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Novel Limiter Pump Topologies

by

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Novel Limiter Pump Topologies*

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ABSTRACT

The use of limiter pumps as the principle plasma exhaust system of a magnetic confinement fusion device promises significant simplification, when compared to previously investigating divertor based systems. Further simplifications, such as the integration of the exhaust system with a radio frequency heating system and with the main reactor shield and structure are investigated below.

The integrity of limiters in a reactor environment is threatened by many mechanisms, the most severe of which may be erosion by sputtering. Two novel topologies are suggested which allow high erosion without limiter failure.

Novel Limiter Pump Topologies

by Joel H. Schultz

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The availability of tokamak fusion reactors will be a strong function of the integrity of the limiter or other first material surfaces in direct contact with the plasma. The lifetime limitations of the first surface are due to physical and chemical sputtering, arcing, thermal cycling and electromagnetic loads and are accelerated by very frequently occurring fault modes of operation, including disruptions, electron runaway, ion ripple losses and plasma position offset, especially during heating. The fundamental limitations on any material exposed to all of these failure mechanisms simultaneously appear to be more severe than those on any other single subsystem of the reactor, including the blanket and shield walls. Various schemes such as magnetic divertors or ergodic field coils have been proposed to alleviate some of the failure modes. However, all of these techniques add a certain amount of additional complexity to the tokamak reactor. Unfortunately, there is also a widely held belief that tokamak reactors are already too complex and costly to be competitive with other forms of electric power. Recent experimental successes tending to confirm the validity of the suggestion that limiter pumping be used as the dominant plasma exhaust mechanism could lead to a significant reduction in reactor complexity and cost. However, limiter pumps may then become the weak link in reactor availability. We will investigate whether further topological simplifications can be achieved with limiter pumps of reasonable structural integrity, while retaining the perceived benefits of a limiter pumping system.

The novel concepts reported here are concentrated in the area of integration of the pumping system and an rf launching system including a slow-wave limiter pump, a Faraday cage limiter pump and a resonant cavity limiter pump, and integration of the pumping system and the magnet support system, including a Brambilla grill torque frame. The more fundamental problem of limiter reliability is addressed by a single cigarette limiter concept and, to a lesser degree, by the slow-wave limiter. Finally, a long-life, control rod limiter will be introduced as an adjunct to an ICRF waveguide launcher.

(A) Integration of Limiter Pumping and RF Launching

Almost all of the radio frequency wave launching structures that have been proposed for use in a

tokamak reactor can also be used for vacuum pumping. Lower hybrid launching wave guides have been used as vacuum ports on JFT-2 [NA80], while an ECRH cavity on EBT-I served as an overall vacuum plenum. If rf launching ducts and vacuum pumping ducts are entirely common, then there will be no large holes in the system, other than the vacuum ducts. This will be a significant aid to pumping design, increasing the designer's knowledge of where the gas is, as well as limiting inventories of recycling tritium and helium. The elimination of separate rf heating ducts will also make neutron and radiation shielding considerably easier by making the torus less porous. Perhaps an improvement on the order of 2 could be expected. The elimination of separate ducts should also permit better coverage of available space with blanket modules. While this might have a significant, but only second order (< 10 %) effect on the total electrical output of the reactor, it might make the critical difference in whether the reactor can achieve net tritium breeding.

To make the rf launching structure common with the limiter has never been done successfully to the best of our knowledge, because of the problems associated with rf breakdown and gas evolution from the ceramic structures associated with rf launchers. Three alternative topologies can be suggested that have no ceramic structure in contact with the plasma and no more severe electrical field breakdown problems than the original rf launching concept without a limiter.

The NUWMAK demonstration reactor design [SC78] suggested the possible use of a resonant cavity antenna, as shown in Figure 1. If the cavity were pushed out from the wall toward the plasma and were protected by carbon armor, the resonant cavity box would also be a limiter. If somewhat smaller holes were drilled in the rear of the box, separate from the coaxial input feeds, the box could also be part of the vacuum pumping system. This system, having about 1/3 of its holes along field lines, with considerable freedom in selecting the aspect ratio of the holes, could probably achieve the high neutral gas concentrations demonstrated in the plasma probe experiments of Taylor [TA80] and Jacobson [JA80]. However, because of the double layer of leakage holes in box and the armor, as well as the rf shield vacuum pumping holes in rear of the box, the structure would probably not be as effective an rf launcher as the original NUWMAK concept. Electromagnetic forces during disruption would be high, especially on the front, top and bottom faces of the box, although internal bracing could make the box considerably stronger against electromechanical forces than conventional limiter concepts.

A variant on an ICRF antenna concept, proposed recently by Colestock [CO80] for ETE, is shown in

Figure 2. In this case, the majority of the charged particles are intercepted by a graphite Faraday cage. The ground blade of the limiter/antenna is curved in the familiar Schivell shovel topology to enhance pumping of the significant remaining fraction of charged particles. Overall limiter pumping performance in this concept should be very similar to that of the STARFIRE design. The bottom of the blade is actively cooled, but sufficient protection is provided by the Faraday limiter to prevent rapid erosion of the rear surface or self-sputtering avalanche.

The Faraday cage limiter consists of two grades of graphite: ATJ or POCO for interaction with the plasma and pyrolytic graphite for better heat conduction to the base. This concept originates with Colestock and may or may not be a favorable trade vs. using ATJ alone and limiting differential expansion stresses. The cage pieces are attached to the shielded ceramic base by pins, in order to allow a high degree of thermal and neutron swelling expansion without generating high stresses. The pins might be prevented from escaping the cage by ceramic snap-rings on the ends. As can be seen from Figure 2, a high degree of clearance from the limiter support post can be provided by machinable glass bushings. Electric fields in this region can be designed to well under 1 kV/cm. ICRF antenna experiments on TFR [AD81] have recently reported no breakdown with 17 kV applied to a 6 mm vacuum gap. Almost all of the tokamak heating shots, using this antenna were completed without interruption [AD81]. For the above topology, I believe that arcing is more likely between the Faraday cage and the plasma, irrespective of whether the duct is used as a vacuum pump.

The antenna limiter pump concept has several disadvantages which are common to the antenna itself. There are several ceramic-metal, ceramic-graphite interfaces and the ceramic is a structural member with respect to the graphite limiter. Therefore, eventual life limitation due to neutron ceramic swelling induced crack growth can be expected. Also, the broad ground blade of the limiter is not well suited to support eddy current loads during disruption.

The most unique concept for a combined rf launcher and limiter pump, called a "slow-wave limiter", is shown in Figure 3. This concept is attractive because of the favorable synergistic effects of the topology. The limiter blades enhance launching of the lower hybrid waves into the plasma and enhance pumping of the plasma by the launching grill. The limiter blades themselves are tall enough to provide significant protection to the rest of the first wall and even have a limited degree of redundancy, so that a mechanical failure of a single limiter does not necessarily dictate a system shutdown.

The ideal height of a slow-wave structure bordering a lower hybrid wave launching grill is a half wavelength at a distance of π/b from the mouth of the waveguide. This can have a significant effect on the harmonic content of the wave launched into the plasma, as shown by Shcherbinin [SH79] and Schuss [SC79]. For the frequencies typical of lower hybrid wave launching, this ideal height is usually also a reasonable height for a passively cooled limiter blade. For example, for the FED plasma with a central electron density of $1.1 \times 10^{20} \text{ m}^{-3}$ and central electron and ion temperatures of 15 keV, a good lower hybrid launching frequency (radians/s) for central absorption is

$$\omega = \sqrt{\frac{\omega_{pi}^2(1 + 2n_z\sqrt{(\frac{m_i}{m_e})aT})}{(1 + \frac{\omega_{pi}^2}{(\Omega_{ce}\Omega_{ci})})}} \quad (1)$$

where a_T is a thermal correction factor given by

$$a_T = 3\left(\frac{\omega_{pi}}{\omega}\right)^2\left(\frac{kT_{io}}{(m_i c^2)}\right) + 0.75\left(\frac{\omega_{pi}\omega}{(\Omega_{ce}\Omega_{ci})}\right)^2\left(\frac{kT_{ee}}{(m_i c^2)}\right) \quad (2)$$

ω_{pi} , Ω_{ci} and Ω_{ce} are the ion plasma frequency and the ion and electron cyclotron frequencies, respectively (radians/s). The parallel wave index n_z at the center is determined self-consistently by considering scattering effects at the plasma edge and is typically on the order of 5.

The above values of FED parameters give a desired launching frequency of 1.56 GHz and an ideal vane height of 9.6 cm. This scrape-off structural distance is typical of what has been proposed for tokamak reactors. Furthermore, since the vane will be relatively effective as part of a slow-wave structure down to a height of 1/4 wave length, about 5 cm of erosion is permissible, which is considerably higher than what has been permitted in previous designs. The effectiveness of the vanes down to a quarter wavelength is indicated by Motley's experiments on the H-1 plasma, which showed a three-fold reduction in the fast-wave component, adding four passive quarter-wave vanes to a two waveguide system [MO80].

Since each grill structure might be something like a 6×6 array with 10 launching ports, as shown in Figure 4, there would be a 120-fold redundancy in case of the failure of a single vane. Since each vane is passively cooled, even a gross failure, such as cracking and falling to the bottom of the vacuum vessel might be tolerable. The current limiter design for FED [CR81] shows an attractive topology in which the bottom surface of the reactor might include a series of easily extracted horizontal trays that could catch failed pieces and be periodically cleaned or replaced.

Pumping experiments on Alcator A [OV80] demonstrated that a limiter pump does not have to have anything remotely resembling an ideal Schivell or STARFIRE topology in order to bat a significant fraction of the charged particles in a plasma into a pumping duct. The slow-wave limiter pump acts as a back-stop that knocks charged particles into a pumping duct on one side. A critical trade-off requires more analysis, involving the effectiveness of the limiters as a particle bat, which favors a small number of limiter vanes, one layer on each side of each grill being the ideal, and the effectiveness of the limiters as a slow-wave structure. An infinite series of limiter vanes at 1/2 wave intervals is the ideal for the slow-wave structure, and limiter vanes across the entire poloidal and toroidal extent of the vacuum vessel are the ideal for sharing the plasma heat along a high surface-area structure.

The slow-wave limiter is also very well suited for handling thermal and electromagnetic loads. The broad face of the vane links only the paramagnetic or diamagnetic flux from the plasma poloidal currents. The vane is free to deflect, unconstrained, in the toroidal direction, allowing stress-free response to the dominant minor radial temperature gradients. The thermal gradients in the vane limiter are similar to those in the cigarette limiter, discussed in more detail below.

A possible pumping system configuration is shown in Figure 5. The bends in the waveguide are staggered, so that the orifices of the microwave screen can conduct gas into a common high speed vacuum pumping plenum. A possible problem with this pumping system is that the gas conductivity of the lower hybrid ducts is low, compared with previous limiter pumping concepts. Using the same FED example as above, a conservative specification of rf power transmission of 0.7 kW/cm^2 of absorbed power, as many as 810 waveguides would be required by the lower hybrid launching system. This large number of waveguides would be favorable for window and waveguide integrity, as well as for the vacuum pumping speed. If 50 m^2 of cryocondenser/cryosorber panels are used, the helium pressure at the pump, the microwave screen orifices and the waveguide mouth are listed in Figure 6. The helium pressure of 0.5 Pa at the waveguide mouth is too high. The high pressure drop along the ducts is attributable to the gas entering the viscous regime between the orifices and the waveguide mouth. In this regime, the fourth-order dependence of gas conductance on the effective diameter of the waveguide ducts imposes a large penalty on the long and narrow lower hybrid launching structure. However, no credit was taken for gas plugging by suprathermal particle flow, which appears to be the dominant flow phenomenon in the abovementioned recent experiments in limiter pumping.

If the outer two columns of waveguides are replaced by empty ducts, with appropriate tapers from the mouth of the waveguide to the open section, such that the mouth region is still an open-circuit passive resonator, the gas conductance of the grill can be greatly increased. For the above example, the helium pressure at the mouth of the waveguide decreases to 6×10^{-3} Pa, with the outer two waveguide columns replaced by passive resonators.

(B) Combined Limiter Pumping and Warm Coil Structure

It has generally been recognized that the volume about the outer legs of the toroidal field coils is the most efficient for placement of structure to support out-of-plane loads on those coils. Of the most recent generation of large tokamaks, PLT, PDX and Doublet III all utilize diagonal bracing in this volume as integral parts of the torque frames for their toroidal field magnet systems. Recent design studies by the ETF Design Center, reported at the July Interim Design Review, reported that supporting the coils through cryogenically shrouded shear panels, enclosed within a large common dewar for the toroidal field coil system, led to ease thickness requirements around the outer coil legs which stretched the manufacturing capability of domestic steel companies and dictated low operating stresses, because of the large plate thicknesses required.

A recent TF system structural support study by Tracey (unpublished work by MIT for the ETF Design Center) indicated that a 150 MN load could be taken out to warm structure through a column of G-10 pads with a heat leak of only 12.5 W. Conversely, the severe problems encountered by the TFTR group in installing the last TF coil shear panel, in the face of accumulated tolerance errors could only be compounded by attempting to perform the same task within a cryogenic dewar. Therefore, it may be a good idea to take a fresh look at the use of torque frames or, more specifically, warm structure diagonal bracing, in the TF outer leg area.

Even if the refrigeration load does not preclude the use of warm shear panels or torque frames, it has generally been perceived that shear panels on the top and bottom of the coils are preferred, because of the need to provide access for auxiliary heating, diagnostics and shield and blanket removal. However, it has always been recognized that auxiliary heating structures would have to be removed, before blanket and shield modules could be removed. If the auxiliary heating and vacuum pumping support structures were identical with the warm torque frame and could be assembled with simple, unwelded connections, there would

be a decrease in reactor complexity, without an increase in reactor assembly/disassembly time. A possible configuration of this nature is shown in Figures 7 and 8.

The lower hybrid wave grid is unique among auxiliary heaters, in that it is able to contain a substantial amount of internal structure. In Figure 7, the horizontal shelves of the grid structure are portrayed as being moderately thick. The vertical septa are more restricted, because of the effect of interwaveguide spacing on the spectrum of the launched wave. However, depending on the degree of randomization of wave phasing caused by scattering at the plasma edge, it might be unharful to overall coupling efficiency to have, for example, a thick vertical piece in the center of the grill. An internal lattice structure is even less constrained in vacuum pumping ducts that do not have to transmit rf power and could better optimize other requirements of strength vs. weight and accessibility.

For ICRF launching structures, whether they are antennae, coaxial cables or waveguides, there could not be any internal structure, but they could still have a strengthened case as the linch-pin of the diagonal bracing structure. Since all rf structures and vacuum ports would require a moderately thin gravitational support structure and a moderately thick neutron shield, the torque-carrying case might not even add any additional steel to that already required. For example, if an average running load of 10 MN/m on the outside legs of the coil were taken out across an 8 m span [HO80], entirely through a warm torque structure, and the moment-free beams about the case were limited to compressive and tensile stress of 150 MPa, each of the eight beams between a pair of coils would require a cross-sectional area of 0.13 m^2 . If it is desired to keep the thickness of all structural plates below 3 inches, the compression elements, which can not be finely divided into rods or cables because of buckling, could be constructed of tubes or I-beams. For example, a 3 inch thick tube would require an inner diameter of 10 inches and an I-beam with three equal members would require a length of 20 inches. The sample drawings, taken with ETE dimensions, allow space for either alternative. Neither dimension is as thick as the characteristic thickness of an auxiliary shield, which would be about 70 cm or 30 inches.

(C) Cigarette Limiters for Higher Reliability

Actively cooled first surfaces have fundamental limitations on their lifetimes, because they have an optimum wall thickness for any material. If the material is too thin, its life will be limited by sputtering and

arc-ing erosion. If it is too thick, it will be limited by thermal stresses and crack growth. Another problem with actively cooled first walls is that a single virtual leak of even the most innocuous coolant, e.g. helium, is sufficient to require reactor shutdown for a substantial period of time. Passively cooled first surfaces have the disadvantages that they must run very hot, perhaps enhancing sputtering losses, that design against thermal stresses is very difficult, and that radiative heat losses must ultimately be transferred and removed to actively cooled, albeit better protected, walls.

Radiatively cooled systems such as graphite armor over a fraction of the first wall surface have been proposed for several conceptual designs, including early versions of ETF. This concept has the advantage that a single disruption or unabsorbed neutral beam will not destroy the continuous first wall supporting the armor. For long life operation, it has the disadvantage that only a small amount of erosion is permitted and that if, for example, 3 out of 4 sides of the vacuum vessel are protected by armor, the radiative heat load is all concentrated on the fourth side. A radiatively cooled, cigarette limiter system that permits a high amount of erosion, a low concentration factor for removal of radiant heat and the possibility of gross failure of several limiters without needing to shut down the system is shown in Figures 9 and 10. A similar concept, involving small mushroom-shaped buttons, was recently independently proposed for the Zephyr experiment [KO80].

The high aspect ratio cigarette shape has advantages over the small mushroom shape for a radiatively cooled system because of its higher erosion tolerance, its superior viewing angle of cooled surface and its higher radiating surface area. The mushroom concept shares a possible high degree of redundancy and permits running at lower temperatures through more effective conduction cooling. If most of the vacuum vessel surface is covered with cigarettes, the scrape-off distance should be very low, no more than one poloidal gyroradius. This permits a very high amount of erosion, several centimeters, before the limiter system must be replaced. A unique advantage of the cigarette limiter concept is that it is partially self-correcting against concentration of the plasma heat load. Those cigarettes that have higher heat loads will erode more rapidly, until their heat loads have been reduced to the level of those of their neighbours.

A calculation of the tip temperatures of 100 mm cigarette limiters of molybdenum and ATJ and pyrolytic graphite is shown in Figure 11. The viewing factor of far parts of the reactor for radiative cooling is assumed to equal 0.2, while the viewing factor for the cooled surface in the immediate vicinity of the base of the cigarette is calculated to equal

$$F = \frac{D^2}{4H^2 + D^2} \quad (3)$$

where H is the height of the cigarette and D is twice the distance between cigarettes. The viewing factors for radiative cooling are perhaps overly conservative. However, the curves indicate that radiative cooling is relatively ineffective, despite the large surface area of the cigarettes. The curves also suggest that conductive cooling should be adequate if the height of the cigarettes were reduced by a few centimeters.

(D) Life-of-the-Reactor Control Rod Limiters

If a limiter rod, such as the cigarette limiter, could be continuously fed into the plasma, it would have no theoretical lifetime limitations. This would be similar to the mechanism used successfully in carbon arc lamps for over a century. A series of rods, driven in a manner similar to control rods in a fission reactor, might perform this function. A possible configuration is shown in Figure 12. In this figure, the rods surround a large, rectangular waveguide used for launching ICRF waves into the plasma, such as the $2 \text{ m} \times \frac{1}{2} \text{ m}$ waveguide recommended by General Electric at the ETFR Interim Design Review. The rods also knock particles into the waveguide, enhancing its pumping speed. The rod travel is effected by a hydraulically driven piston, restrained by the spring forces of a hollow, flexible shaft with a stationary end which is the vacuum seal of the control mechanism. An elevation view of the system, as seen from the plasma, is shown in Figure 13.

The principal problem in designing a life-of-the-reactor control rod limiter will be the final sleeve bearing before the limiter rod enters the scrape-off region of the plasma. This must maintain adequate contact for conduction cooling of the rod through the water jackets, while not impeding the travel of the rod, despite neutron and thermal induced swelling. One possibility would be the use of copper multilams, as shown in Figure 13. These were lifetested by Westinghouse (unpublished) in an early stage of the TFTR program for possible use in internal equilibrium field coil joints and survived 400,000 cycles without failure, while maintaining good electrical contact at the joint. Since copper can endure a higher neutron fluence than stainless steel before embrittlement, the multilams should retain their springiness for the life of the first wall. Phosphor bronze multilams might be used to prevent loss of springiness at higher temperatures.

(E) Evaluation of Limiters as RF Launchers

None of the limiter pump concepts above should have a significant effect on the efficiency of rf launching. The dipole antenna limiter is essentially identical to the topology of a nonpumping antenna. The resonant cavity antenna may be harmed by the double layer of holes through the armor and case, but is probably the least interesting of the four limiter-launcher combinations. The rectangular ICRF waveguide should be unaffected by the control rod limiters, which could only support very high order modes of rf electric fields. Only the lower hybrid wave vanes could conceivably have a significant effect of the slow-wave vanes on wave-coupling to the plasma. On reflection, however, I do not expect that effect to be very high. One way to look at it, is that there is little reason to expect that additional vanes would be more helpful than additional waveguides in eliminating unhelpful harmonics in the wave spectrum. The Alcator A waveguides when at their optimum radial position demonstrated only 13 % global reflectivity, with only 2 waveguides. Coupling efficiency was a much stronger function of the plasma edge density gradient than of anything else. In theory, one can always position a waveguide at the place of optimum density gradient, but the combination of a higher gradient of the density gradient, caused by being in the limiter shadow, along with some expected differential erosion of the waveguide exits in a reactor, make it unclear whether significant improvements in efficiency can be achieved with additional slow-wave elements. Also, the large reactor ports will probably have at least 6 elements in a grill, so the launching system will be that much closer to the theoretical ideal performance of the infinite grill, without the aid of additional passive elements. If the forthcoming PLT experiments with a 6 element grill achieve efficiencies of greater than 90 %, then it should not be possible to achieve big improvements using a slow-wave limiter.

The effect of pumping on the waveguide or rf cavity, however, should be beneficial. There has been some confusion on this point, because rf dielectric breakdown has a pressure at which the breakdown electric field is a minimum, so it is not always clear at first sight whether one wants a higher or a lower vacuum. This minimum pressure is certainly an evacuated state, but it is not totally clear whether it will be above or below the pressure in the waveguides if nothing active is done to control that pressure. Below about 4×10^{-3} torr, breakdown is dominated by secondary electron resonance breakdown, or multipactor. Multipactor breakdown is independent of gas pressure. Above 10^{-2} torr, breakdown is dominated by diffusion-ionization avalanche, or Paschen breakdown. Paschen breakdown is a strong function of pressure and has a pronounced electric

field minimum. The electric field breakdown values measured for these two mechanisms in air at different pressures always turns out to be more than adequate for the needs of rf launching, e.g. 9 kV/cm for multi-pactor breakdown at 1 GHz at low pressure. Unfortunately, real life waveguides feeding tokamaks have had lower breakdown fields. These were presumably caused by the seeding of gas in the limiter by ions, perhaps by the use of hydrogen, instead of air, and probably because high VSWRs during off-normal conditions caused electric fields in the waveguides that were considerably higher than the nominal values. The Alcator A waveguides have achieved power densities of 4.5 kW/cm^2 with the rf window behind the ECRF surface [SC81]. On shots with global reflectivities of 0.3 or higher, breakdown was observed at 4.5 kW/cm^2 . With the two windows 2 inches removed from the plasma edge and the ECRF surface pressurized, an arc occurred during a plasma disruption at a transmitted power density of 4.5 kW/cm^2 and one window was damaged by the migration of braze material. A postmortem at Varian indicated no tracking or sputtering onto the window surface. Since that time the undamaged window has transmitted 8 kW/cm^2 with no breakdown and the damaged window has been successfully returned to service at 4 kW/cm^2 . The Alcator experiments indicate some superiority for operating with the ECRF surface pressurized. However, the absence of sputtered particle deposition in the Alcator A window does not prove that window fogging will not occur in commercial reactors with integrated particle fluences that are at least 10^4 times as great as those in the Alcator experiment. For example, assume that a skin depth of iron would render a window opaque. If the coating is ferromagnetic, this could be as little as $.001 \mu\text{m}$ at 1 GHz, corresponding to only 10 monolayers. In 10,000 hours or 1 year of operation, this would be deposited by a partial pressure of iron at the window of only 10^{-11} Pa , which could only be achieved by removing the window from the vicinity of the plasma.

Ohkubo [OH77] has reported the most realistic tests on a simulation of rf breakdown in a waveguide with a window that I have discovered, including tests on breakdown at about 800 MHz in a resonant cavity, with and without a ceramic plate, with and without ion seeding by an ionization gauge, over a broad range of pressures. Unfortunately, I believe that there are at least one, possibly two, typographical errors at critical points in the paper, so I am not sure that I have correctly interpreted the results, nor have I been able to find anyone in the United States who is familiar with this experiment. However, my interpretation of the results are that breakdown in seeded gas is essentially constant from the highest vacuum to 4×10^{-3} torr, and that the lowest reported breakdown field across a ceramic is 2.2 kV/cm. The Alcator A breakdown at 4.5

kW/cm^2 with the window behind the ECRF layer corresponds to a field of 3 kV/cm . There appears to be a deterioration of the breakdown field in Ohkubo's results at the transition to medium vacuum ($\approx 10^{-3} \text{ torr}$).

My interpretation of all this is that the tokamak experimental evidence proves nothing either way about the favored pressure range, especially since 4 kW/cm^2 is more than adequate for plasma heating. However, basic principles indicate that it is better to operate in the secondary electron breakdown range, which is insensitive to ambient pressure and shows adequate behaviour in both laboratory experiments and tokamak heating experiments, rather than to be in the avalanche breakdown range, where Murphy's law dictates that the window will always be at the field minimum of the Paschen curve. Furthermore, if the vacuum pump is placed between the plasma and the window, it should be very easy to ensure that the window will be in the secondary electron breakdown range, while it will be difficult to design to a desired pressure at the window, if the pumping duct is in a completely separate arm of the torus.

(F) Evaluation of RF Guides as Pumps

The vacuum pumping speed of some of the RF guides is limited by their other requirements. The lower hybrid wave grills and the shallow and leaky plena behind the cigarette pumps appear to be particularly limited in their pumping speed. The other concepts are not particularly limited in speed, and the dipole antenna pump in particular should have the same characteristics as the STARFIRE design. There is an optimum pumping speed for the achievement of a tokamak mission and an optimum particle capture probability at the interface between the pump and plasma. High speed is desired to achieve low ash build up during pulses and fast pump down between pulses. Low speed is desired to achieve high fractional burnup, low tritium inventory and low fueling costs. Until the boundary conditions at the plasma-limiter-pump are considerably better understood than they are today, it is not clear which of the above concepts is superior from the point of view of pumping speed. However, some limitations can be deduced, on which I will comment.

A very simpleminded argument can be made, if the vacuum ports are the only significant holes in the wall, as may be the case with a common heating and evacuation system, that almost any plasma-pump interface will have an adequate particle capture probability. Today, in PDX, Doublet III and ISX-B screening factors for both hydrogen and impurities on the order of 10 have been reported. Since screening is primarily a function only of the integral of density with respect to diffusion length, it is certainly likely that screening

at least this good will also be achieved in reactor grade plasmas. If the alpha creation time of a reactor-grade plasma is 50 times the particle confinement time and the holes in the wall cover 1 % of the vacuum vessel surface, and the screening effectiveness of the plasma is 10, then the probability of a particle leaving the plasma recentering would be 0.9 and the steady-state helium concentration of the plasma would be 20 %. This is approximately the ideal compromise helium concentration. The above argument suggests that it is not obviously impossible that adequate ash removal can be achieved without any enhancement of the probability of a particle entering the pumping system, such as is effected by divertors or limiter pumps. Thus, it is unclear whether one wants a higher speed system, such as the Schivell shovel antenna or a lower speed system, such as the slow-wave limiter.

If helium ash removal speed is enhanced during burn by plasma plugging then the most limiting factor on pumping speed becomes gas pumpdown between pulses, particularly of helium. Since plasma initiation is typically at a density of about 1/10 the density during burn, I would think that the helium concentration should be reduced by at least a factor of 10, and that this must be considered a lower bound on the required pumping speed, since other gas species will be present. If 20 seconds is allotted to pump down a 250 m^3 volume in 20 seconds, then a pumping speed of

$$S_{\text{pump}} \geq V_{\text{vessel}} \ln\left(\frac{p_{\text{initial}}}{p_{\text{final}}}\right) t \quad (4)$$

or $30 \text{ m}^3/\text{s}$ is required. This is no problem for the cryopanels; the large ducts connected to them or the large ducts associated with the resonant-cavity box, the dipole antenna limiter, the unblocked pumping ducts associated with the cigarette limiter pumps or the ICRF rectangular waveguide. However, it is a very severe problem for the lower hybrid waveguide grills and it can be nontrivial for the microwave screens, as calculated above.

(G) Conclusions

- The clever idea of making the rf launcher and the limiter pump common probably adds nothing significantly worthwhile to the performance of either the launcher or the pump, while adding some constraints to both.
- However, the banal idea of making the rf guide and the vacuum pumping duct common appears to

have many important benefits, including more space for the blanket, better personnel and magnet shielding, higher rf breakdown field and simpler pump design.

- Using rf heating and making heating and pumping ducts common also allows a partial return to a warm structure torque frame, significantly easing the TF magnet system structural design.
- The use of long or renewable limiter elements may allow reactor operation with high integrated erosion rates.

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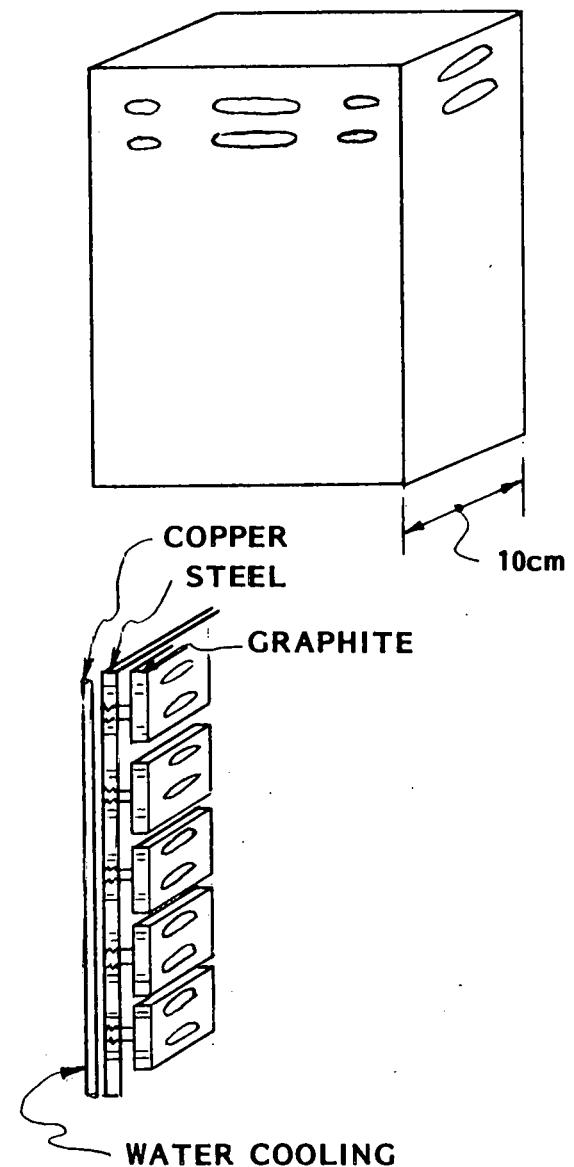
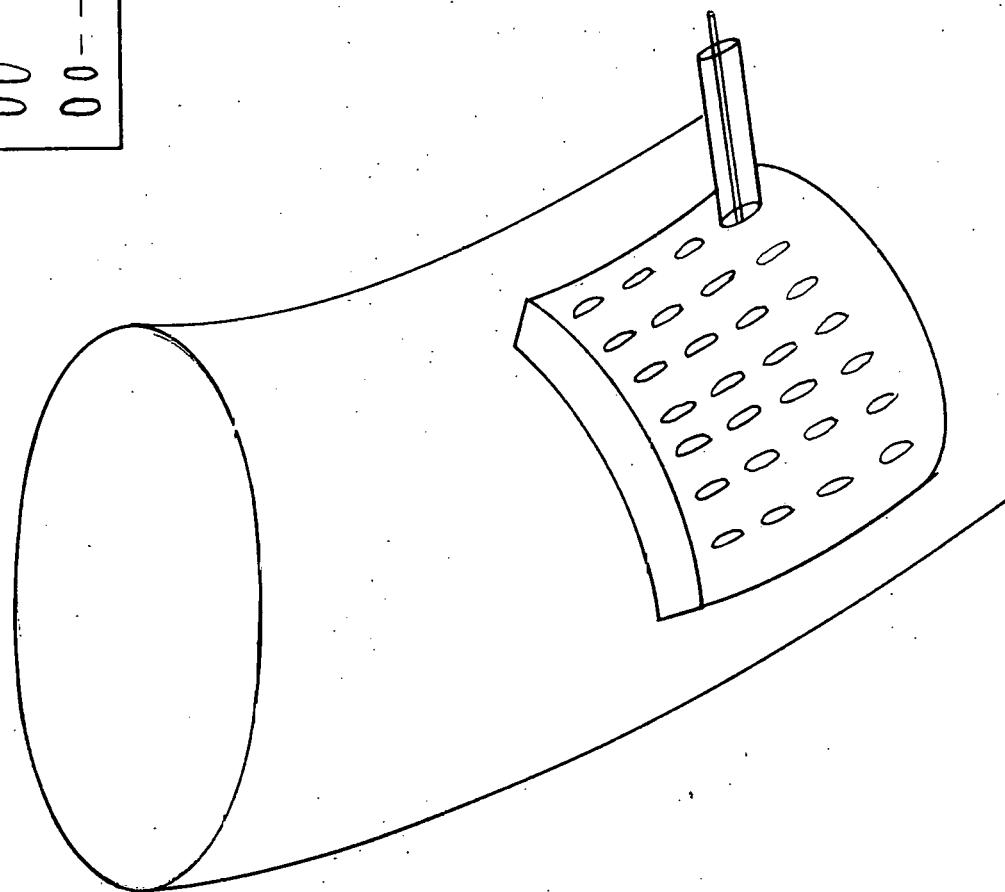
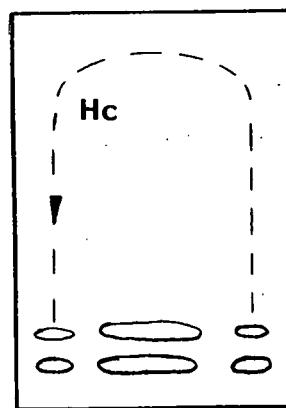
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FIGURE 1
CAVITY-APERTURE ANTENNA, PUMP AND LIMITER

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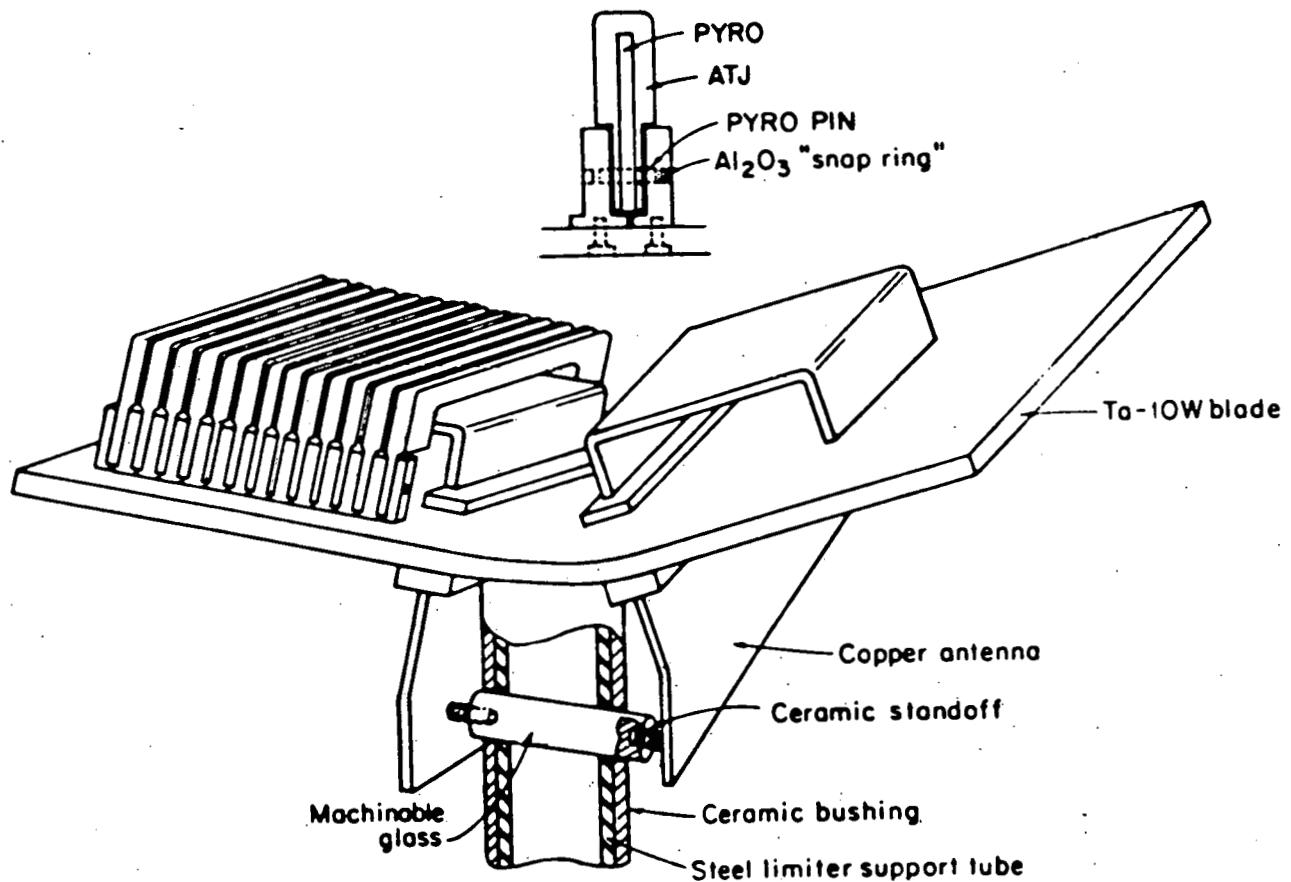
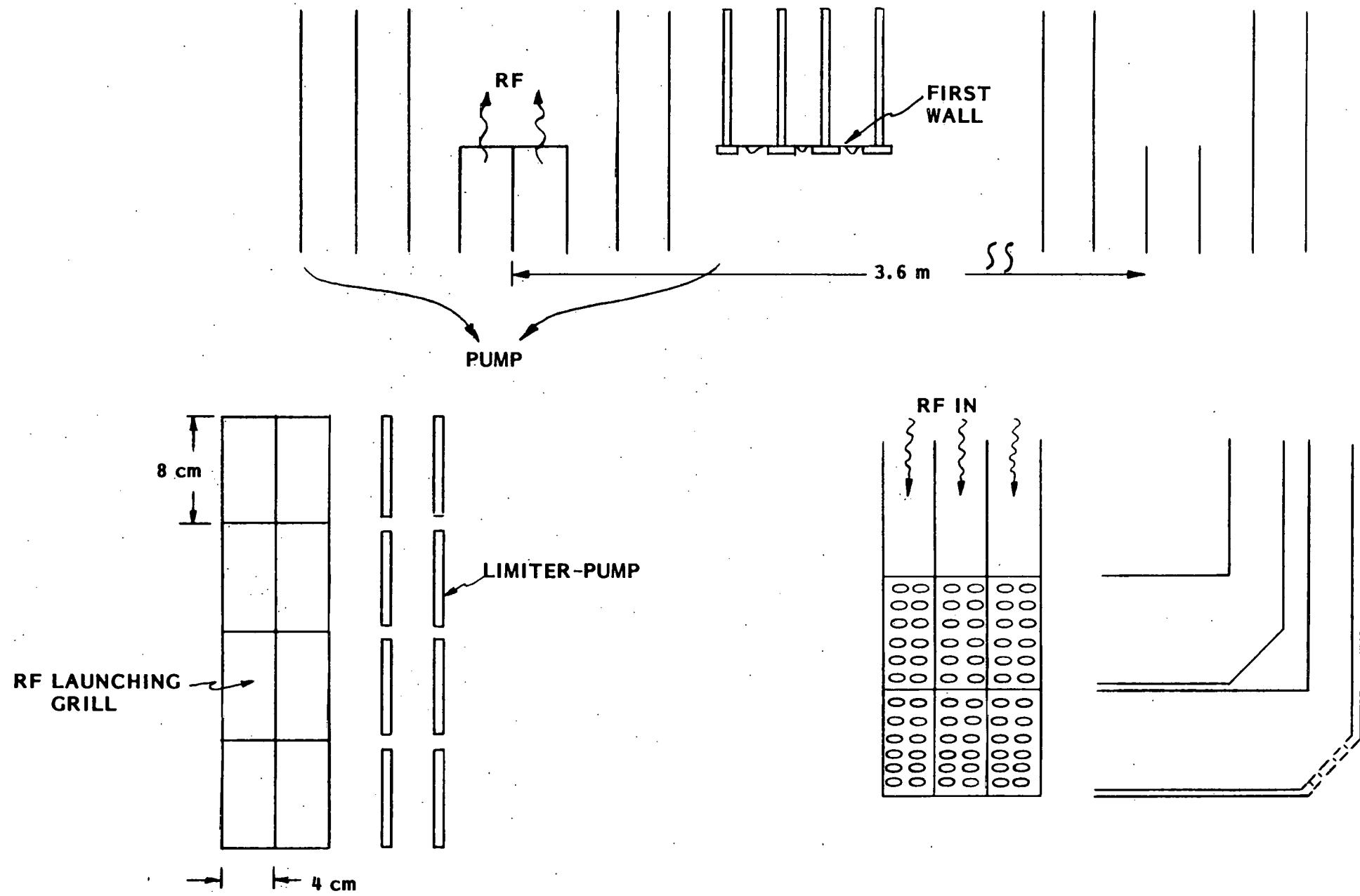


FIGURE 2
A FARADAY-CAGE LIMITER, DIPOLE ANTENNA AND A GROUND PLANE PUMP

FIGURE 3
A SLOW-WAVE LIMITER WITH A LOWER HYBRID WAVE LAUNCHING VACUUM PUMP



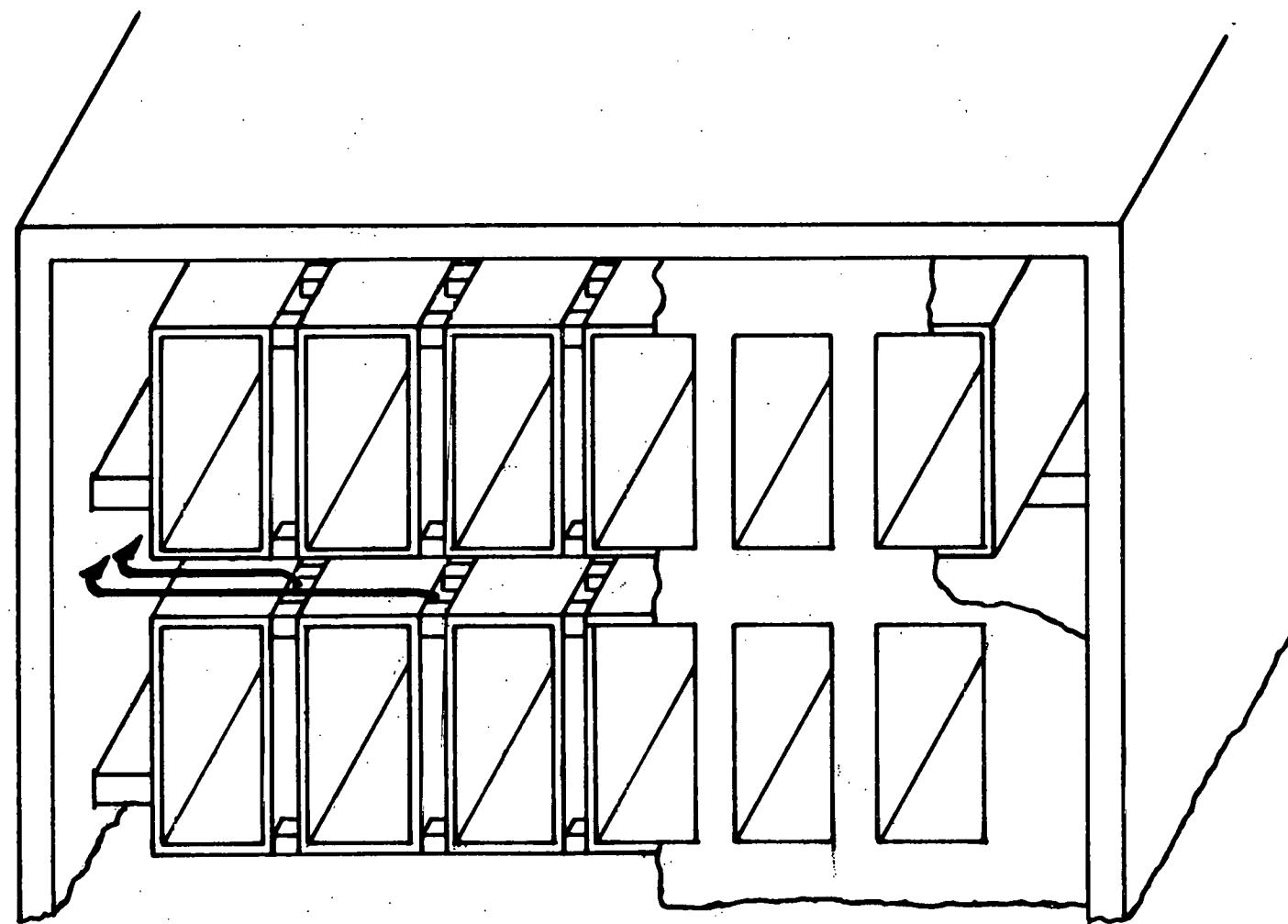


FIGURE 4
A POSSIBLE LOWER HYBRID WAVE LAUNCHING
GRILL STRUCTURE AND COOLING CHANNELS

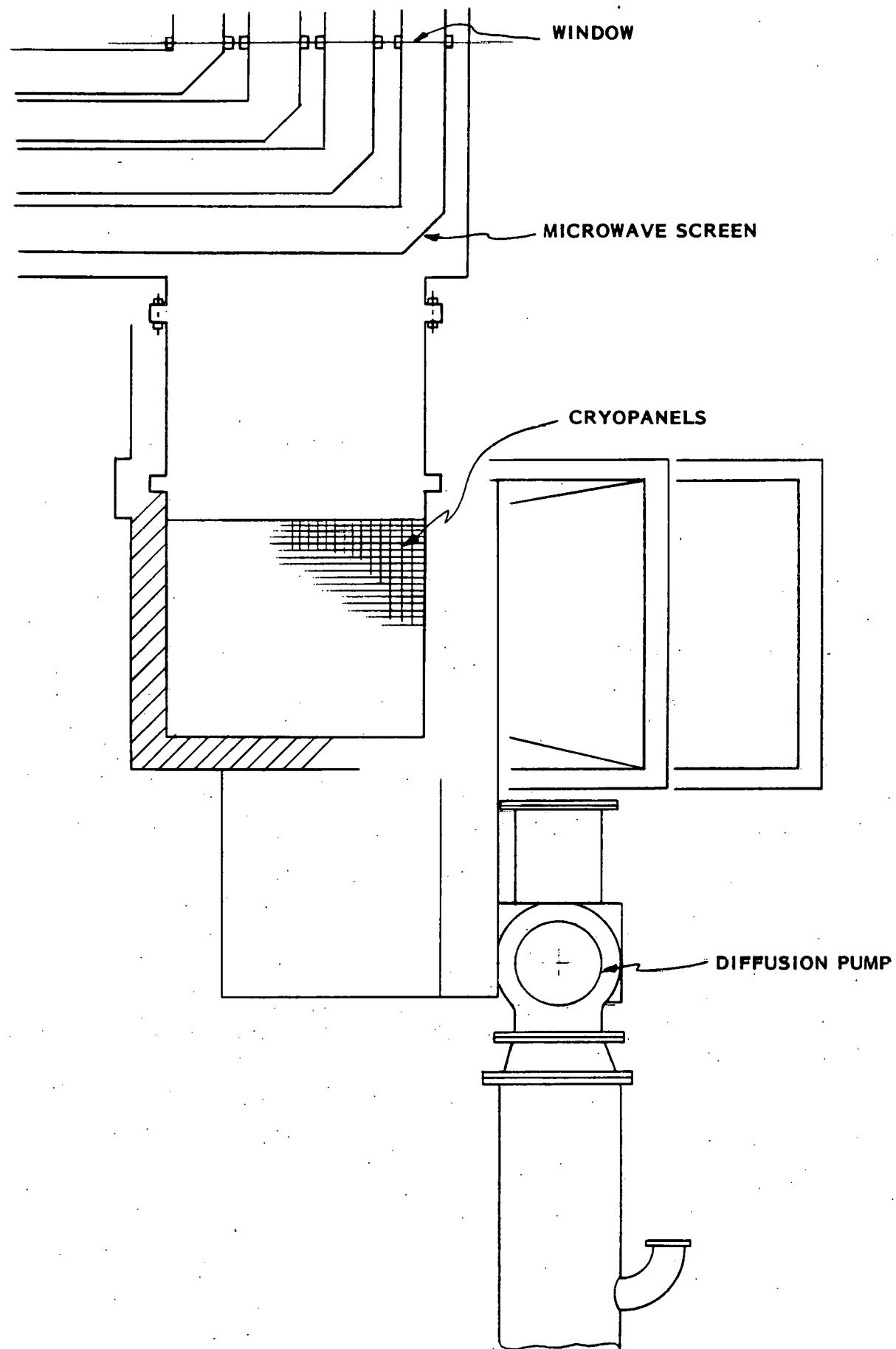


FIGURE 5
A LOWER HYBRID WAVE GRILL VACUUM PUMPING SYSTEM

Figure 6
Speed of Lower Hybrid Limiter Pump - FED

- * All active waveguides - 810 x 13.5 cm x 6.74 cm
 - Helium pressure at pumps - 3×10^{-4} Pa
 - Helium pressure at orifices - 4.5×10^{-4} Pa
 - Helium pressure at waveguide exit - 0.5 Pa
- * 2 passive waveguides -each side
 - immediate taper to large plena
 - only 6×10^{-3} Pa at waveguide exit

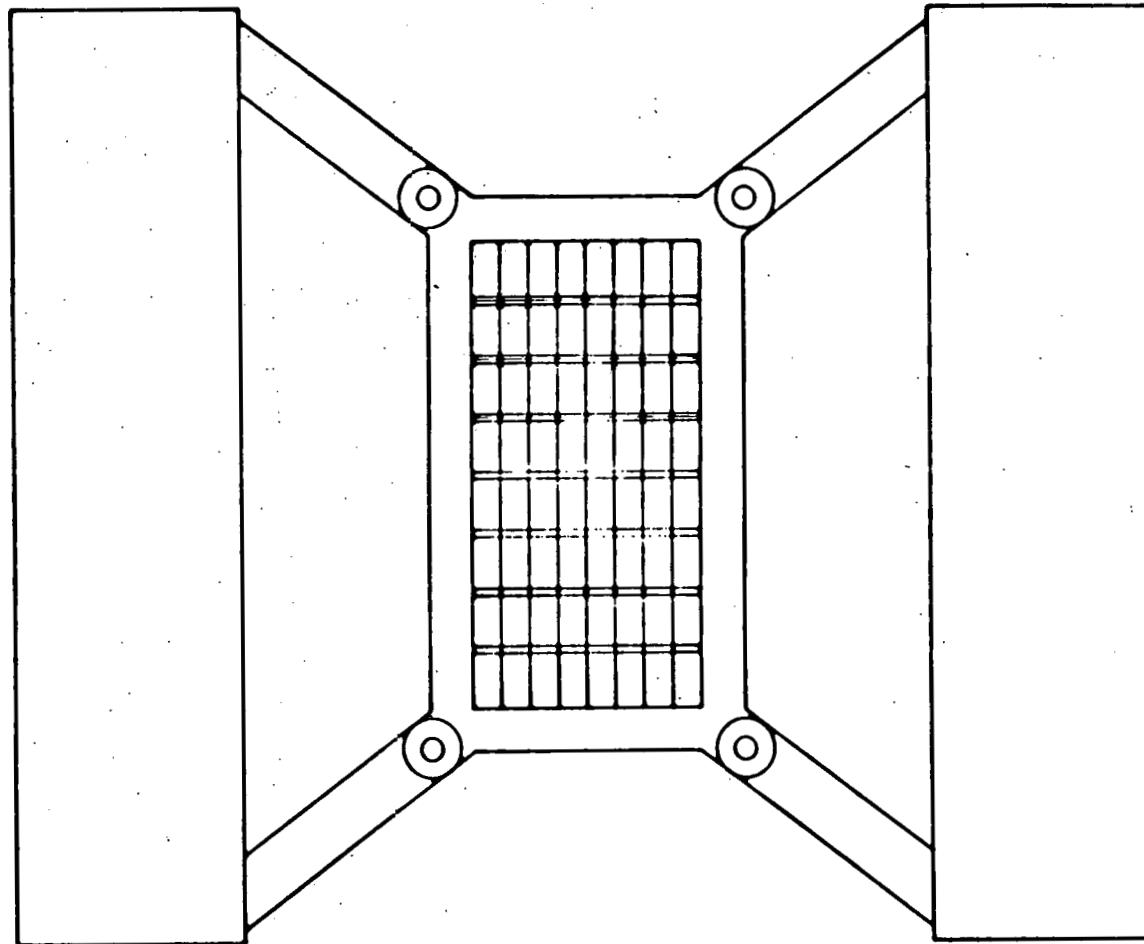


FIGURE 7
ELEVATION VIEW OF A LOWER HYBRID WAVE LAUNCHING GRILL VACUUM PUMP
LATTICE FRAMEWORK SUPPORTED BY A NEUTRON SHIELD PINNED DIAGONAL
BRACING STRUCTURE FOR OUT-OF-PLANE FORCES ON TWO TOROIDAL FIELD COILS

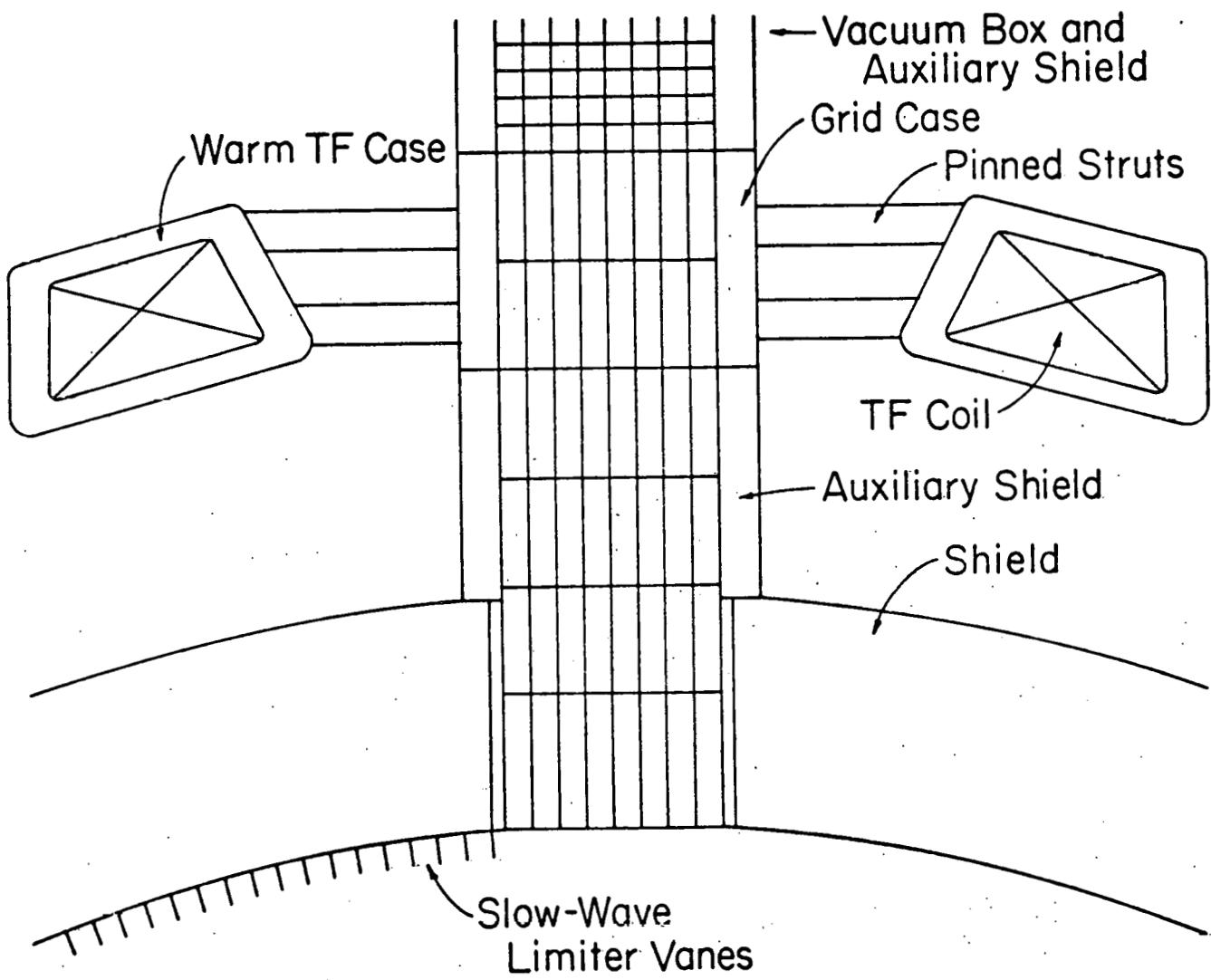
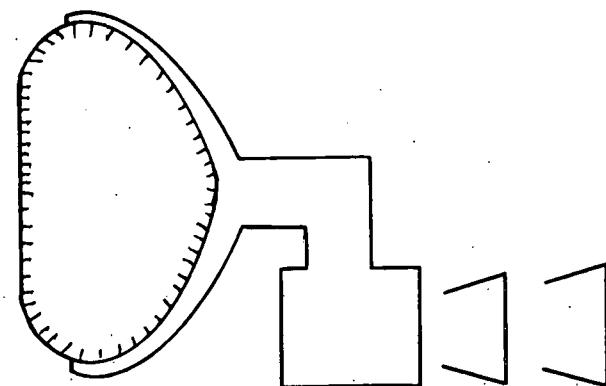
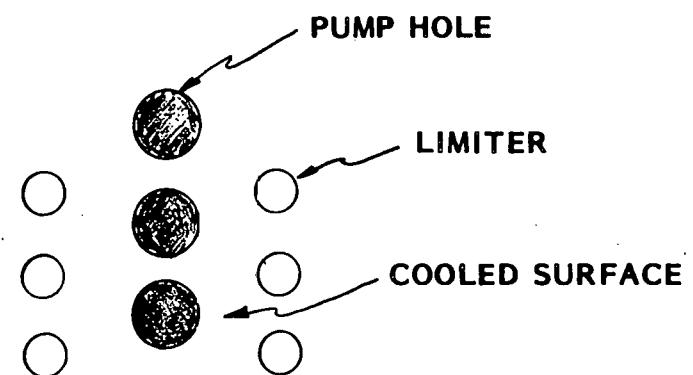
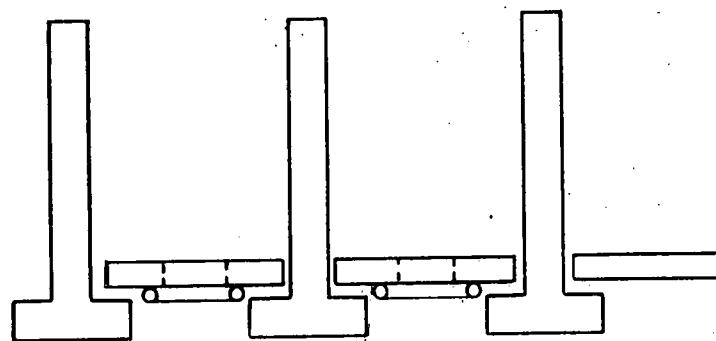


FIGURE 8
PLAN VIEW OF A LOWER HYBRID LAUNCHING, VACUUM PUMPING,
NEUTRON SHIELDING, OUT-OF-PLANE FORCE SUPPORT STRUCTURE

FIGURE 9
CIGARETTE LIMITER-PUMP



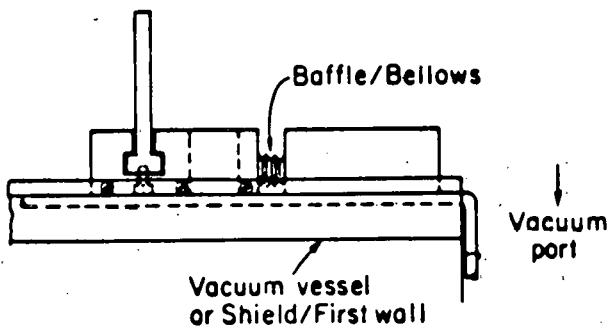
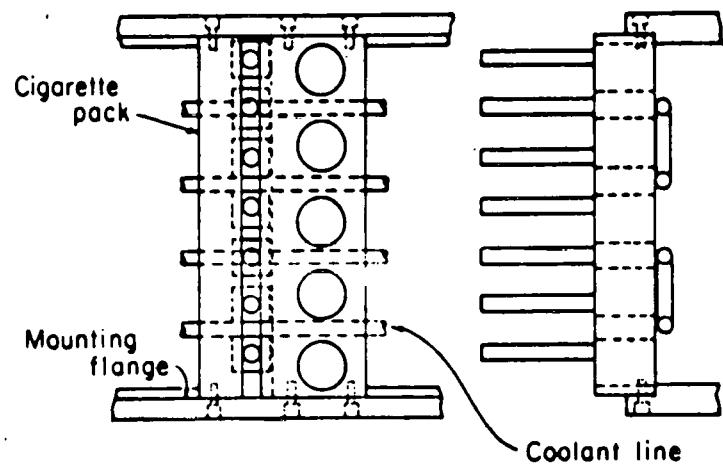
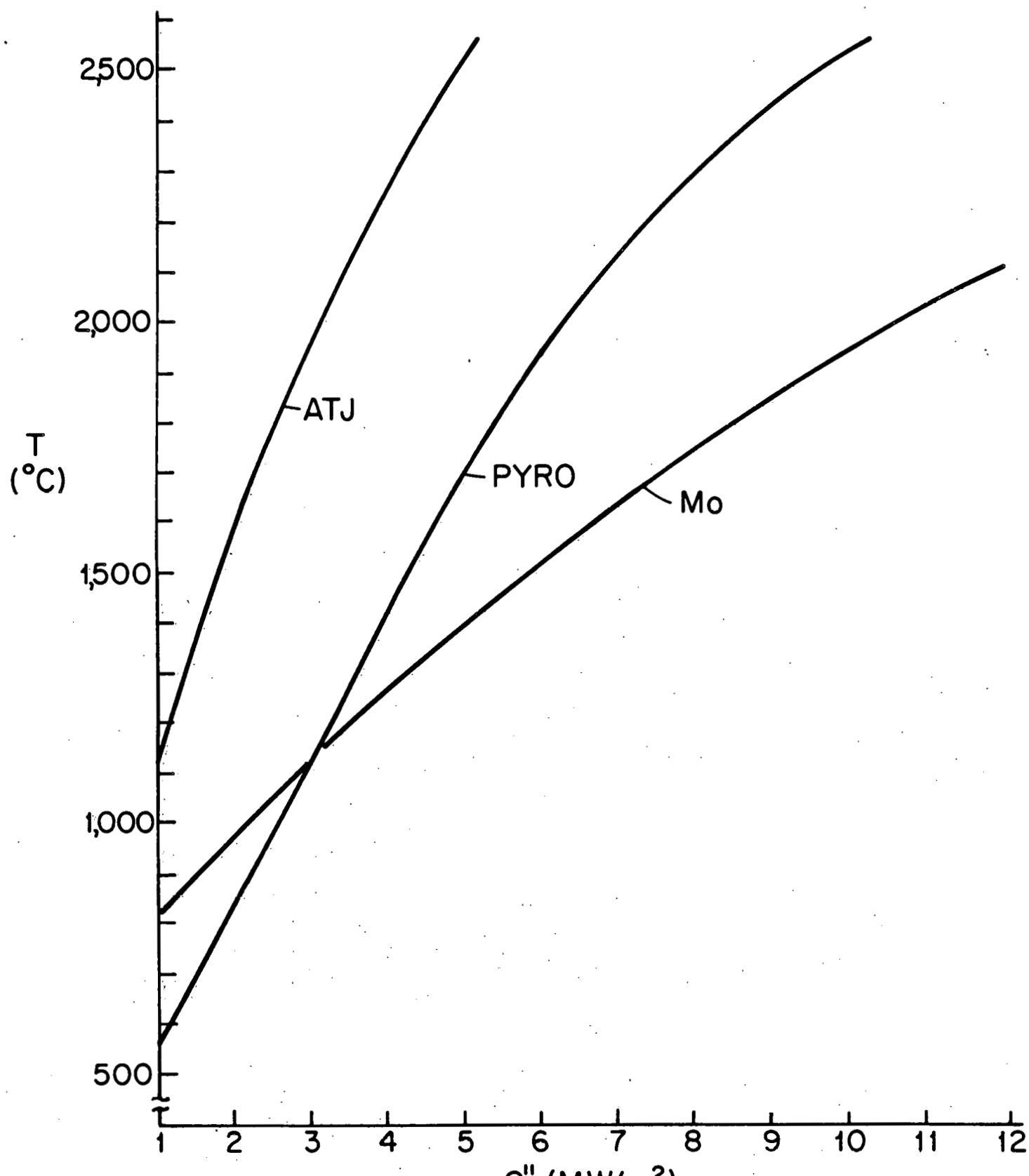


FIGURE 10
A PACK OF CIGARETTE LIMITER-PUMPS



Temperature of 100mm Cigarette Tip

FIGURE 11
HOT-SPOT TEMPERATURE OF CIGARETTE TIP ($^{\circ}\text{C}$)
vs. HEAT LOADING ON TIP (MW/m^2)

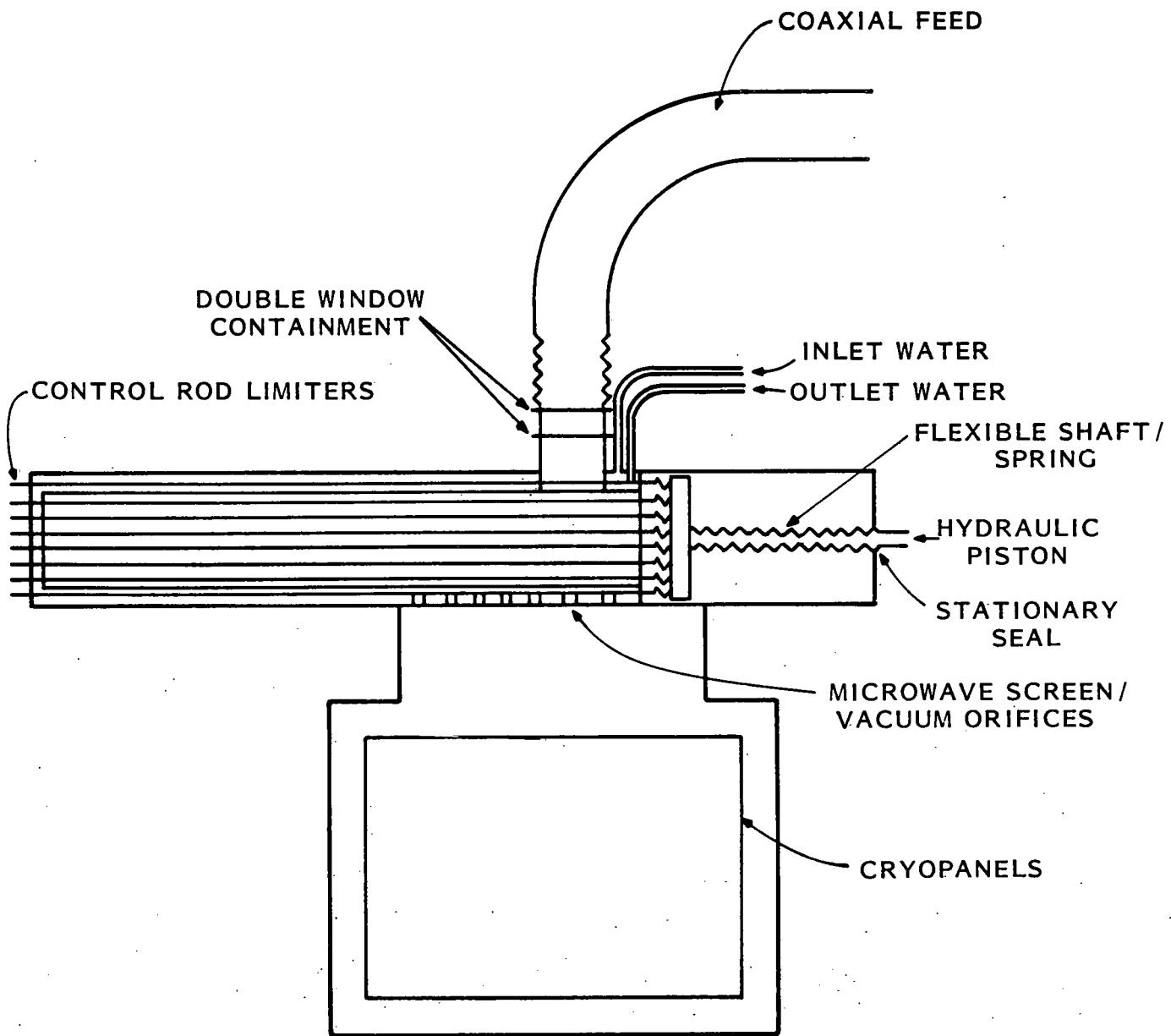


FIGURE 12
LIFE-OF-THE-REACTOR CONTROL ROD LIMITERS
SURROUNDING A RECTANGULAR ICRF WAVEGUIDE

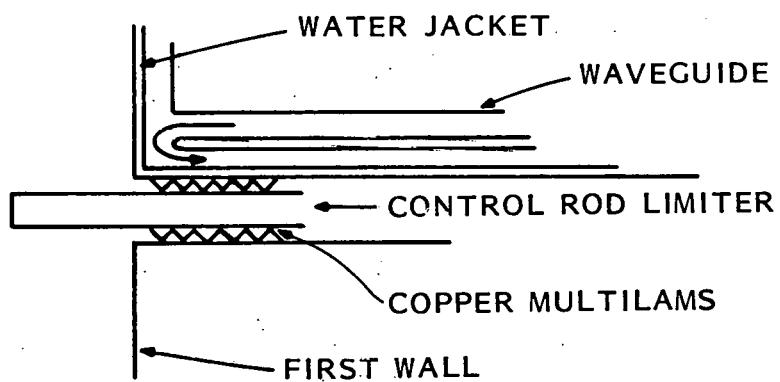
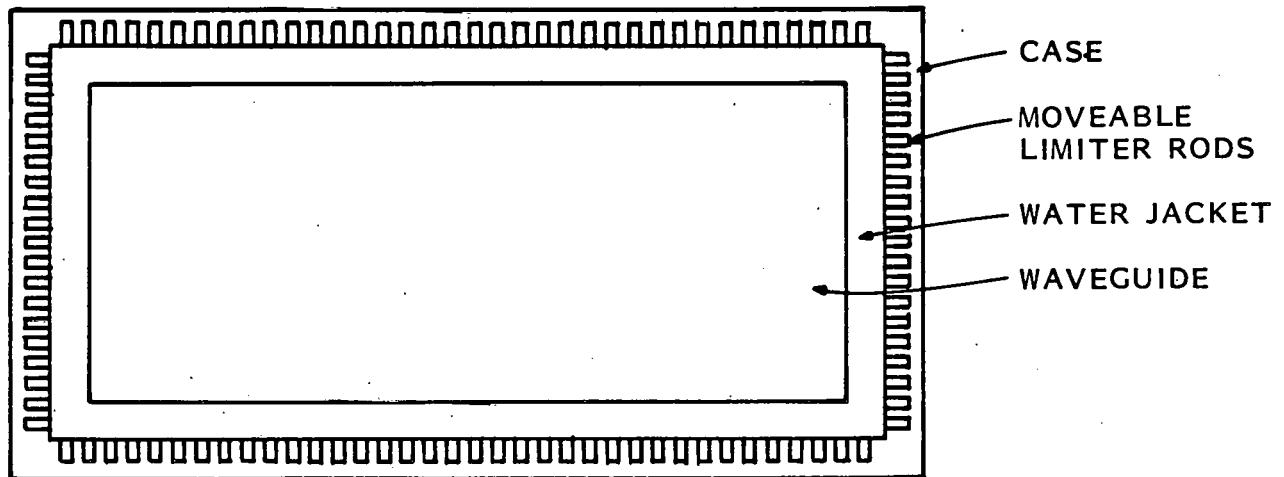


FIGURE 13
ELEVATION VIEWS OF SUPPORT AND
COOLING OF CONTROL ROD LIMITERS

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