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VACUUM PUMPING FOR CONTROLLED THERMONUCLEAR REACTORS*

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SUMMARY

Thermonuclear reactors impose unique vacuum pumping problems involving very high pumping speeds, handling of hazardous materials (tritium), extreme cleanliness requirements, and quantitative recovery of pumped materials. Two principal pumping systems are required for a fusion reactor, a main vacuum system for evacuating the torus and a vacuum system for removing unaccelerated deuterium from neutral beam injectors. The first system must pump hydrogen isotopes and helium while the neutral beam system can operate by pumping only hydrogen isotopes (perhaps only deuterium). The most promising pumping techniques for both systems appear to be cryopumps, but different cryopumping techniques can be considered for each system. The main vacuum system will have to include cryosorption pumps cooled to 4.2°K to pump helium, but the unburned deuterium-tritium and other impurities could be pumped with cryocondensation panels (4.2°K) or cryosorption panels at higher temperatures. Since pumping speeds will be limited by conductance through the ducts and thermal shields, the pumping performance for both systems will be similar, and other factors such as refrigeration costs are likely to determine the choice. The vacuum pumping system for neutral beam injectors probably will not need to pump helium, and either condensation or higher temperature sorption pumps can be used.

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VACUUM PUMPING FOR CONTROLLED THERMONUCLEAR REACTORS

INTRODUCTION

Controlled thermonuclear reactors (CTRs) require unique combinations of vacuum pump requirements. Significant development will be required to obtain operating data and to demonstrate the performance of the relatively few suitable pumping methods. A commercial Tokamak may require pumping speeds of more than 5×10^6 l/sec in the main vacuum system alone, and neutral beam injectors may increase the total speed requirements several fold more. Although pumping speeds this high, and greater, have been achieved in several large vacuum systems, particularly in space simulation vessels, and although some of these high pumping speeds have been achieved with hydrogen at pressures near those of interest in Tokamaks, the unique combination of these requirements with substantial quantities of helium, with very high recovery efficiency, and with essentially zero release of the pumped gases (e.g., tritium) to the environment is unique to CTRs. This paper will address the requirements of Tokamak reactors and experiments, but most of the requirements and solutions will be similar for other fusion devices.

Two large high vacuum pumping systems are required for Tokamaks: (1) a main vacuum system to pump down the torus between pulses and to remove impurities during the pulse and (2) a vacuum system to remove unaccelerated deuterium (perhaps tritium) from the beam drift tube. In addition, a roughing system and a few smaller vacuum pumps for fuel processing will be required. The main vacuum system will pump deuterium, tritium, helium, and other impurities from the torus. The beam vacuum system currently appears likely to pump only a single hydrogen isotope, probably only deuterium. Conventional roughing pumps may be used, but great care will be required to insure that no unacceptable quantities of tritium escape to the environment or that personnel exposures during maintenance be excessive.

Main Vacuum Pumps

The main vacuum system is that which removes the bulk of the unburned fuel, helium ash, and impurities from the torus between pulses and perhaps during the pulse. The ducts to these pumps will be located near divertor impact surfaces if divertors are used; otherwise the ducts could be located in almost any position around the minor radius. The ports should be evenly spaced around the

major radius. As noted earlier, these pumps must be capable of removing D, T, helium, and any other outgas or sputtered impurity from the torus. Essentially complete recovery of valuable tritium must be possible with virtually no release to the environment.

The high vacuum pumping speed requirements may be set by either the allowable pump-down period between pulses or the required removal rate for impurities during the pulse. The pump-down rate can be readily calculated, and allowable pump-down times appear to be obtainable with reasonable pumping speeds. For example, an Experimental (Tokamak) Power Reactor (EPR) currently being designed at ORNL (and elsewhere) contains an 8.30×10^5 l torus (and duct) volume to which are attached 40 high vacuum pumps with effective speeds of 50,000 l/sec (for D-T) each (1.1×10^6 l/sec total correcting for duct conductance). This system would pump the torus from 10^{-5} torr to a base pressure of 10^{-8} torr in 5 sec. This is considered a reasonable between pulse pump-down period for EPR [1]. In commercial power reactors, one would minimize the down-time between pulses to less than approximately 10% of the pulse time, preferably to much less. Thus commercial reactors with short pulse times are likely to require greater pumping speeds than reactors with longer pulses. Vacuum pumping for impurity control is not well understood, and it is even questionable if vacuum pumping during a pulse will be significantly helpful.

The pumping speed of the main vacuum system is likely to be limited or severely reduced by the conductance of the duct systems. The ducts must extend through the blanket shield and TF coils. The duct length will not vary greatly with reactor size (power). Since the vacuum ducts must pass between the TF coils, the separation between coils less the thickness of adequate coil shielding sets a limit on one dimension of the duct. Rectangular rather than circular ducts give maximum use of the available space between coils.

The conductance of the ducts will be reduced considerably by shielding requirements. Turns will be required in the ducts to prevent neutron streaming down the duct, and each turn reduces the conductance of the duct. In one respect, shielding problems are likely to affect the conductance in large reactors more than in small reactors. As the reactor major radius gets larger (and the separation between TF coils increases) one might expect the duct size to increase. However, it is more difficult to shield large ducts to prevent neutron streaming, and increases in duct dimension much greater than 1 m may not be practical. Thus more rather than

larger ducts may be used. Another reason for expecting conductance limitation in the ducts is the competition for blanket volume. At best, vacuum ducts and neutral beam drift tubes will occupy several percent of the blanket surface. This will result in loss of breeding capabilities; so every reasonable effort will be made to minimize the number and size of vacuum ducts until lower conductances can no longer be tolerated.

When the pumping speeds required, the need to recover essentially all pumped fuel, and the necessity to prevent releases of tritium to the environment are considered, many pump types such as mechanical pumps, sublimation pumps, and ion pumps have to be ruled out. Mercury diffusion pumps have been selected [2] for the Tokamak Fusion Test Reactor (TFTR), but these pumps require other backing pumps. The ability to scale-up mercury diffusion pumps to large Tokamak reactors handling orders of magnitude more tritium is questionable. The pumping systems which currently appear most attractive for the main vacuum systems for larger reactors are cryosorption and cryocondensation pumps. Cryosorption pumps can meet all of the requirements of CTR systems. Cryocondensation pumps will not pump helium, but they can be backed with cryosorption pumps to fill all CTR needs.

Cryosorption pumping of helium and hydrogen isotopes have been studied at ORNL. The pump under study is a commercial pump manufactured by the Excalibur Corp. (Model 1106). This pump contains a 320cm^2 sorption surface with 30 g of molecular sieve which is cooled to liquid helium temperatures. The sorption surface is surrounded by two sets of chevrons which act as thermal shields. The inner chevron is cooled by helium boiled off from cooling the sorbent surface. The temperature of this chevron can vary depending upon pumping conditions, but at relatively low operating pressures, the manufacturer indicates that the temperature is approximately 20°K . The outer chevron is cooled with liquid nitrogen (77°K). Some recent ORNL data from this pump are shown in Fig. 1. The pumping speed for deuterium is shown at pressures exceeding 10^{-3} torr. At low pressures, the pumping speed is constant at approximately 3.1 l/sec-cm^2 . The pumping speed remains constant until the pressure reaches 1×10^{-4} torr; then as the pressure is increased further, the pumping speed increases to a high of 5.6 l/sec-cm^2 at 3×10^{-3} torr. We were not able to operate the pump above 3×10^{-3} torr; since the cryosorption panel could no longer be kept cold. This may correspond to the critical boiling rate for helium. The increase in pumping speed from 1×10^{-4} to 3×10^{-3} torr is believed to result largely from the change from molecular to viscous flow through the chevrons. At the extremely high boil-off

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rates, the first chevrons may have become cool enough to act as condensation panels. The pumping rates shown can be maintained while large quantities of deuterium accumulate on the sorption panel; we have tested loading to 10 times the theoretical maximum sorption capacity. That is, cryosorption pumps can operate as condensation pumps with deuterium, and probably with tritium as well. Regeneration of this pump has been rapid, requiring only seconds after the liquid helium is removed from the cryopanel.

Since either condensation or sorption pumps appear to be effective in pumping deuterium and tritium, on what basis should one choose between the two techniques? First, one should note that the pumping speed for either system will be limited by conductance to the panel, not by performance of the panel itself. Better pumping speeds are likely to come from better chevron design or from elimination of a chevron. One basis for the choice will be the refrigeration costs (liquid helium consumption). One advantage of metal condensation panels is that highly polished surfaces can be used which have very low thermal emissivities. Recent results [3] from Lawrence Livermore Laboratory indicate that this low emissivity is maintained even after substantial quantities of hydrogen or deuterium are condensed. The emissivity of molecular sieve surface, however, can not be improved significantly by polishing, but the refrigeration costs for molecular sieves can be reduced several fold by operating the surfaces at higher temperatures, perhaps near 20°K. The capital costs for sorption panels are likely to be higher than for base metal panels, but the cost of panels will be only a small portion of the overall pump cost.

Vacuum pumping studies at ORNL are aimed at answering some of the questions just raised. Cryosorption pumping of mixed gases (helium and hydrogen isotopes) and cryosorption pumping of hydrogen isotopes at higher temperatures (15 to 20°K) are in progress or planned for the next few months.

Neutral Beam Vacuum Pumps

Pumping of unaccelerated gas from the change-exchange region of the beam and from the burial vault for deflected beams requires very large pumping speed capabilities. Some current beam designs enclose as much of the beam line as possible with pumping surfaces. The current ORNL design [1] for an EPR provides for approximately 10^6 l/sec pumping capacities for each of twelve 85 MW injectors. If there is no need to pump helium, then cryocondensation or higher temperature cryosorption pumps can be used alone, e.g., without 4.2°K cryosorption. Since maximum pumping

speeds will be needed, there will be incentive to use only a single chevron. Without helium pumping, the helium partial pressure in the drift tube and throughout the beam system will, to a first approximation, be the same as the helium pressure within the torus, while the beam port is open. For a 10% burn, this could be 10% of the torus pressure, and this could be undesirable. For near term machines with much lower fraction burns, there is not likely to be a need for helium pumping in the neutral beam system.

Although neutral beam injectors may nominally handle only deuterium, enough tritium will diffuse up the drift tube to contaminate the deuterium sufficiently that most safety requirements of the main vacuum system will be used. Tritium inventory consideration, however, will not require frequent regenerations; so it will be possible to operate the pumps for several days between regenerations. Condensation pumps will be capable of storing more deuterium than 15-20°K sorption pumps. The pumps will be regenerated and the deuterium recycled to a beam feed storage tank. A side stream will go to an isotope separation system (cryogenic distillation) to prevent buildup of tritium in the beam feed.

Roughing Pumps

As in all high vacuum systems, roughing pumps will be required to pump-down the torus to a pressure where the main high vacuum system can take over. With cryosorption or cryocondensation pumps in the main vacuum system, the roughing pumps should reduce the pressure to approximately 10^{-3} torr or below before the high vacuum pumps are started. Since the system will be brought up to pressure only occasionally, several minutes can be allotted for roughing. A relatively small roughing duct and modest pumping speeds can be used. The ORNL design [1] for EPR, like many other designs, uses mechanical roughing pumps, three 5000 cfm each Roots Blowers and three 500 cfm primary mechanical pumps. This system will "pump down" the EPR torus in approximately 24 min.

The discharge from the roughing pump must be considered to be contaminated since tritium will out-gas from the torus walls once the reactor has begun operation. The roughing pump discharge will exhaust through a tritium clean-up system before it is released to the atmosphere.

Although the current ORNL design calls for Roots Blowers, consideration also is being given to large cryosorption pumps operating at liquid nitrogen temperatures (77°K) for roughing. The important question in the choice is whether it will be

possible to accidentally fill the torus to atmospheric pressure with fuel (50% tritium). Discharge of this much tritium through the blower and the atmospheric clean-up system would be possible but not desirable. Molecular sieve pumps at 77°K would provide better containment but they have limited capacities for deuterium and tritium. Several large pumps would be required. This is just one of several questions or choices which will require more study of several facets of the overall vacuum, containment, process, and feed system.

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