Vacuum System Design

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J.M. Donhowe

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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The vacuum requirements for a Tokamak controlled-fusion reactor are such that static vacuum systems can no longer be relied upon, because the equipment is too large in volume and a large gas throughput requires high pumping speeds. This design is based on an optimization of the mercury diffusion pump with freon and liquid-nitrogen cooled traps, augmented by the extensive use of cryopumping at liquid helium temperatures to achieve pumping speeds in the multi-million liters per second range. The system is incorporated into the modular design of the Tokamak, a complete vacuum system being contained in each of the twelve sectors of the torus.

The vacuum system design is based on steady state operation at a diffusion rate of 3.56 x 10^{22} D+T+He atoms/sec. This represents a throughput of 2.6 x 10^{3} torr-ℓ/sec of D+T atoms and 107 torr-ℓ/sec of helium. In addition, outgassing to be expected from the vacuum wall must be considered. Estimates vary from 1.5 to 6 x 10^{-9} torr-ℓ/sec per cm^{2} surface. Initial bake-out of the vacuum wall before assembly could reduce this, but the most pessimistic estimate results in a gas throughput of 0.2 torr-ℓ/sec from this source.

To maintain a sufficiently large mean free path in the divertor, at 10^{-5} torr, a pumping speed of 2.6 x 10^{8} ℓ/sec for helium at thermal energies is required. This is a factor of 25 beyond the range of present day technology, so trapping and burial of ions in a liquid lithium surface in the divertor region will be relied upon. A description of the essential components of the vacuum system and the lithium trapping surface, all located in or outside the devertor region follows.

There are four divertor slots. Each set of two, the upper and the lower, is connected to a plenum outside the twelve D-magnets. The pumps are arranged in four rows, three pumps side-by-side, attached to each plenum. For each set of three, the outer two are cryopumps and the center is a mercury diffusion pump. The circular orifice to each pump is 75 cm in diameter. Since the cryopumps must be serviced periodically, only one set of 96 is operated at a time, while the other set is being degassed.

Mercury Diffusion Pumps

Mercury diffusion pumps are chosen to obviate the problem of hydrogenation of the pump oil, as would be the case if a fractionating oil diffusion pump were to be used. The pump is mounted outside the D-shaped magnet, the blanket, and the shield. The Edwards 24M4 pump is suitable, and its aperture is 75 cm and height 130 cm. Its pumping speed for hydrogen, unbaffled, is 14,000 ℓ/sec. When an allowance is made for the flow conductance of the liquid-nitrogen cooled baffles and traps, ductwork, and plenum the net pumping speed for helium is 8×10^5 ℓ/sec at 10^{-4} torr.

Cryogenic Pumps

Augmenting the diffusion pump with cryopumps is a reasonable way to increase pumping speed for deuterium and tritium. Cryopumps of 2×10^5 ℓ/sec capacity are available, and they are relatively small. In this design, the aperture to each pump is 75 cm in diameter. These pumps rely on cryotrapping with liquid-helium cooled charcoal absorption, with a liquid-nitrogen cooled shield. Evacuation with the diffusion pumps to 10^{-4} torr or less before cooling with liquid-helium on the inner component of the pump will even cryopump helium in the 10^{-5} torr range. These pumps are shut off from the rest of the system by remotely-controlled valves, so that while 96 of them are in use the other set is degassed.

The cryopumps are in service only during the final evacuation after ignition, below 2.5×10^{-4} torr and during the 1000 second burn. All cryopumps are valved off during the cooling, evacuation and refueling cycle of 100 seconds between burn sequences.

Backing Pumps

The diffusion and cryogenic pumps, in parallel, must be backed by pumps which can take a gas load of 2.6×10^{3} torr-ℓ/sec. Roots blower pumps in combination with a mechanical forepump provide a mechanical system of high pumping speed in the range 760 to 10^{-2} torr. Roots blower pumps are preferred to vapor booster pumps because the rotors are not lubricated. Oil must be provided only for the various gears and bearing required in the operation. The Heraeus VPR6000A pump in series with a Heraeus VPR1600 pump and backed by a 130 cfm forepump is attached to each set of three parallel pumps on the plenum. The VPR6000A - VPR1600 tandem arrangement pumps 1600 ℓ/sec at 0.3 torr, dropping off to 1400 ℓ/sec at 10^{-2} torr. For 96 of these pumps, the throughput is 50,000 torr-ℓ/sec. The fore pressure is 10 torr, so the pumps are adequately backed by a 130 cfm forepump at each of the 96 pumping stations.

Trapping in Lithium

An efficient means of trapping hydrogen isotopes in lithium might be devised because of the large heat of formation of the hydride. However, trapping will continue only as long as the concentration near the surface remains low. Efficient trapping of 96% of the incident ions will continue up to doses of 2×10^{19} particles/cm^2.(1) Theoretically, all the molecules striking the lithium surface will condense, and be trapped, until the pressure is reduced to the vapor pressure of the gas at the temperature of the surface.

It is proposed to trap deuterium and tritium ions in a liquid lithium surface placed in each divertor slot. Liquid lithium at a temperature maintained at 325°C flows down a vertically oriented stainless steel sheet. It is collected in a trough at the bottom and is cycled through a tritium scrubber. If the sheet is no more than one meter high, efficient trapping will be sustained. Where a meter fall under gravity is difficult, a "venetian blind" design may be used. Experimental data (1) indicates that 95% of the incident dueterium and tritium ions will be trapped at 325°C. There is no experimental data for the trapping of helium in liquid lithium. Since the surface is flowing, it is estimated that 50% of the energetic alphas will not diffuse to the surface after burial in the lithium surface. However, in order to attain a base pressure of 1×10^{-5} torr, 90% of the helium must be trapped.

There is no experimental evidence to support an estimate of the trapping of helium in liquid lithium. Since the residence time in the divertor of any part of the flowing lithium surface is less than 100 seconds, it can be assumed that 50% of the helium will diffuse toward the surface and escape if the diffusivity is greater than 1×10^{-6} cm^2/sec. McCracken (1) predicted that the diffusion rate could be estimated from the self-diffusivity of the metal. That implies D ~ 12 x 10^{-5} cm^2/sec, a very high number. However, his prediction was based on an experiment in which 1 MeV alphas bombarded a thin sheet of Mg.(2) The conclusions of this experiment were: (1) inert gas bubbles do not form in Mg; (2) helium diffuses via a mechanism involving vacancies; (3) as helium atoms are considerably larger and have very different electronic structures from Mg^{++}, the size differences rather than the charge differences between the inert gas and host atoms determine the diffusion and solution properties. All of this suggests that only experimental evidence can indicate how much trapping of helium can be expected in liquid lithium.

The mass rate of flow of liquid lithium, per unit length of the stainless steel sheet, is 0.025 kg $m^{-1}sec^{-1}$ for a fluid thickness of 5mm. Ignoring magnetohydrodynamic effects, the mean velocity of fall is 1 cm/sec. Allowing for a decrease in flow rate due to the magnetohydrodynamic force, the mean residence time of lithium in the particle flux should be less than 100 seconds if efficient trapping is to be maintained. Therefore, the vertical height of the collector plate is chosen to be less than one meter.

The energy flux due to particles impinging on the lithium surface is 100 watts/cm^2. Nearly all of the heat is conducted through the lithium to the wall behind it. Pressurized helium cooling from the back side of the plate (225°C) must cool the stainless steel so that the temperature of the lithium is no greater than 325°C. Then the vapor pressure of lithium will be less than 10^{-5} torr, and substantially no re-emission of trapped particles occurs.

Tritium Recovery

Tritium recovery is considered only as a problem, and not a solution. The exhaust from the forepumps can be compressed and stored in gas cylinders. This dodges the problem of loss of tritium and hydrogenation of the oil in the pumps. For this reason mercury diffusion pumps and Roots blowers are preferred. Recovery of tritium from the oil in large (130 cfm) forepumps is an unsolved problem.

Pumping Speed

The volume of the torus, exclusive of divertor slots, is 7750 m^3. The surface area is 2830 m^2. The initial pump-down time from 760 torr to 10^{-2} torr is 65 minutes. Using diffusion and backing pumps alone, the additional pump-down time to 10^{-5} torr is 4 minutes. The total pumping speed for 96 diffusion pumps and the same number of cryopumps is 2×10^7 ℓ/sec, and the flow conductance of the divertor slots and ductwork is the same. Thus, for a throughput of 2.6×10^3 torr-ℓ/sec the base pressure is 2.6×10^{-4} torr. With lithium trapping at 95% efficiency, the base pressure for steady state operation can be reduced to 10^{-5} torr.

The pump-down time for portions of the cycle of operation, which included purging, fueling, ignition and evacuation is considered in another section, "Recycle and Shutdown."

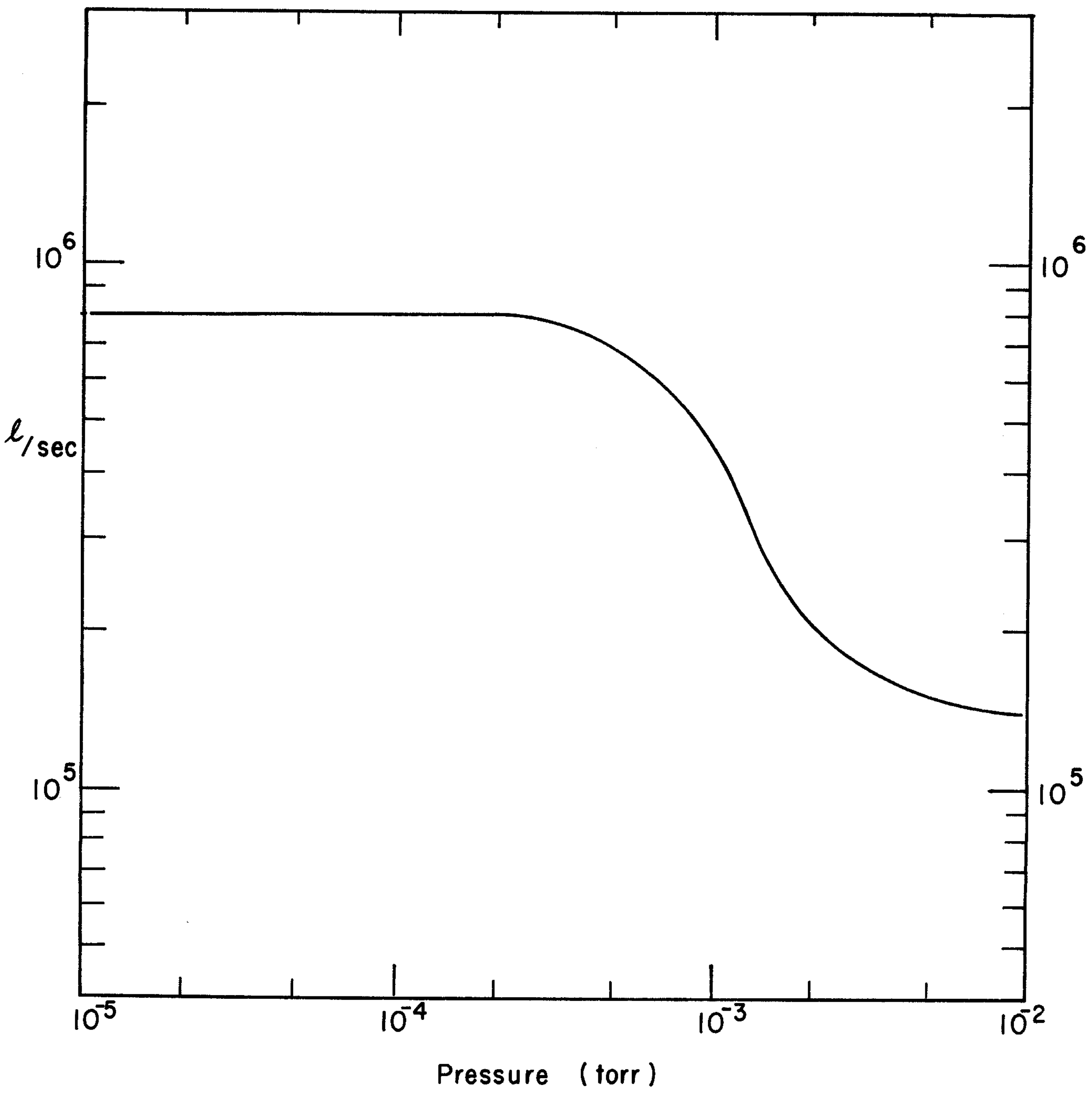
Leakage Rate

Each of the 12 sectors of the torus is sealed by copper gaskets, with bellows allowing for distortion due to stress and temperature changes. It is estimated that the leak rate of each seal, of 40 meter

Pumping Speed for Helium (ℓ/sec)

(Mercury Diffusion and Backing Pumps Only)

(Pumping Speed for D,T ~ 10-15% Greater)



circumference, is equivalent to an orifice .06 cm^2 in area. If the exterior of the torus is at atmospheric pressure, this leakage represents a throughput of air of 2.8×10^4 torr-ℓ/sec. One of the reasons for evacuating the building housing the torus is to reduce this load on the vacuum system. If the building is evacuated to 1 torr, the throughput is reduced to 38 torr-ℓ/sec, which is 1.4% of the fueling rate.

Building Evacuation

The volume of the building is $\sim 8 \times 10^4$ m^3. Stokes Microvac (912-H) mechanical vacuum pumps are available, which have a rated capacity of 730 cfm. Actually, the pumping speed varies from 310 ℓ/sec to 260 ℓ/sec over the pressure range 760 to 1 torr. One hundred of these pumps can handle a throughput of 3×10^4 torr-ℓ/sec at 1 torr. At 760 torr, this throughput would be caused by a leak equivalent to an orifice .06 cm^2 in area.

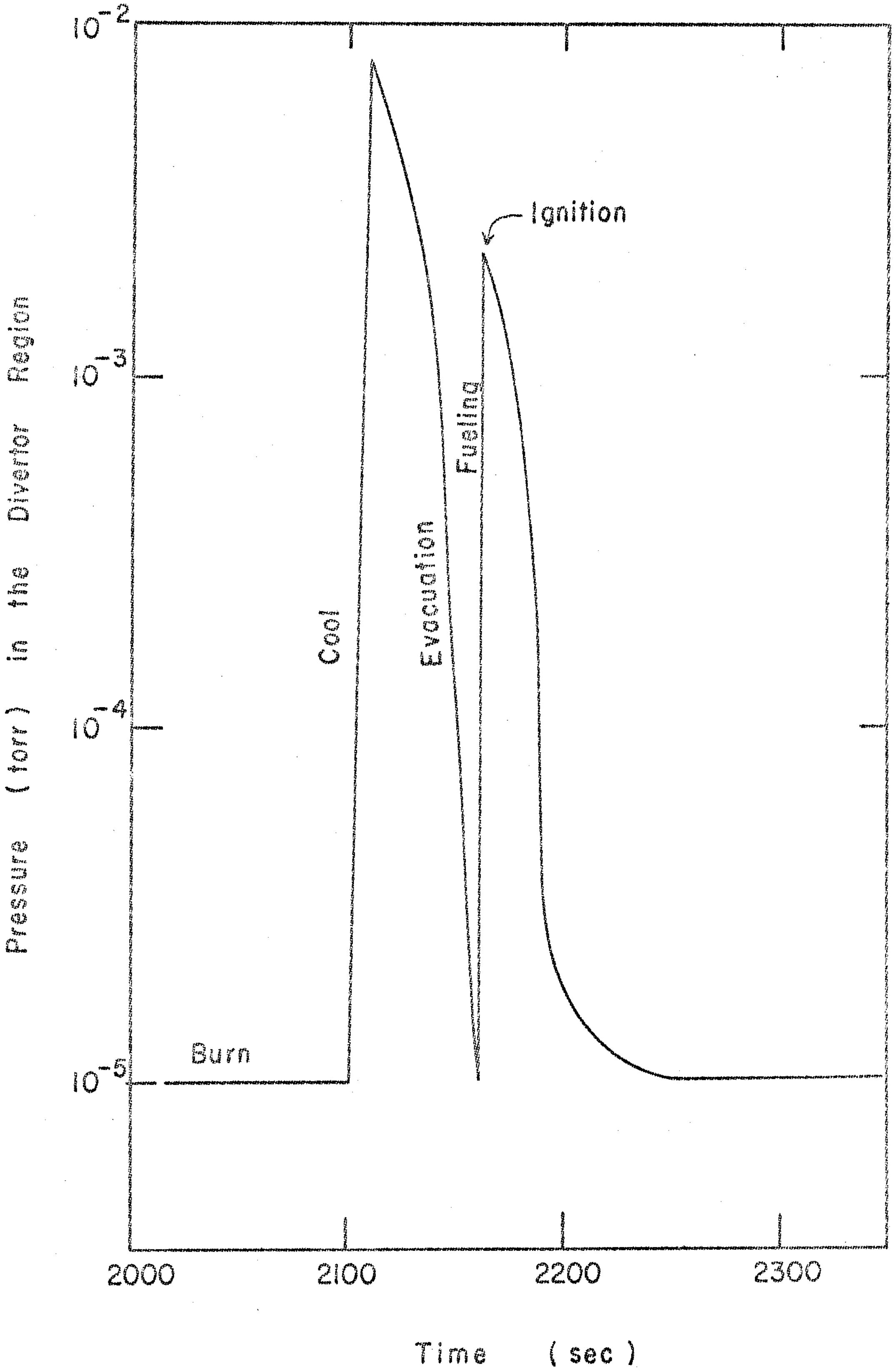
Recycle and Shutdown

A time sequence of operation, based on a 1000 second burn time, will be estimated. The 96 diffusion pumps, with a net pumping speed of 8×10^5 ℓ/sec, will be operated continuously. The cryopumps will be valved off at the cessation of the burn interval, and will not be re-opened to the vacuum chamber again until evacuation following ignition has reached a pressure of 2.5×10^{-4} torr. The flowing liquid lithium surfaces in the divertor slots will be exposed to the chamber during the entire sequence. It is assumed that the lithium will trap 95% of the deuterium and tritium ions, and 70% of the alpha particles.

The plasma is first cooled to the wall temperature of 750^{o}K, during which the pressure will rise to ~8 x 10^{-3} torr. It is assumed that this cooling process will take 10 seconds. Subsequent evacuation of the chamber to 1 x 10^{-5} torr will require 50 seconds. Fuel is loaded through the divertor slots to n ~ 3 x $10^{13}/cm^{3}$. This implies a static pressure of 2.3 x 10^{-3} torr. The process will require only milliseconds. After ignition, fueling will continue through the eight ports provided for this purpose, and the diffusion loss rate will rise to 3.56 x 10^{22}particles/sec. Evacuation of the vacuum region (~ 1.5 x $10^{6}\ell$) to 2 x 10^{-5} torr will require less than 40 seconds, and if 90% trapping of helium in the liquid lithium surfaces can be maintained, the base pressure for quasi-steady state operation will be 1 x 10^{-5} torr. Half of the cryopumps will be opened to the system after the pressure has dropped to 2.5 x 10^{-4} torr, and will continue in operation until the burn cycle terminates. Dependence on the mercury diffusion pumps and lithium trapping for all other evacuation will greatly lengthen the interval of efficient operation of the cryopumps before servicing is necessary. Since these pumps will not pump helium, the base pressure will be attained only if 90% of the alphas are trapped in lithium. If only 50% of the alphas are trapped, the base pressure will be 5 x 10^{-5} torr, the residual gas being mostly helium.

References

1. McCracken, G., B.N.E.S. Nuclear Fusion Reactor Conf., Culham, 1969.
2. Glyde, H.R. and Mayle, K.I., Phil. Mag., Vol. 12, P. 919, 1965.


Pressure (torr) in the Divertor Region
Time (sec)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
2000
2100
2200
2300
Burn
Cool
Evacuation
Fueling
Ignition