Vacuum System Design

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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 cryo-pumping at liquid-helium temperatures to achieve pumping speeds in the multi-million liters per second range. These pumps are backed by two Roots blower pumps and a high capacity roughing pump. 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.

Throughput

If the confinement time is τ, the amount of fuel introduced into the reactor per second is

$$\frac{2\pi^2 R a^2 n}{\tau} = \frac{2\text{x}10^9\text{x}10^{14}}{10} = 2\text{x}10^{22} \text{ atoms/sec.}$$

In order to maintain equilibrium this must be pumped out, per second. A fueling rate of $2\text{x}10^{22}$ particles/sec represents a gas throughput of 10^3 torr-ℓ/sec:

$$Q = \frac{2\text{x}10^{22}}{6\text{x}10^{23}}\text{x}760\text{x}22.4\text{x}\ \frac{500}{273} = 10^3 \text{ torr-}\ell\text{/sec.}$$

To maintain a sufficiently large mean free path in the divertor ($\sim 10^{-5}$ torr) a pumping speed of $\sim 10^{8}$ ℓ/sec at thermal energies is required. This is a factor of ten beyond the range of present day technology, so trapping and burial of ions in a wet or evaporated surface in the divertor region will have to be relied upon. In D-T ions trapping is >95% effective.

Mercury Diffusion Pumps

Mercury diffusion pumps are chosen to obviate the problem of hydrogenation of the pump oil, if a fractionating oil diffusion pump were to be used. The diffusion pump must be small enough to be mounted inside the D-shaped magnet winding, and outside the blanket and shield. The Edwards 24M4 pump is suitable, as its aperture is 75 cm and height only 1.3 m. Its pumping speed for hydrogen, unbaffled, is 20,000 ℓ/sec. Usually a factor of four should be applied at this point to allow for reduction in pumping speed due to baffles, tubulation, and traps. With a large plenum at the terminal of the divertor, a factor of two is reasonable, allowing for the freon and liquid-nitrogen cooled trap.

Cryogenic Pumps

Augmenting the diffusion pump with cryopumps is a reasonable way to increase pumping speed. The plenum for each divertor slot, in each of the twelve sectors, easily allows for two 75 cm diameter holes side by side, tucked under the windings but outside the blanket and shield. Cryopumps of 2×10^5 ℓ/sec capacity are available, and they are small. These pumps rely on cryotrapping with liquid-helium cooled charcoal adsorption, 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.

Backing Pumps

The diffusion and cryogenic pumps, in parallel, must be backed by pumps which can take a gas load of 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 by the various gears and bearings required in the operation. It has an advantage over the vapor booster pump of its small size. These could be located either inside or outside the D-windings.

The Heraeus VPR6000A pump in series with a Heraeus VPR1600 pump backed by a 130 cfm forepump on each of the four divertor slots of each sector of the torus is adequate. The VPR6000A - VPR1600 tandem arrangement pumps 1600 ℓ/sec at 0.3 torr, dropping off to 1400 ℓ/sec at 10^{-2} torr. For 48 of these pumps, $Q = 48 \times 1600 \times .3 = 25{,}000$ torr-ℓ/sec. The fore pressure is 10 torr, so the pumps are adequately backed by a 130 cfm forepump.

Calculations

The flow conductance of the divertor slots must not impede pumping. The flow conductance through tubulation of crossection A, perimeter H, length L, mean velocity $\bar{v}$, is

$$F = \frac{\frac{4}{3}\bar{v}}{\int_0^L \frac{H}{A^2}\, d\ell} .$$

For slots of 30 cm width through 3 m of blanket and shield, the conductance of each slot is 3×10^6 ℓ/sec. For four slots $F = 1 \times 10^7$ ℓ/sec.

a) diffusion pumps $S = 10{,}000$ ℓ/sec, baffled, and

48 pumps mean $S_1 = 480{,}000$ ℓ/sec.

b) cryopumps $S_2 = 48 \times 2 \times 10^5$ ℓ/sec $= 9.6 \times 10^6$ ℓ/sec.

$$S_p = S_1 + S_2 = 10^7 \text{ ℓ/sec}$$

$$\frac{1}{S} = \frac{1}{S_p} + \frac{1}{F} = \frac{1}{10^7} + \frac{1}{10^7}$$

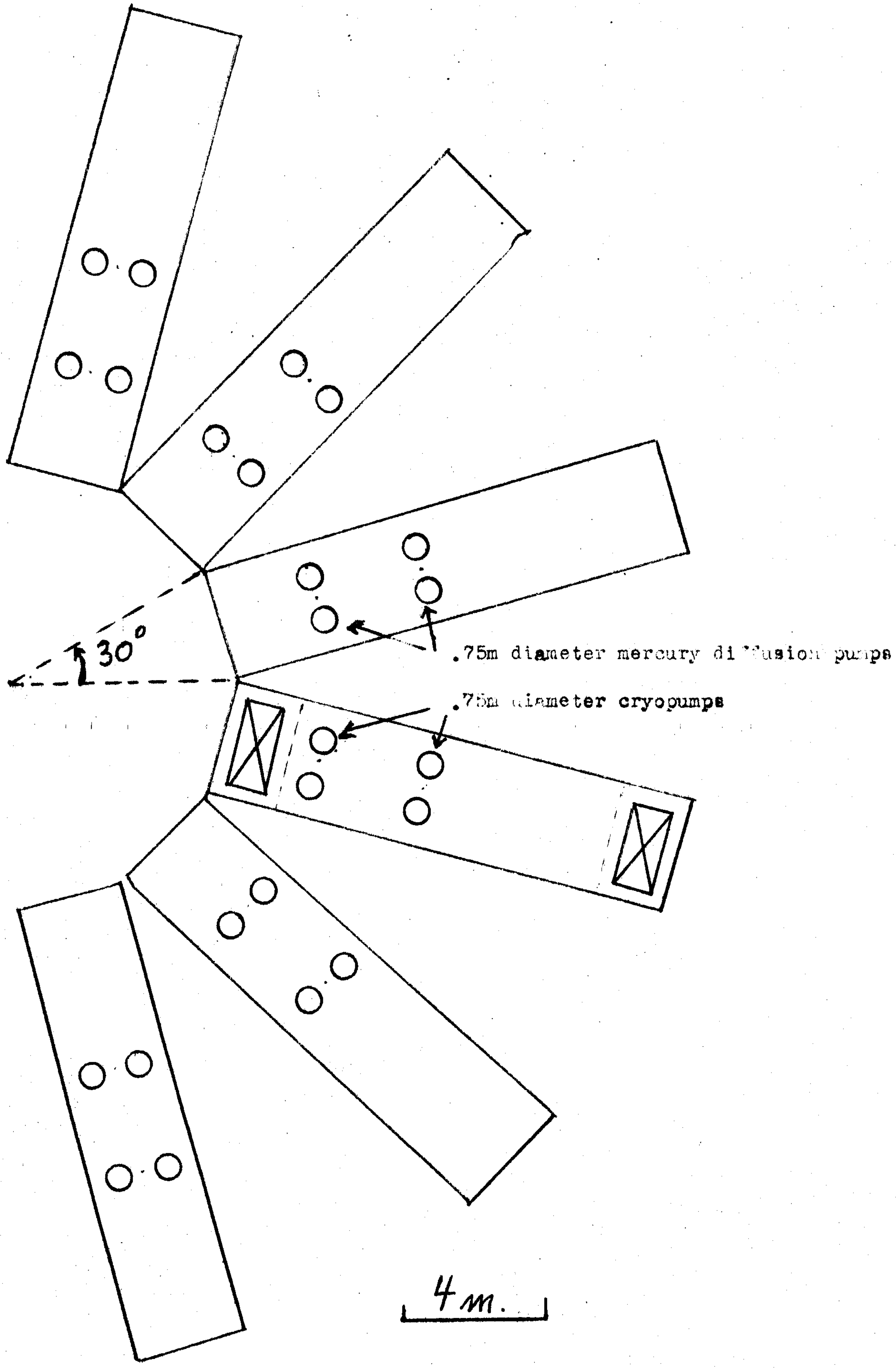
so $S = 5 \times 10^6$ ℓ/sec

$p = 2 \times 10^{-6}$ torr

$Q = 10^3$ torr-ℓ/sec

Tritium Recovery

Tritium recovery is considered only as a problem, and not a solution. The exhaust from the forepump 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.



ARRANGEMENT OF VACUUM PUMPS