribution of neutron flux and the distributions of particle and heat fluxes on all surfaces of a complex geometry, including the flux of charge-exchange neutrals, the direction of travel of a disruption, how concentrated the heat and particle deposition from a disruption will be, the spatial distribution of electron flux at major reorganizations of plasma flux surfaces, concentrations of hot ion loads due to magnetic field ripple and concentrations due to plasma position or shape shifts during heating and cooling.

Material properties that must be understood include crack toughness, ion and neutral particle sputtering characteristics, and the response to the simultaneous deposition of neutrons, hydrogen, helium and other first-

wall atomic species in a material. While significant data now exist on the crack growth behavior of many materials, given a known stress history, essentially nothing is known about the crack growth behavior of any material in the face of simultaneous erasure of cracks by erosion, filling of cracks by redeposition, changes in the chemical composition of the crack surface and morphological changes in the bulk surface, such as peeling and pitting.

The mechanism by which plasma-wall interactions change the plasma and the interactions themselves must also be understood. The plasma-wall interactions change the composition of the plasma by releasing wall particles into the plasma and by implanting plasma particles in the walls. During transients, such as disruptions, a cloud of first-wall particles may intercept the flux of hydrogen and helium particles from the plasma and increase electron heat flux by lowering the sheath potential. Similarly, higher Z materials with self-sputtering coefficients higher than 1 at a given plasma edge temperature may cause self-limiting oscillations of self-sputtering avalanches of first-wall material.

Of the many interacting phenomena which must be understood in order to write a realistic specification, only vaporization for a known heat flux, physical sputtering for a known particle energy and orientation distribution, magnetic stresses for a given field-time distribution and material crack growth behavior of a few candidate materials, in isolation from erosion and redeposition are well characterized. If a worst-case analysis, with no margin of safety, is used for all of the uncertainties of plasma-wall behavior, there is no material which can survive interaction with a thermonuclear plasma for long. Given the very high ratio of the knowledge needed for a credible design specification and what is now known, it is optimistic to hope that the uncertainties can be substantially reduced in time for a next step device. Thus, it may be more profitable to explore logical, rather than quantitative, design principles in order to find a good first wall design.

Toward a Strategy for Reliable Design Identification of Figures of Merit

The use of dimensionless figures of merit as an aid to evaluating designs is common in the fusion program, the two most popular being total beta, the ratio of thermal to magnetic energy, and Q, the ratio of fusion power to auxiliary heating power. Even if it is not possible to predict accurately the value of either figure for a given reactor design, they have both been extremely useful in focusing the experimental and reactor study programs. Since the integrity of limiters and first walls may be as critical to the success of fusion as global transport and stability, figures of merit should also be discussed for plasma-first wall interactions.

Possible candidates for useful figures of merit include the ratio of the fraction of particles pumped to the fraction of particle energy deposited on a limiter or collector and the ratio of the average wall loading to the peak particle heat loading on the limiter or collector. Nondimensional figures of merit include J/cc of absorbed energy to failure for a given heat flux and particles/cm² of integrated particle fluence to failure for a given particle flux. These figures are similar to the commonly used measures of radiation resistance, such as the rads of absorbed radiation frequently used to predict the radiation life of a proposed magnet insulation, and neutron fluence (n/cm²) used to predict second-wall life.

Identification of Desirable Features

Since the race between crack growth and erosion can't be quantified, it may be profitable to look for

nonquantitative features that will improve the reliability of a design. Topological features that can be identified include:

- [1] Redundancy: If a limiter or armor part could fail without requiring reactor shutdown, this would probably be the single most desirable topological feature that could be identified. A more easily achievable goal is to design limiter or armor tiles such that the loss of a single part does not require replacement of the entire first-wall.
- [2] Clearance: The distance between the first wall-plasma interface and the any active coolant should be long, in order to maximize total erosion to failure, and to allow some degree of self-correction for nonuniform heating, by which differential erosion would reduce the heat loading on the more highly loaded sections.
- [3] Small toroidal dimensions: First wall component parts should be small in the dimensions transverse to the minor radius, in order to minimize simultaneously thermal and magnetic stresses.
- [4] Maintainability: All parts of the first wall should be rapidly replaceable.
- [5] Vacuum integrity: Moveable components, such as limiter blades, should be removeable without breaking vacuum.
- [6] Renewable surfaces: If possible, high erosion parts such as limiters, should have a continuous feed mechanism.

Clearly not all of these goals can be achieved simultaneously, and some, such as redundancy and renewable surfaces, may not be individually achievable. However, the pursuit of these goals may be the path to reliability. The recent invention of a blade limiter for the Fusion Engineering Device [FL81] achieves the goals of maintainability and the potential of removal without breaking vacuum. A new concept, described in section C.4, attempts to achieve most of the goals.

Use of Limiters to Simplify Reactor Design

While the lifetime of limiters and first-wall armor is a sufficiently difficult problem in its own right, limiter design should also be used to improve overall reactor design. The most significant advance in this direction is the use of limiters for helium exhaust, instead of divertors. The only other plausible function remaining for a limiter that could significantly simplify reactor topology is the use of the limiter as an rf wave launching structure, as proposed previously by the author [SC81].

Almost any limiter structure can be used to launch some kind of rf wave, as illustrated in Figures 1-3. However, large structures such as antennas or resonant cavities, which must bear high eddy current and thermal loads in addition to the substantial heating from the rf itself are unlikely candidates for reliable designs.

The slow wave limiter pump shown in Figure 2 is unique in that it not only can be used to launch rf waves, but may actually improve the efficiency of wave launching over that by a waveguide grill with no limiter. This conclusion is strongly suggested by the work of Shcherbinin and Schuss on the effect of wall corrugations on lower hybrid wave launching [SH79]. In this topology, the limiter acts as a slow wave structure for the toroidally directed lower hybrid wave.

RF launching limiters have the disadvantage that it is difficult for them to achieve broad coverage of the torus wall. They are perhaps no worse in that respect than most limiter designs, but they can clearly not be "global limiters". For example, the previously discussed [SC81] control-rod limiters (Figure 3), surrounding

ICRF waveguides, cover only 0.05 % of the first-wall surface. However, since the total exposed surface area of these limiters is 100 times the area of their tips, steady-state radiative cooling is possible. A radiatively cooled concept with double the heat absorbing capacity of the control rod limiters and far greater pumping speed is discussed in section C.4.

In order to improve overall system performance, the presence of a limiter pump should not degrade the performance of the rf launching system. It has been objected that moving the rf window behind a bend and allowing particles access to pumping ducts through a microwave screen will severely degrade the power handling capability of an rf waveguide, due to electron cyclotron resonance breakdown. However, a review of the experimental evidence in tokamaks [HO81], reported in Appendix A, suggests that this is not the case.

A Possible Limiter Topology: The Sewer Limiter

An important advance in limiter topologies was suggested recently for the Fusion Engineering Device [FL81]. This blade limiter pump, shown in Figure 4, has several advantages, including

- [1] A probably adequate in-burn exhaust system with some concentration of neutral density on the pump side of the limiter
- [2] Limiter pumping through a horizontal grill, instead of a carefully shaped, flux-line following structure
- [3] Horizontal installation and removal
- [4] Possibility of rapid removal and replacement of limiter, after detection of a failure, such as a leak. If a piece of the limiter armor breaks off, repair would require in-vessel manipulators similar to the repair of in-vessel armor.
- [5] Possibility of limiter removal without breaking vacuum
- [6] Possibility of testing as many limiters at once as there are shield modules, allowing rapid determination of the most reliable mounting and cooling concepts.

However, this concept does have some disadvantages, including:

- [1] Cantilever construction not particularly strong against electromagnetic induced forces on disruption
- [2] Relatively complex bonding scheme, close to maximum heat and particle flux.
- [3] Particle drift currents to ground on disruption may induce large torques on the limiter blade.
- [4] Small radius of curvature in hydraulic path will probably cause vibrations in blade. Hydraulic path may cause a velocity stagnation region near the tip of the limiter blade.
- [5] The voltage between blades is sufficiently high to cause a perceived requirement for current shunts between blades, increasing electromagnetic forces during a disruption, and adding the reliability of a shunt bond to system requirements.

A variation on the blade design, called the "sewer" limiter, shown in Figure 5, eliminates many of the shortcomings. The sewer limiter resembles a sewer grating on the bottom of the vacuum vessel, running in a continuous toroidal annulus about the vessel. The construction of this grating is similar to that of an ion extraction grid used in neutral beam sources [PA79]. Either an actively cooled version, with inlet and outlet headers on either side of the sewer, or a passively cooled version, similar to that recommended by Fink for ion extraction grids [FI78] may be feasible.

If an actively cooled system is used, off-the-shelf fluted tubes, such as those recently purchased for use

in neutral beam dump calorimeters [ST81B] could provide a very cost-effective solution. The 3/8 " tubes can support burn-out fluxes of 2 kW/cm² with water speeds of only 0.2 m/s [ST81B]. A system of 1.0 " tubes, spaced by 1/4 " gaps between tubes would require 1000 tubes for a tokamak plasma with a 6 m major radius. If commercially available, internally finned copper were used, the cost of tubing, at \$5.00/ft, would be \$3,200 for a 20 cm span. Even if molybdenum rails, such as have been used experimentally for neutral beam sources, were used, the cost of tubing, based on ion extraction grid costs, would be only \$800 K [PA81]. A 20 cm molybdenum fluted tube would weigh 1.0 kg, which should be within the capabilities of powder metallurgy technology for carbon or molybdenum tubes.

The heat absorption capability of a 20 cm wide sewer grid with a 6 m major radius is shown in Figure 6 for different sizes of rods for carbon, molybdenum and molybdenum coated with carbon. The last represents what may happen automatically if all first-wall armor is carbon or could represent the performance of a graphite with the conductivity of molybdenum. Almost all plausible concepts are dominated by radiation cooling. This implies that if greater power handling is needed to achieve adequate pumping speed, more than one grill should be used and that refractories with small vapor pressures significantly above 2000 C should be investigated.

In comparison with the FED limiter blades, the sewer topology would have the following advantages.

- [1] It is supported at 2 points, instead of 1, while still being free to expand axially.
- [2] Since the total voltage between grids during a disruption is less than a fraction of a volt, no shunts would be necessary to prevent arcing.
- [3] Small tubes should have lower ac losses than armor tiles. Drift currents to ground during a disruption will be down both ends of the tube, cancelling net out-of-plane forces.
- [4] Using efficient, unidirectional internally finned or swirl tube technology, tubes will run cooler for the same flow rate.
- [5] The peaking factor of maximum heat flux to any tube to average heat flux should be close to 1, since only toroidal asymmetries matter.

A passive system, such as the one shown in Figure 5 , should have all of the advantages of the active system, except for nos. [2] and [4]. If it can be designed so that vaporization is negligible, it would have the further advantages of:

- [1] True redundancy: Several of the fingers could drop off or seriously erode, without constituting limiter or pump failure. If the armor were made of sufficiently small pieces, such as cigarette limiters [SC81], failed armor pieces could be collected in the trap shown in Figure 5, without requiring system shutdown. If the trap included a hard vacuum valve, it could be replaced without breaking vacuum.
- [2] By breaking up the loop between grates, ac pulsed losses and stresses would be lower than in the actively cooled design.
- [3] A much higher degree of erosion would be permissible before failure, probably several centimeters.
- [4] Differential erosion would tend to limit accelerated erosion due to hot spots.
- [5] The topology for radiative cooling is much better than that of the cigarette limiters, being somewhat better than an infinite plane radiating on both sides.
- [6] If the armor is a low Z material such as graphite, it is possible to conceive of a limiter made of a high

thermal conductivity, high Z material, such as molybdenum or copper, which becomes sufficiently coated with graphite to avoid self-sputtering avalanche without requiring anomalously low edge temperatures.

[7] Since the rod is simply supported on only one end, thermal stresses should be low.

A combined active-passive system, as shown in Figure 7, should have a lifetime nearly equal to that of the sum of a passive system's and an active system's lifetime, individually. The hollow rods in the figure are actively cooled, until the first rod in a header grouping leaks. After that, the first coolant channel is valved off and the farther channel is valved on. All the rods in a header grouping are then passively cooled, until the integrated system erosion has become too high for adequate plasma pumping. The erosion rate of the actively cooled system is expected to be lower than that of the passively cooled system, since evaporation will be negligible and sputtering will be unenhanced by high temperatures. When a rod begins to leak, total erosion should be very small in comparison with allowable erosion of a passive system, so the overall lifetime should be close to the sum of the lifetimes of each approach.

The grating concept defined above shares the advantage with the FED limiter concept that pumping speed can be traded off against heat flux *in situ* by moving the plasma up and down. An alternative concept would be to sacrifice some of this flexibility by placing gratings on the top, as well as the bottom of the reactor, spreading the heat flux and doubling the achievable pumping speed. It would then require a change in the plasma shape to trade pumping speed vs. heat flux. A third alternative would be to remove the grating altogether. The sewer limiter concept is topologically similar to the Doublet III expanded boundary experiment and, perhaps, represents the practical embodiment of the helium pumping concept demonstrated by that experiment [DE81]. A continuum of concepts, ranging from a completely open throat to a close-packed grating, could be tested in Doublet III to elucidate the trade-offs between pumping effectiveness, neutral pressure, helium enrichment and heat flux concentration. Once the design principles are better understood, the grating concept also can trade off pumping speed vs. neutral particle concentration, by selection of the distance between grating rods.

Carbon cloth armor

Armor has traditionally been designed as flat plates, breaking the first wall into modules following the contours of the supporting vessel. The previously-identified topological advantages of a structure that is long in the radial direction and short in the toroidal direction suggests other topologies, such as cigarette and slow wave limiters. However, since the purpose of breaking the limiter up is not only to diminish forces, but to diminish the stresses due to those forces and prevent an armor piece from being torn from its supports, the possibility of a flexible structure that is free to deflect is suggested.

The possibility of using carbon cloth as protection for the first wall was suggested by Kulcinski in the UWMAK II study [KU75]. Two problems were identified in the study: outgassing and swelling. A third problem, poor thermal conductivity, was not limiting under the assumptions of the UWMAK II study, but was investigated at more length by McDonnell-Douglas [FI76]. The results of these studies were that the outgassing of carbon cloth may not be excessive and must be determined by in-reactor experiments. Thermal conductivity was found to be poor, in comparison with bulk graphites or metals, and neutron swelling was high in comparison with bulk graphites.

Neutron swelling of carbon cloth is very high in certain weaves [GR77], leading to the rejection of carbon

cloth by some investigators. For example, after an irradiation of 7.3×10^{21} n/cm² the axial shrinkage of a Thornel-50 fiber was 20 %. However, other fibres, such as C-20, had diameter changes of no higher than 4.0 % over a neutron irradiation of 10×10^{21} /cm². According to Gray [GR77], none of the irradiated cloths with two-dimensional weaves were mechanically damaged by the shrinkage, although cloth with a three-dimensional weave deteriorated substantially. An irradiation of 10×10^{21} corresponds to a neutron wall-loading of 1 MW-yr/m², which is not considered to be an adequate lifetime for a first-wall by those who rejected carbon cloth because of excessive swelling. However, it is far greater than the limiter replacement time calculated by investigators including the effects of erosion in their designs. For example, the FED blade limiter was calculated to require replacement after 0.05 MW-yr/m² [ST81A].

The most serious problem of attempting to design simultaneously for long length (high wall clearance) and high heat loading using carbon cloth is its poor thermal conductivity. The thermal conductivities reported by Fival et al [FI76] ranged from 25 W/m-C for a rigidized T-50 fiber along the axial direction to 0.8 W/m-C for a nonrigidized fiber along the transverse direction at 1300 C. By contrast, at 1300 C, the thermal conductivity of ATJ graphite was reported to be 40 W/m-C and the conductivity of pyrolytic A-B was 80 W/m-C. A heat flux of 1 kW/cm² on the tip of a rod or hanging cloth with an axial conductivity of 25 W/m-C, would only permit a rod length of 2.5 mm for a 1000 C rise. Thus, the cloths tested cannot provide a long life against erosion, unless effective cooling can be provided entirely by radiation. The existence of high erosion rates in carbon has been inferred in PLT [CO80], where 0.2 mm grooves were completely erased in less than 3 burn hours. Although net erosion is a strong function of material and edge temperature, the use of carbon as a limiter material in a high duty cycle reactor appears to be strongly limited by erosion unless the distance from the first coolant channel can be high, either by radiation cooling or using a higher thermal conductivity grade of graphite, along with favorable scaling of long-term erosion and redeposition rates.

Higher thermal conductivity graphite cloths than those reported in the above studies are available. Union Carbide has manufactured a cloth with a room temperature conductivity of 180 W/m-C (VC01-41, now discontinued), and can modify their most popular carbon cloth (VCB-45) to obtain this conductivity [TO81]. A special yarn with conductivity equal to that of copper at room temperature (390 W/m-C) has been manufactured in small quantities. The higher thermal conductivity yarns are more brittle and more expensive than the VCB-45 standard cloth. For example, VC01-41, with half the conductivity of copper, would cost about \$100/lb, while the graphite yarn with the full conductivity of copper would cost about \$1,000 /lb in small quantities or \$400 /lb for a 100 ton order [TO81]. In order to achieve higher overall conductivities, special yarns can be used with a weave in one direction from the plasma edge to the coolant. These weaves can also be bound with phenolic and carbonized, forming a carbon paper. There is thus an almost continuous tradeoff between thermal conductivity on the one hand, and ductility, overall resistance to tearing and cost on the other. This tradeoff can only be resolved by in-reactor testing.

Conclusions

- Certain qualities can be identified for first-wall topologies and materials that are known to be desirable, without a detailed knowledge of the load.
- Desirable topological features include redundancy, maintainability, clearance, small toroidal size, vacuum

integrity and renewability.

- Overall system economies could be achieved by unifying the design of the vacuum, exhaust and heating systems.

- A novel "sewer" limiter design has been proposed with several features promoting the possibility of higher limiter longevity.

- Flexible armor may be achieved through the use of carbon cloth or paper.

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Appendix A: Existence of Electron Cyclotron Resonance Breakdown in Unpressurized Waveguides

Unpressurized waveguides may have worse power transmitting capabilities than pressurized waveguides. In particular, it has been suggested that if the electron cyclotron resonance layer in a waveguide is not pressurized that the power handling capability of the waveguide will be severely reduced. It is well known that air or SF₆ at one atmosphere or higher will indeed have better dielectric strength than partially ionized hydrogen at medium vacuum. However, as soon as a wave passes through a window, it will be in hydrogen at medium vacuum even in the extreme case of the window butted against the plasma scrape-off layer. Therefore, the real question is whether windows remote from the plasma-first wall interface perform better or worse than windows close to the interface. From every point of view other than instantaneous electrical breakdown – thermal stresses, neutron damage, coating of the window by sputtered particles – it is clear that it is better to have the window relatively far from the plasma and preferably behind a bend. If electrical breakdown can be shown to occur at higher fields when the window is close to the plasma, then window placement involves a difficult tradeoff. If electrical breakdown can be shown to be lower when the window is close to the plasma or simply indifferent, then the window should be placed far from the plasma.

The lower hybrid wave windows in Alcator A have achieved higher power transmission densities than any other rf windows in tokamaks. The first waveguide type that was tried was an Al₂O₃ window, removed from the plasma and behind a bend [SC81A]. Up to 4 to 4.5 kW/cm² of power transmission was achieved. At 4.5 kW/cm², however, symptoms of near breakdown conditions, such as a rising reflection coefficient, were observed. The power transmitted through 2 waveguides was limited to 90 kW by the available klystron ratings. The ECRH layer was in vacuum, and the lower hybrid ducts did not have a separate pumping system.

In a second set of experiments, the Al₂O₃ windows were only 2 " away from the plasma and the ECRH layer was pressurized. In the early phase of these experiments, the power was worked up to 90 kW through 2 waveguides, for an average power density of 4.5 kW/cm². At this power density, a plasma disruption caused a 15 ms arc across one of the windows at a power density of 4.5 kW/cm². The long, destructive nature of this arc was caused by an incorrectly wired arc detection diode, and did not represent a fundamental limit on power handling ability, as shown by later experiments discussed below. Braze material migrated across the window. It was suggested that sputtering of first wall material onto the window had created the breakdown path; however, a postmortem by Varian, the manufacturer, indicated that this was not the case and that the surface of the undamaged window was clean of first wall material. The damaged window had braze material, stainless steel (first wall) and molybdenum (limiter) on it, but the cleanliness of the undamaged window suggests that it was all deposited during the arc. (This does not mean that the proposed failure mechanism cannot happen for fusion reactors with three to four orders of magnitude higher integrated sputtering deposition.) The breakdown was presumably initiated by the change of plasma conditions during the disruption causing a high VSWR at the window. The damaged window was ultimately conditioned back to 90 kW, representing a transmitted power density of 8 kW/cm² through a single wave guide, far in excess of the achieved power density in other machines. Schuss [SC80] believes that no other machine has achieved much better than 1 kW/cm². The power density of 8 kW/cm² represents an rf electric field of 5.5 kV/cm².

The experience on Alcator A suggests that one might be able to achieve something like twice the power

density with the window close to the plasma as with it behind the ECRH layer. However, several qualifying statements have to be added to such a conclusion. There is no evidence to tie the breakdown in the first set of experiments with the ECRH layer. The waveguides were unevacuated, except by the main torus vacuum system and may have had significant neutral pressures at high plasma density. Overskei [OV81] reported a neutral pressure rise of 3×10^{-2} torr in limiter-pumped ports and 3×10^{-3} torr in non-limiter ports at the highest plasma densities in Alcator A. The Alcator A rf waveguides did not have pressure gauges, so the possible incipient breakdown at 4.5 kW/cm^2 cannot be distinguished from multipactor or even Passchen breakdown. Furthermore, 4.5 kW/cm^2 is considerably more than one needs or is likely to specify for a commercial reactor, which should have sufficient space for heating at 1 kW/cm^2 , and is likely to specify lower than state of the art power densities for the sake of system reliability. Finally, achievable power densities at beginning of life should be distinguished from achievable power densities at end of life. Fogging due to sputtering or power density limitations due to thermal fatigue and neutron swelling crack growth will all lead to lower power densities in a window close to the plasma.

The six waveguide, lower hybrid wave launching system in Versator transmits power to the plasma at a density up to 0.5 kW/cm^2 [LU81]. Each waveguide is 0.85 cm wide by 25.4 cm high; the launching frequency is 800 MHz [PO80]. The rf window of Versator is removed by a meter from the plasma and is behind a bend in the waveguide. The total launching power is limited to 150 kW by the rating of the klystron driving the launching system. Bakeout of the stainless steel grill at 350 C, frequent rf processing and occasional titanium coating are used to enable pulses of up to 50 kW total power. There is evidence that plasma forms in the waveguides at rf power levels above those used in the above experiments. It is my understanding that there is no conclusive evidence that ECRH breakdown is a factor. Evidence of breakdown, such as arc tracks in the waveguide, occur at the waveguide mouth, not at the electron cyclotron resonance layer. The waveguide mouth, however, tapers toward the plasma so the maximum electric field is not at the ECRH layer.

The waveguide is evacuated through a microwave screen in front of the window. When this evacuation is on, the pressure in the waveguide is reduced by about a factor of two. However, experimenters on Versator have frequently not used this vacuum system, since the main vacuum pumps have been adequate. The pressure in the waveguide is about 10^{-4} torr, pumping only through the main vessel pumps, and about 5×10^{-5} torr with the waveguide pumping system on.

RF heating experiments at the Princeton Plasma Physics Laboratory have been influenced strongly by early experiences on ATC, according to Hooke [HO81]. In a relatively dirty system, with the windows far removed from the plasma, breakdown occurred frequently at low power levels. A quick fix, involving removing the distant windows and placing a piece of teflon at the mouth of the waveguide was successful in improving the rf power density into the plasma. Since that experiment, Princeton has designed rf launchers with the ECRH layer pressurized. However, the waveguides in question on ATC were not inspected to determine where breakdown was taking place. While Hooke believes that Passchen breakdown is not likely, breakdown may well have been due to multipactor rather than ECRH breakdown.

Experiments on PLT with lower hybrid waveguide launchers have achieved 50 kW per waveguide from 4 waveguides on good days. 25 kW per waveguide is more typical. Typically, the reflection coefficient from

the plasma is about 5 % at low power, rising to 30 % above 25 kW. On good days the reflected power is still about 30 % at 50 kW, while on typical days there is no additional power transmitted to the plasma at 50 kW than at 25 kW. The individual wave guide dimensions are 22 cm x 3.5 cm, so 25 kW corresponds to about 0.3 kW/cm². This is not a debugged system, and Hooke hopes that the original aims of 200 kW/waveguide can still be obtained. 400 kW per waveguide has been obtained on the testbench. This, however, is an indication that pressurizing the waveguides, by itself, is no guarantee of high power density. One possible limitation is that the waveguide mouths are flat and close to the limiter, and there is a fairly large neutral flux and a large toroidally streaming flux of charged particles against the mouth of the waveguide. It is hoped that this situation will be ameliorated by replacing the current waveguides with toroidally shaped waveguides.

Hooke argues that there are no fundamental limitations at this power density. JFT-II has 4 waveguides of similar size and frequency and has transmitted 300 kW, or 75 kW per waveguide, with little problem. JAERI is planning to upgrade this system to 700-800 kW. The JFT-II system has the windows behind the ECRF layer and pumps differentially on the waveguide through a microwave screen. JFT-II also employs titanium gettering.

Hooke believes in the existence of ECRF breakdown [HO81], and says he has even observed it for ICRF heating. However, he also believes that the cleanliness of the system is more important than pressurizing the waveguide. The experimental evidence either way, as reviewed in this survey, is inconclusive on this point. Given the obvious benefits in ease of assembly and expected window lifetime of remote window mounting, remote mounting is strongly indicated for next step tokamak reactors.

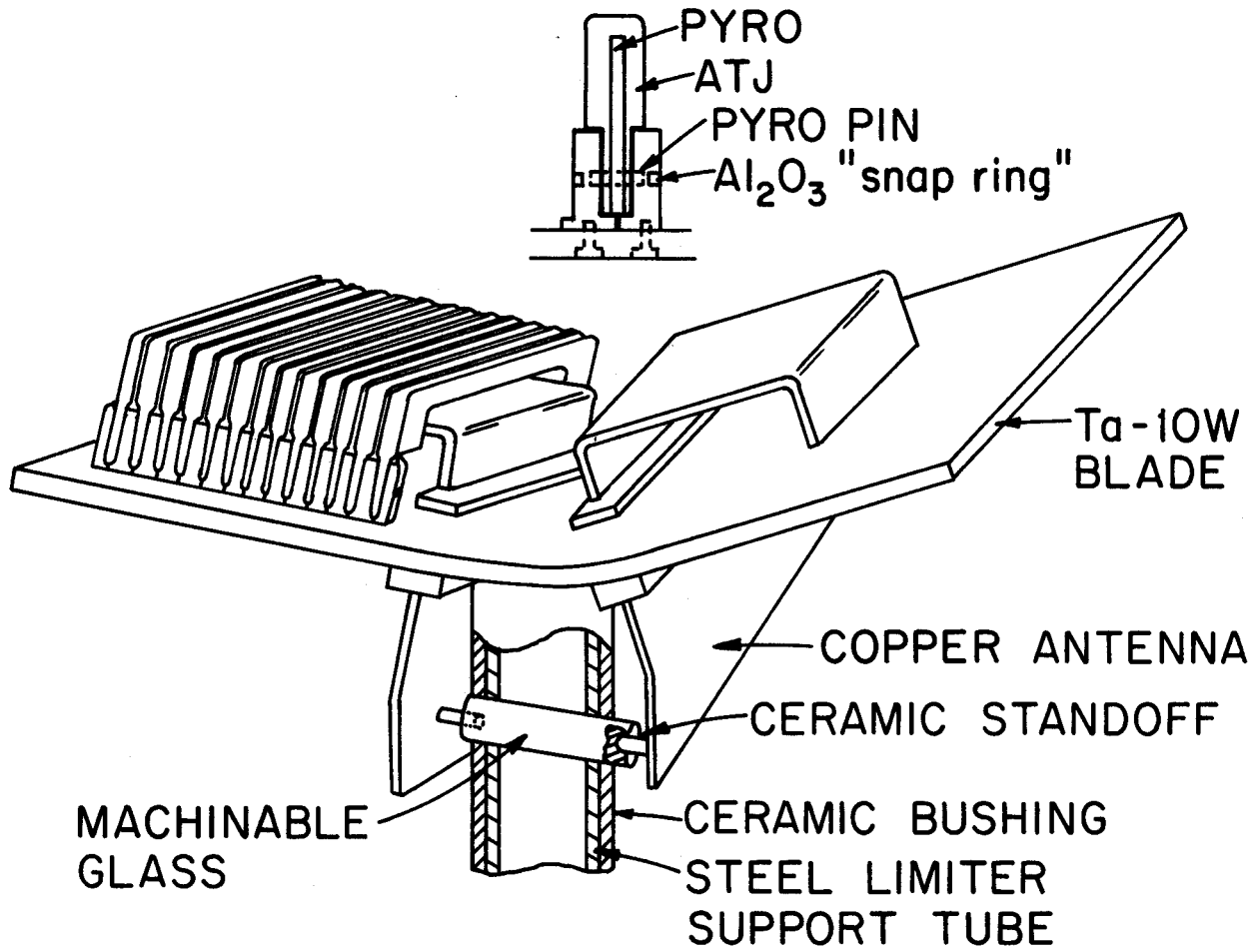


Figure 1
 A Faraday - Cage Limiter, Dipole Antenna
 and a Ground Plane Pump

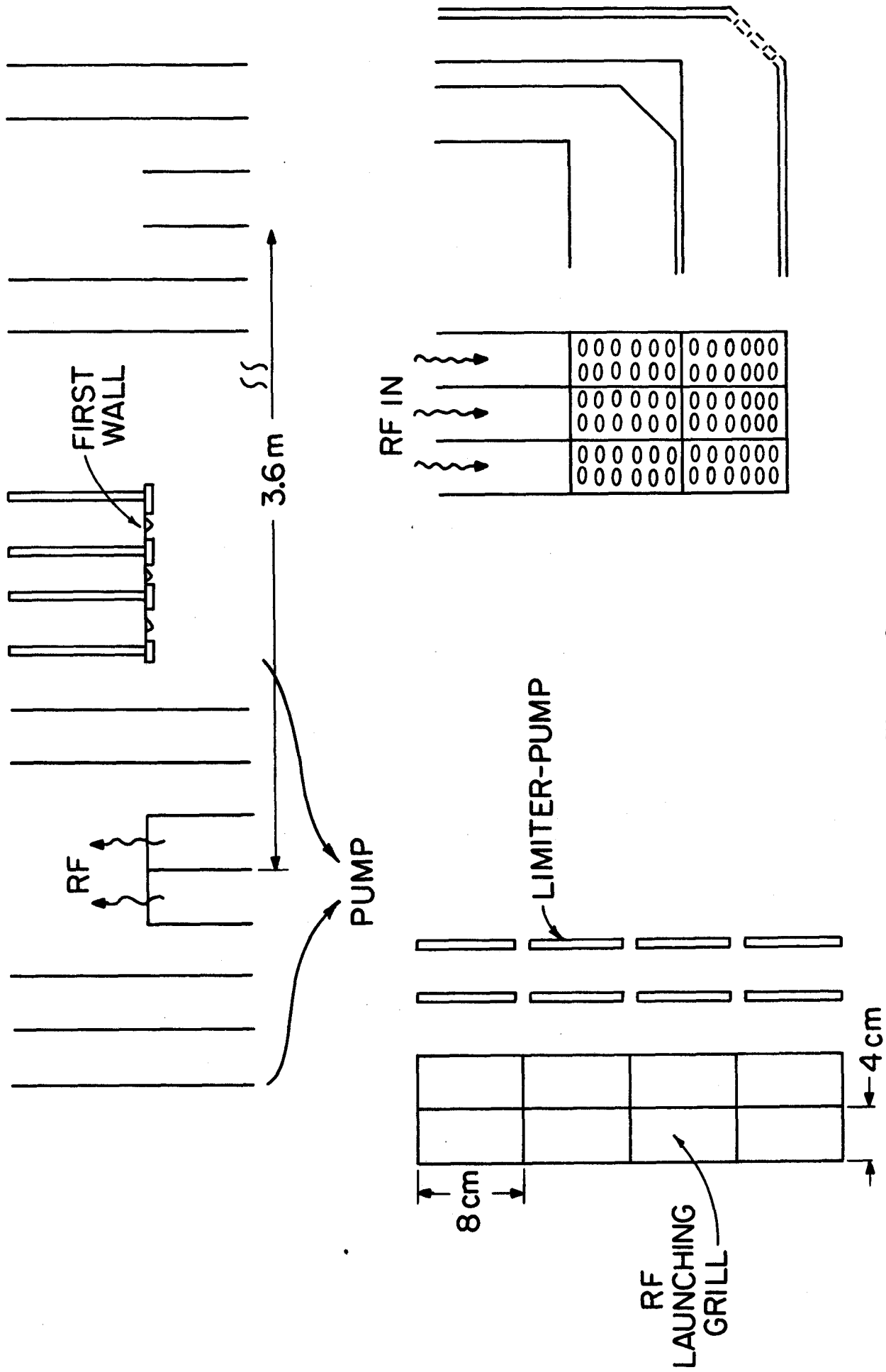


Figure 2
 A Slow-Wave Limiter with a Lower Hybrid Wave Launching Vacuum Pump

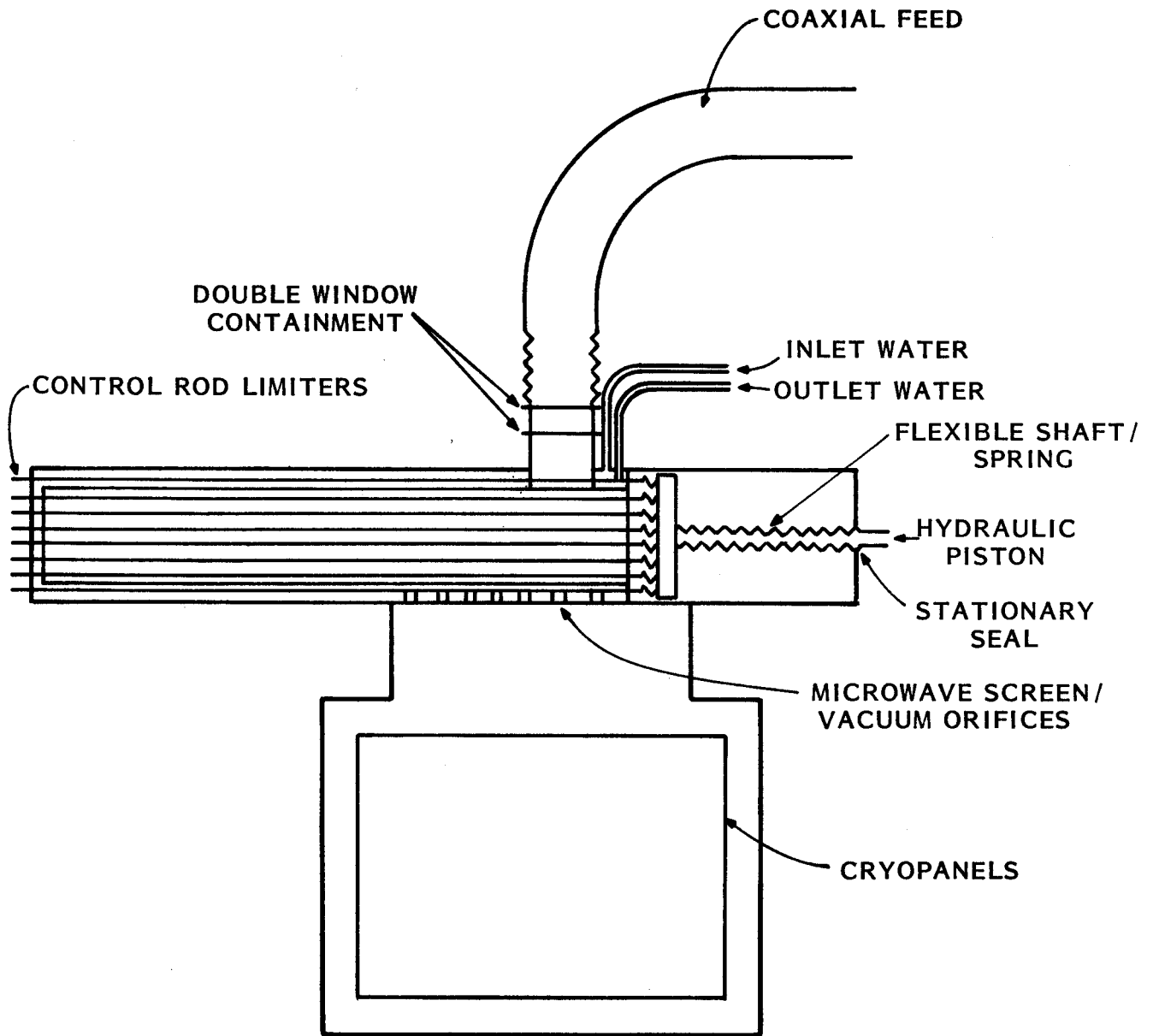


Figure 3
A Control-Rod Limiter

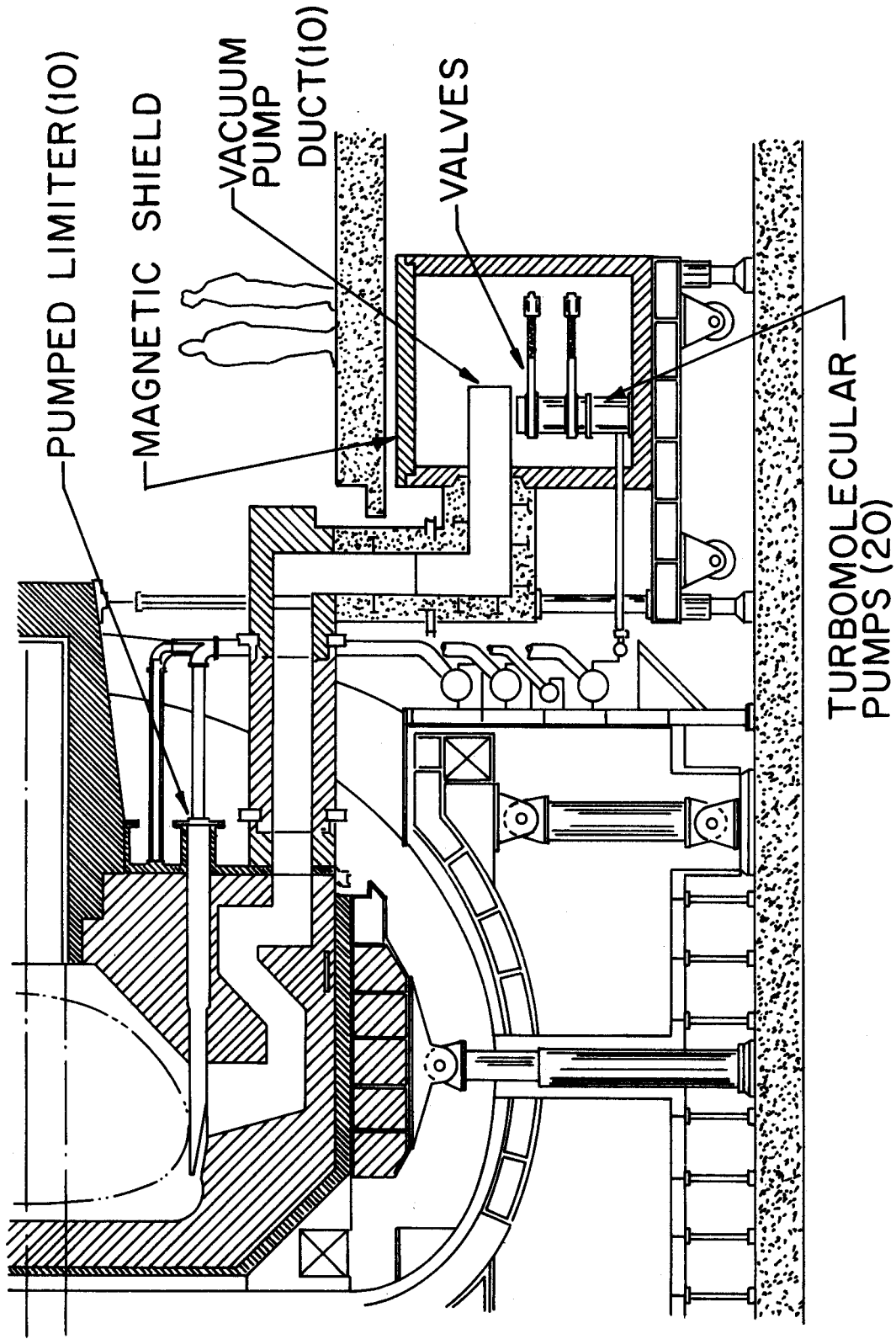


Figure 4
 Limiter Pumping System for FED
 (courtesy of Fusion Engineering Design Center)

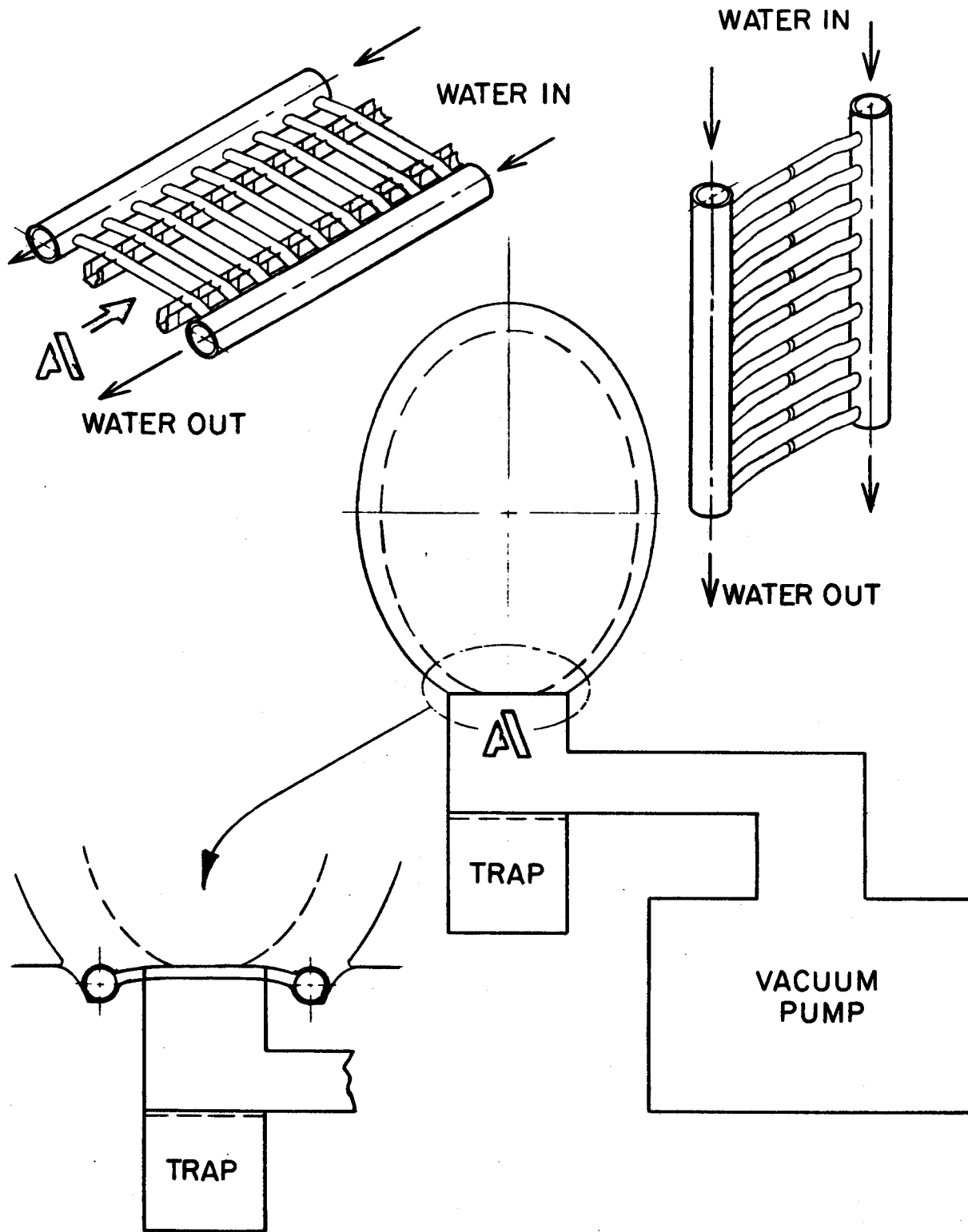


Figure 5
Sewer Limiters:Two Configurations

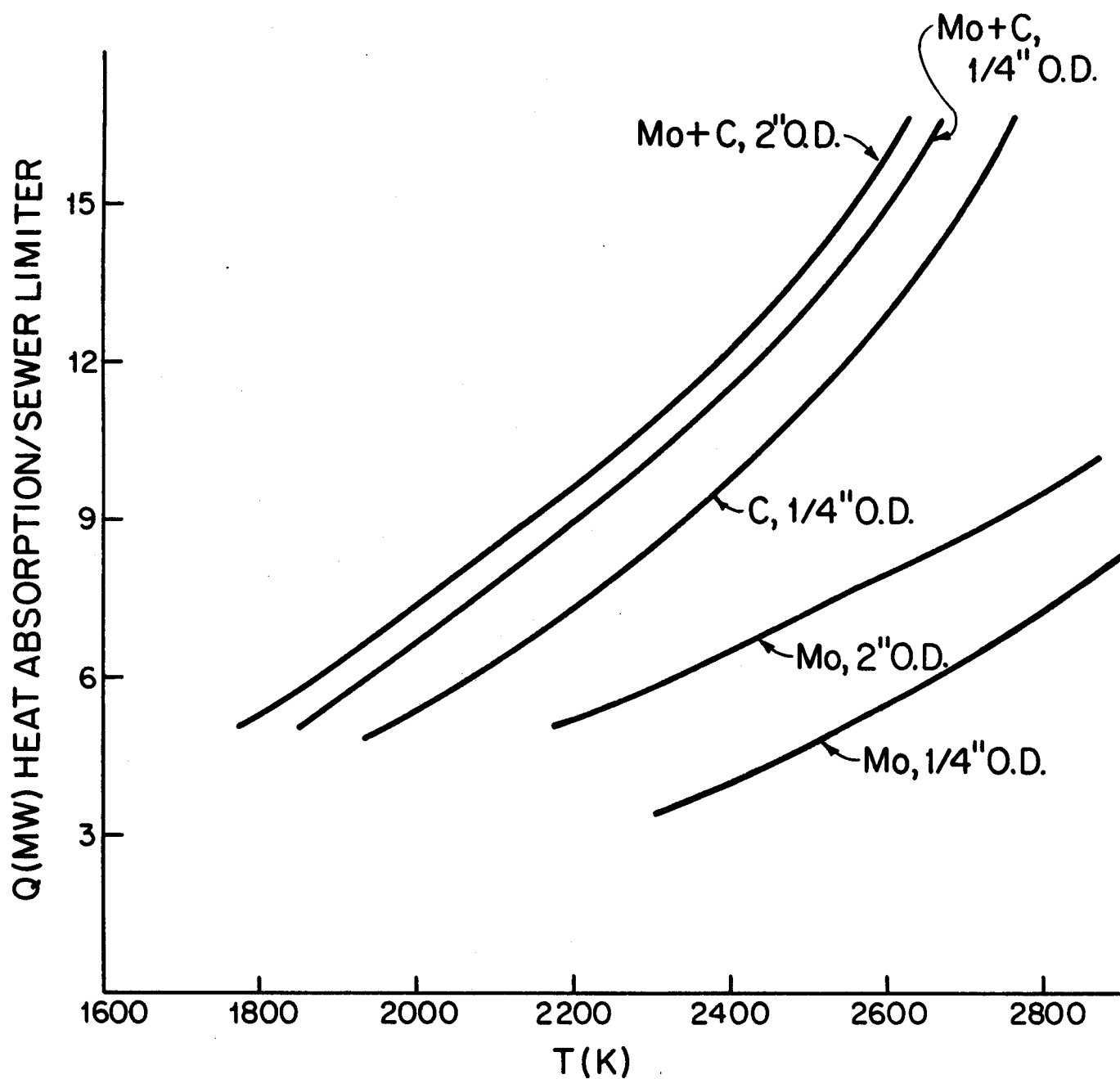


Figure 6

Heat Absorption Capability of Toroidal Limiter Grids (20 cm \times 6.0 M Major Radius) vs Peak Temperature for Carbon, Molybdenum, and Carbon-coated Molybdenum Rods with 1/4" and 2.0" Diameters.

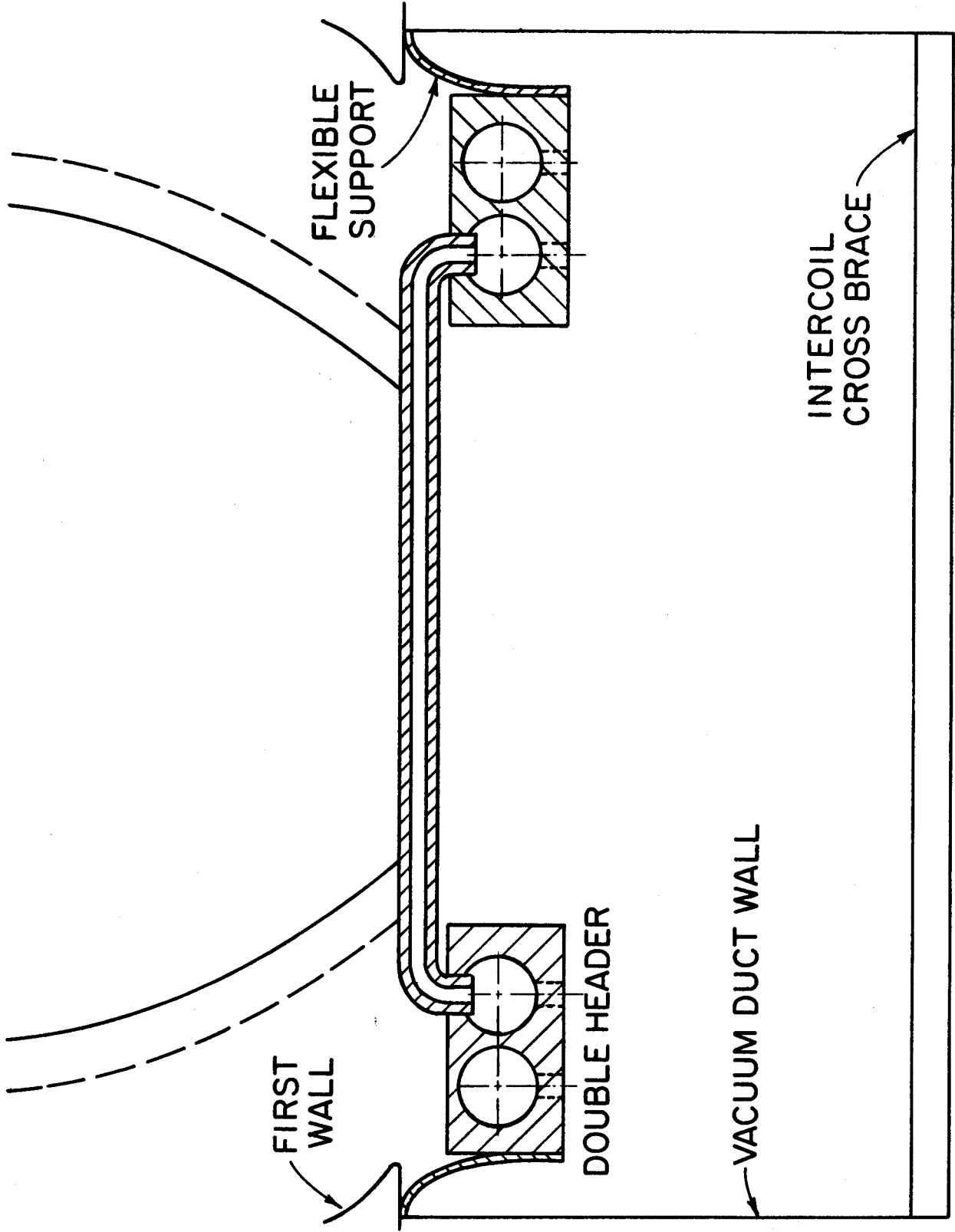


Figure 7
Active-Passive Cooled Limiter Tube

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