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VACUUM PUMPING OF TRITIUM IN FUSION POWER REACTORS

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Summary

The high vacuum pumping requirements of fusion reactors are well enough defined to identify several candidate vacuum pump designs. The most promising approach is cryogenic pumping, because staged or compound cryopanels are capable of producing high specific pumping speeds for both helium and hydrogen isotopes. Compound cryopumps of three different designs will be tested with deuterium-tritium (DT) mixtures under simulated fusion reactor conditions at the Tritium Systems Test Assembly (TSTA) now being constructed at the Los Alamos Scientific Laboratory (LASL). The first of these pumps is already in operation, and its preliminary performance is presented. The supporting vacuum facility necessary to regenerate these fusion facility cryopumps is also described. The next generation of fusion system vacuum pumps may include non-cryogenic or conventional-cryogenic hybrid systems, several of which are discussed.

Requirements

The problems associated with high vacuum pumping

Requirements

The problems associated with high vacuum pumping of fusion devices are well documented: pulsed operation at very high pumping speeds; handling mixtures of both radioactive tritium and helium in the exhaust stream; maintenance difficulties arising from inaccessibility and material activation. At the LASL Tritium Systems Test Assembly (TSTA), all the principal hardware required for fuel processing in DT-burning reactors will be tested and qualified. Among the functions included at TSTA are removal of helium and other impurities, isotopic separation, DT mixing, plasma fuel injection, transfer and high vacuum pumping, and vacuum pump regeneration. To be acceptable for fusion applications, TSTA high vacuum pumps must meet the following requirements:

- Provide highest pumping speeds;
- Pump mixtures of DT, helium, and plasma chamber impurities;
- Produce base pressures of 10 ntorr or less;
- Be unaffected by pulsed gas loads and brief excursions to pressures of 1 mtorr.

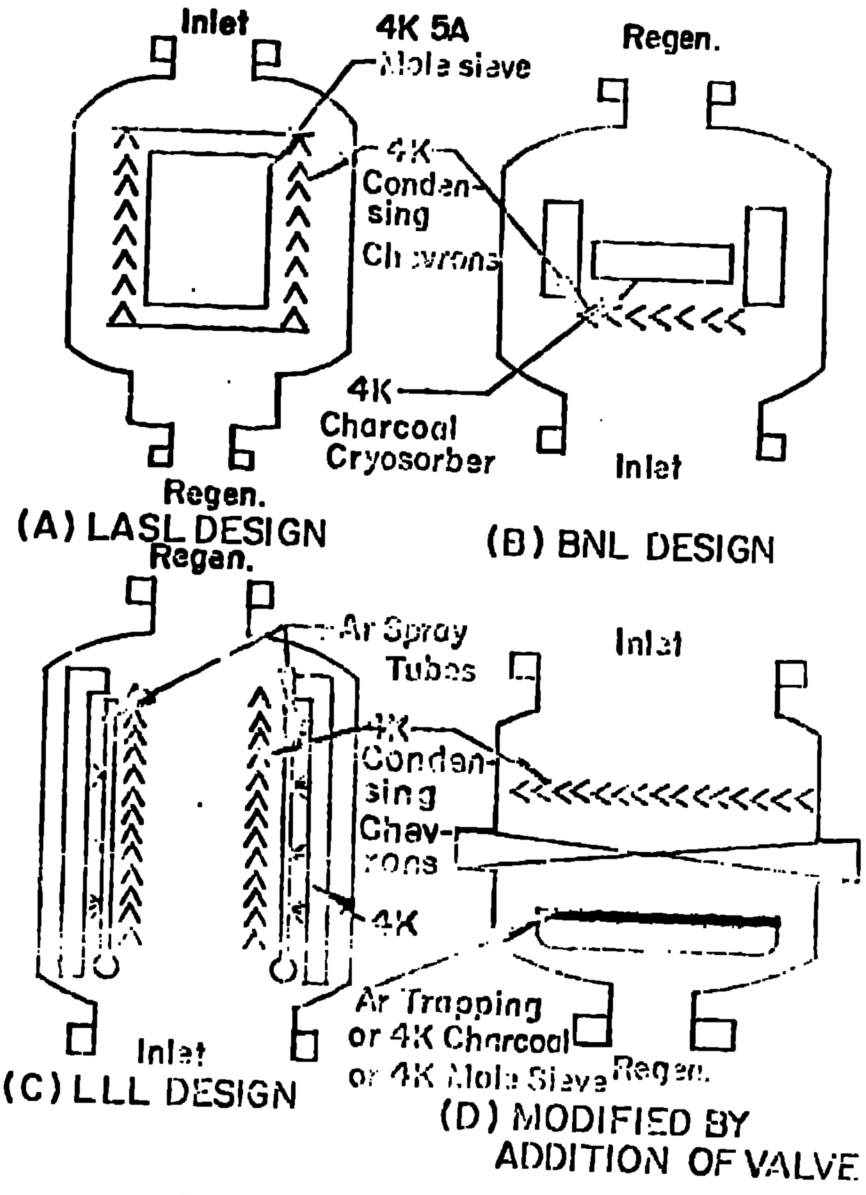
In addition to the above requirements the following features are desirable:

- Helium separation during pumping;
- Low maintenance design.

Candidate Pump Designs

LASL-TSTA Cryopumps (Fig. 1)

Several pump designs should meet the requirements given above; a common feature is placement of a hydrogen pump in series with a helium pump. Another feature, desirable in some designs and mandatory in others, is a valve or conductance limiter between stages. The pumps to be evaluated first under the TSTA program are two-stage cryogenic pumps. One of



(A) LASL DESIGN

(B) BNL DESIGN

(C) LLL DESIGN

(D) MODIFIED BY ADDITION OF VALVE

Fig. 1. Compound cryopump designs (LN_2 surfaces not shown).

these pumps has been procured by LASL and is already operational; the other two pumps will be fabricated and supplied to LASL by Brookhaven National Laboratory (BNL) and by Lawrence Livermore Laboratory (LLL). Design pumping speeds for all the TSTA cryopumps are 16 m^3 s^{-1} for deuterium and 1.5-5 m^3 s^{-1} for helium. Design capacities for these same gases are 2 moles and 0.2 mole respectively.

The LASL-conceived pump, Fig. 1(A), has a 35-cm-diam top inlet port, a 15-cm-diam helium regeneration port at the bottom, and a 4-cm-diam side port for DT regeneration. Concentric cylinders form the two stages: the outer cylinder consists of 90° vertical copper chevrons; the inner, shielded cylinder is an annulus coated with 5A molecular sieve. Originally intended for operation with a closed cycle refrigerator, the LASL pump is presently cooled by continuous liquid helium flow. Charcoal is the adsorbent in the BNL cryopump, Fig. 1(B); the panels are flat, and the pump inlet is at the bottom. BNL has developed a new method of bonding charcoal to the cryopanel by casting it in a matrix of a low-melting alloy.[1] The tritium compatibility and thermal conductivity problems inherent in epoxy bonded designs are thus avoided. Cylindrical geometry and radial flow characterize the LLL pump, Fig. 1(C). After passing through the 77 K shields and 4 K DT-cryocondensing chevrons, helium is cryotrapped by continuous argon spray on a smooth 4 K surface. The argon, which is injected through vertical spray tubes, traps one part of helium to every 15-30 parts of argon.[2] Helium reservoirs within the pump bodies maintain the cryo-surfaces near 4 K for both the BNL and LLL cryopumps.

In each of these pumps helium is separated from the other torus effluents as a consequence of the basic pump design. If this separation is to be maintained during panel regeneration, the helium evolution rate must be carefully matched to the regeneration pump speed; otherwise excessive pressures will cause gaseous conduction and thermal runaway. The helium is regenerated first, since it can pass over the frozen DT on the condensing panel without being condensed or adsorbed. Once the helium is desorbed, the helium regeneration pump may be valved off, and the contents of the cryocondensing panel is vaporized and pumped away by a different set of pumps at fairly high pressures. During this phase the helium cryosorber must be kept warm enough to prevent DT from readsorbing on it.

Valve for Stage Separation (Fig. 1(D))

Separation of the pump stages with a valve or conductance limiter is desirable on some pump designs. For compound cryopumps the advantage of a valve is that the He/DT separation achieved during normal operation can be maintained even while the pump is being regenerated at high pressure (1-10 torr). Regenerating both pump panels simultaneously at high pressure could increase the pump duty cycle from 50% to over 80% and result in a significant system cost savings, because the number of pumps needed is greatly reduced. An absolute valve is not necessary because traces of DT can be removed from the regenerated helium by an auxiliary tritium waste treatment system before it is expelled. Significant helium leakage to the DT stage must be limited, because helium degrades the efficiency of the cryogenic distillation columns that separate the hydrogen isotopes. A valve between stages also eliminates contamination of the cryosorber by gases evolved from the cryocondenser. There is then no need to heat the cryosorber during regeneration, further cutting cycle time and extending the life of to over 80% and result in a significant system cost savings, because the number of pumps needed is greatly reduced. An absolute valve is not necessary because traces of DT can be removed from the regenerated helium by an auxiliary tritium waste treatment system before it is expelled. Significant helium leakage to the DT stage must be limited, because helium degrades the efficiency of the cryogenic distillation columns that separate the hydrogen isotopes. A valve between stages also eliminates contamination of the cryosorber by gases evolved from the cryocondenser. There is then no need to heat the cryosorber during regeneration, further cutting cycle time and extending the life of the cryosorber.

Alternate Pumping Arrangements

Physical separation of the pump stages with a valve or conductance limiter is mandatory on the pump designs shown in Fig. 2. These hybrids use an oil diffusion pump or turbopump for the helium. During DT regeneration, the conductance limiter is closed, and the gas on the DT stage (condenser or getter) is regenerated and taken off to be purified for reuse. A conductance limiter, rather than an absolute valve, can be used to separate the stages during DT regeneration. Leakage of DT to the helium pump can be prevented by maintaining a slightly positive pressure of D_2 on the helium side of the conductance limiter.

Pressurization with gaseous deuterium prevents tritium contamination of the diffusion pump oil or turbopump bearing lubricant; maximum deuterium pressure is approximately 10 torr, well below the

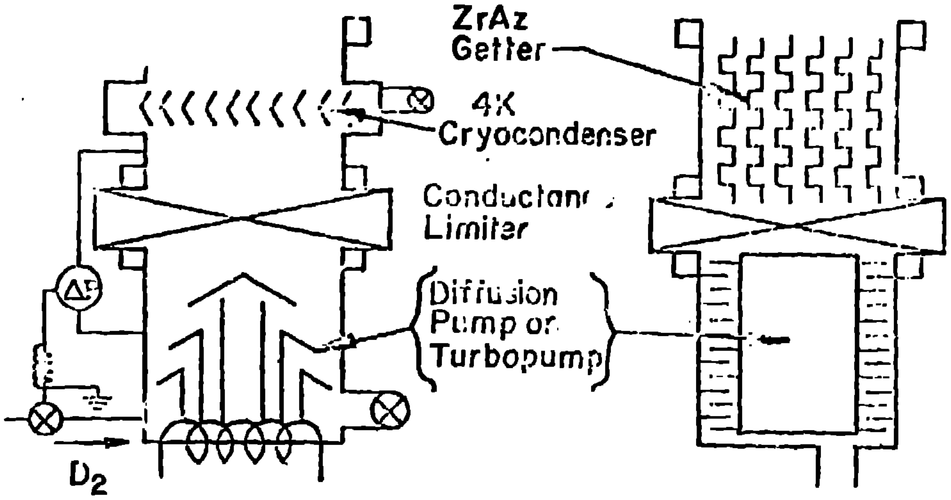
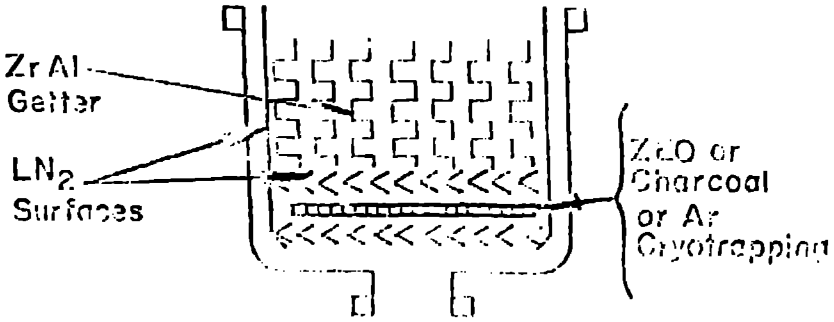


Fig. 2. Valved hybrid fusion vacuum pumps (LN_2 surfaces not shown).

explosive range. If the turbopump has magnetic bearings, slight tritium leakage can even be passed through the turbopump and removed by the TSTA tritium waste treatment system. Currently available turbopumps are too small for fusion applications, but pumps as large as 10 m^3 s^{-1}, have been built, so turbopumps suitable for helium may become commercially available.

As an alternative to cryocondensation a non-evaporable getter can pump the DT gas, as indicated in Fig. 2(b), but some precautions must be observed with this approach. The reversible DT-sorption capacity of the getter is degraded by pumping active gases. Liquid nitrogen traps upstream of the getter remove condensable impurities (H_2O, NH_3, CO_2) but some permanent gases and hydrocarbons (CO, O_2, N_2, CH_4) will reach the getter, as the projected hydrocarbon impurity level for plasma exhausts is about 0.1%. If the getter is operated at low temperatures, the adsorption of permanent gases and hydrocarbons will be negligible. Another concern is that base pressure may be too high, but again the solution is to operate the getter at relatively low temperatures. Pumping speed for hydrogen isotopes is nearly constant from 300 K to 675 K, so operating at or below 375 K should give satisfactory base pressures. The final problem with using a getter for DT pumping is that of providing sufficient helium conductance through the getter array, so that the second stage pump is able to maintain a satisfactory helium base pressure within the torus. Vacuum conductance calculations should be made to optimize helium conductance through getter arrays that have adequate DT temperatures, the absorption of permanent gases and hydrocarbons will be negligible. Another concern is that base pressure may be too high, but again the solution is to operate the getter at relatively low temperatures. Pumping speed for hydrogen isotopes is nearly constant from 300 K to 675 K, so operating at or below 375 K should give satisfactory base pressures. The final problem with using a getter for DT pumping is that of providing sufficient helium conductance through the getter array, so that the second stage pump is able to maintain a satisfactory helium base pressure within the torus. Vacuum conductance calculations should be made to optimize helium conductance through getter arrays that have adequate DT capacity and pumping speed.

One further approach to staged pumping of hydrogen isotopes and helium is shown in Fig. 3. The advantage of this configuration is that the helium panel may be regenerated at high pressure without thermal



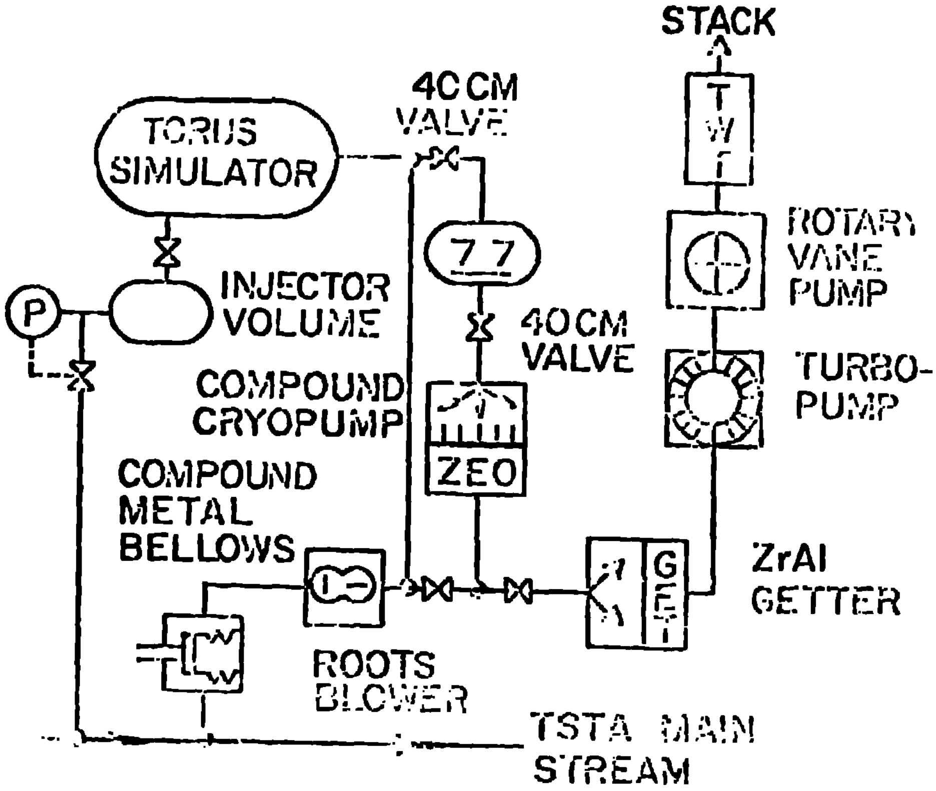


Fig. 4. TSTA vacuum system.

effects causing the simultaneous release of the DT on the adjacent getter, so no valve is needed between stages. During getter regeneration the cryosorber must not be contaminated by the evolved DT, but this can be prevented by concurrent heating of the sorption panel.

TSTA Vacuum System

General Description

The TSTA vacuum system (Fig. 4) is a test stand for evaluating high vacuum pumps for fusion reactors, and its key features are:

- DT gas injection
- Torus simulator volume
- 40-cm absolute valves
- Liquid nitrogen trap
- Helium regeneration pumps
- DT regeneration pumps.

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- *DT gas injection*
- *Torus simulator volume*
- *40-cm absolute valves*
- *Liquid nitrogen trap*
- *Heliu regeneration pumps*
- *DT regeneration pumps.*

Compound cryogenic pumps are readily evaluated because of the special pumping path used only for helium regeneration. The objective of the vacuum system is to test the torus high vacuum pumps and their supporting hardware under realistic conditions of pressure, gas mixture and duty cycle for long periods. The appropriate gas mix is diverted from the TSTA main stream and injected into a torus simulator, from which it is pumped by one of the TSTA cryopumps and then returned to the main loop during the regeneration cycle. The helium is not returned to the main process stream, but is exhausted through a Zr-Al getter by a magnetic bearing turbopump and oil-sealed rotary vane pump. The room temperature

TABLE I

CRYOPANEL REGENERATION PARAMETERS

Requirement	Cryosorber (He)	Cryocondenser (DT)
Base Pressure[a]	10^{-8}	$5(10)^{-2}$
Peak Pressure During Regen.	$2(10)^{-4}$	1-100
Exhaust Pressure	800	300-500
Organic-free	No	Yes
Double Containment	No	Yes

[a] All pressures given in torr

getter captures any trace amounts of DT evolved during helium regeneration. The helium has already been filtered by its passage over the 4 K cryocondensers.

<u>Regenerative Pumping Trains</u>

Separate pumps are used for regeneration of the helium cryosorber and DT cryocondenser panels because the requirements differ: some characteristic of both processes are given in Table I.

<u>Cryosorber Regeneration</u>. To regenerate helium from a cryosorber panel requires high helium pumping speeds at pressures below gas conduction densities. This requirement can be met with a turbopump backed by an oil-sealed rotary pump. Because we could not absolutely ensure that there would be no DT contamination of the helium, we chose a magnetic-bearing (non-lubricated) turbopump and a hermetically sealed rotary pump with ducted exhaust.

<u>Cryocondenser Regeneration</u>. For DT panel regeneration two pumps meet the base pressure requirements, but neither is completely satisfactory in its normal configuration. The Normetex* bellows-scroll design has been used successfully for European UF_6 applications for more than 25 years. This pump is completely free of organics and is driven through a metal bellows seal. The TSTA application calls for a smaller pump than the production model, and a prototype is being built and tested by Normetex. It will be installed in TSTA later if the prototype tests are successful.

An alternate design derives from Roots blowers, which are readily available in a variety of sizes. The main drawback of currently available pumps lies in the design of the rotor shaft seal that separates the dry pumping chamber from the gearbox and bearing lubricants. On some recent models, this seal has been upgraded from an open labyrinth to a piston ring

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Either the Roots or Normetex pump requires a forepump to complete compression and transfer back to the main process loop at 500-800 torr. We have chosen metal bellows pumps for this application because of their freedom from organics, simple and reliable design, and long service life. To achieve the required throughput and overall compression ratio, two double-stage MB-601 pumps, manufactured by Metal Bellows Corp.,†† are arranged in a series-parallel configuration.

Secondary Containment

Double containment is provided for all the DT-regeneration (Roots and metal bellows) pumps. At TSTA a DT pressure in excess of 75 torr is the

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**Ferrofluidics Corp., 144 Middlesex Turnpike, Burlington, MA 01803

†† Metal Bellows Corporation, 1075 Providence Highway, Sharon, MA 02067

† Leybold Heraeus, 200 Seco Road, Monroeville, PA 15146

general criterion for double containment. The Roots blower case is a casting, made in sections sealed with elastomer o-rings. Tritium will permeate both these materials, so double containment is provided even though operating pressure is well below 75 torr. We will also replace the elastomeric static seals with metal compression seals if possible. Secondary containment of the rest of the vacuum system is not contemplated because of low DT pressure, relatively small inventories of tritium within the cryopump, and the high mechanical integrity inherent in hard seals and vacuum chamber walls.

Valve Selection

Elastomers are not normally used for fusion devices because they are not tritium-compatible. Polyimide or metal seals are used on all TSTA valves except for the large gate valves that close for cryopump and cold trap regeneration. Economy was one reason for using elastomers in this location. In the 40-cm size needed, a polyimide valve costs four times as much as a soft seal valve. Several laboratories and manufacturers are working on the problem of absolute hard-seal valves,[3] but fusion vacuum system designers need to balance the high costs of large hard valves against the known deficiencies of elastomers. One design practice is a double sealed gate with independent evacuation between the seals. More data is needed to enable designers to predict seal life and to establish replacement schedules for elastomers exposed to tritium at the concentrations encountered in high vacuum systems. Virtually no low-concentration exposure data exists, and the nature of tritium-organic interactions makes it difficult to predict seal life from existing data, most of which come from other types of radiation. The use of soft seal valves in the TSTA vacuum system will provide some of the needed data, and this is another reason for choosing them. Actual seal leakage will be monitored during long exposures to operational DT concentrations, and these data will establish whether elastomer-sealed valves are acceptable in fusion reactor vacuum systems.

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The TSTA Compound Cryopump

General Description

The TSTA cryopump is the first design to adress the unique vacuum requirements of an operating fusion reactor by employing staged cryopanels. Attempts to pump hydrogen and helium on a single cryosurface have met with only limited success. Exposure of a hydrogen/helium gas mix to a 4 K cryocondenser results in negligible helium pumping.[4] If a cryosorber is substituted for the cryocondenser, the hydrogen quickly ices over the sorbent surface and renders it ineffective for pumping the helium. The TSTA design avoids these difficulties by staging the cryopumping process. All the hydrogen isotopes are frozen on an optically dense cryocondensing chevron array, which also shields the second stage cryosorber from all condensable gases so that it can adsorb helium most effectively.

Both panels are refrigerated by continuous flow of liquid helium. The constant heat leak from the transfer line, coupled with a controllable refrigerant flow rate, allows us to vary the quality of helium passing through the cryopanels from liquid to superheated vapor. The resulting temperature control allows us to desorb helium from the molecular sieve without disturbing the DT still frozen on the adjacent cryocondenser. The resulting DT concentration is low enough to permit use of conventional oil lubricated pumps to transfer the regenerated helium through a tritium waste treatment system before it is released from the facility. We have been operating this cryopump since March, 1979, and it has successfully pumped hydrogen, deuterium, helium, and nitrogen, as well as various mixtures of hydrogen, deuterium, helium, and argon.

Pumping Speed Measurements

Our pumping speeds were calculated from measurements of pressure and feed rate. A glass-enclosed Bayard-Alpert gage, with manufacturer supplied sensitivity corrections, was used to determine helium and deuterium pressures. Feed rate was determined by timing the displacement in an inclined oil burette. The burette was calibrated by comparing its volumetric change rate to that calculated from the pressure/time behavior of the sealed cryopump housing as it collected the feed gas. Test gas was admitted to the cryopump by a diffuser ring which directed the gas against the inlet closure plate.

Helium Performance. The molecular sieve was baked out at 525-575 K for 24 h immediately preceding the test. If no bakeout was performed within a few hours before testing, helium performance was degraded substantially. As an example, when the molecular sieve was quickly cooled after bakeout and measurements begun within a few hours, speed gradually decreased with loading from 2 to 1 m^3 s^{-1} as 500 torr L of helium were sorbed. On the other hand, if several days elapsed after bakeout, then the same decrease in speed occurred before 50 torr L had been pumped. The probable cause of this degraded performance is the small but constant pumping of condensable impurities by the sieve during ambient temperature vacuum exposure. This characteristic of molecular sieve limits its usefulness for fusion pumping applications unless the cryosorber is isolated by a valve when it is not pumping helium.

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Fig. 5 shows the speed vs loading of the TSTA 5A molecular sieve for two feed rates. Performance of the LASL cryosorber is compared with data published by Oak Ridge National Laboratory (ORNL). One difference is the higher starting value obtained on the fresh adsorbent by ORNL. This difference probably originates from a conductance limitation in

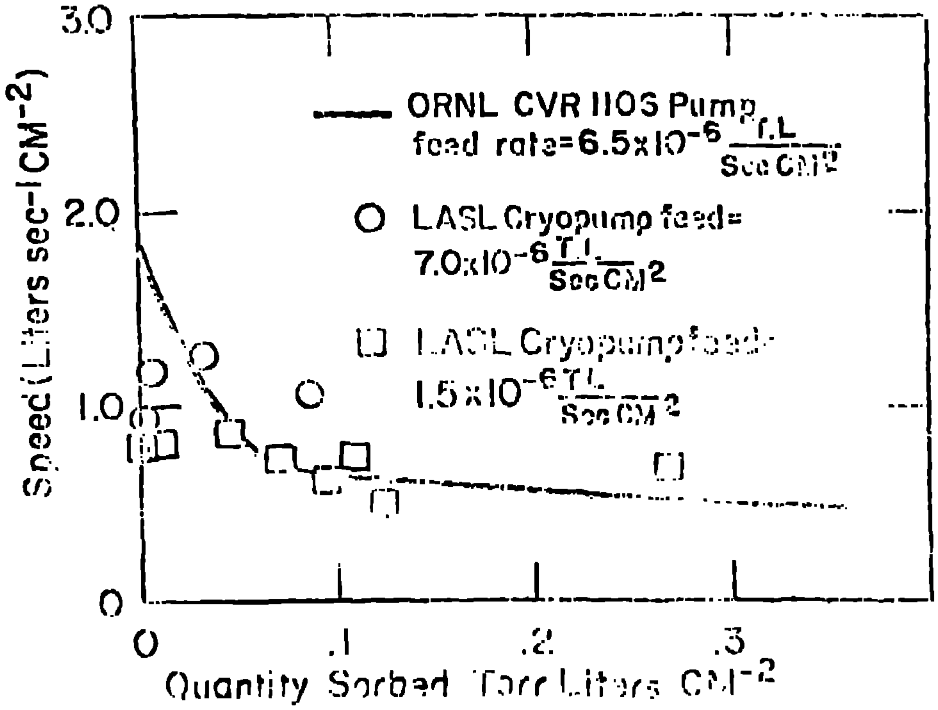

Fig. 5. TSTA cryopump performance (He).

the 77 K chevrons, throat, and 4 K chevrons of the TSTA pump. At a loading of 0.04 torr L cm^{-2}, the diffusion rate of helium into the molecular sieve apparently becomes the limiting restriction on pumping speed and the data become similar. The data of the high-feed-rate run were obtained after the helium sorbed during the first run was pumped away in a controlled pressure regeneration. We accomplished the latter by reducing liquid helium flow to the cryosorber while maintaining normal flow to the cryocondenser, and as transfer line heat leak warmed the inner panel, helium was desorbed at pressures around 10^{-4} torr. We considered regeneration to be complete when the cryosorber temperature reached 15 K.

At higher feed rates the performance of the pump varied greatly, so we report only general observations. As feed rates were increased from 10^{-5} to 10^{-4} torr L s^{-1} cm^{-2}, initial speed declined by approximately a factor of three. At these higher feed rates speed also decreased more rapidly as a function of quantity sorbed. If flow was pulsed on a 2 min on, 3 min off schedule, the speed reduction was not as marked, and base pressure recovered to the starting value during the off period. Flow was varied between 10^{-5} and 10^{-4} torr L s^{-1} cm^{-2} in a pulsed mode with repeatable results until the quantity sorbed became a factor. The implications for fusion pumping are mixed: The reduction in pumping speeds at higher feeds and pressures is disappointing, and this may be the factor which drives cryopump design; on the other hand the quick recovery at lower pressures and cyclic feeds is encouraging. During TSTA operation we will conduct many more experiments with this pump with realistic gas mixtures and pressure loading cycles.

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Deuterium Performance. The design speed for deuterium was 16 m^3 s^{-1}. Actual measured performance ranged from 2 to 8 m^3 s^{-1}. This poor performance may be due to poor cryogenic insulation, which gives rise to warm spots on the cryocondenser panel. Pumping speed measurements with nitrogen tend to confirm this hypotheses, and lead to a predicted deuterium speed of 14 m^3 s^{-1}, substantially in agreement with the design value. We now plan to thoroughly instrument the cryocondenser supports and chevrons to measure temperature gradients. This should provide a basis for modifying the structural supports to improve thermal isolation and augment deuterium pumping performance.

Mixture Performance. Mixtures of deuterium and helium have been pumped at feed rates ranging from 0.01 to 0.3 torr L s^{-1} for several hours. The apparent mixture speed varied from 1 to 8 m^3 s^{-1}, but the speed determination required an assumption of gas mixture concentration within the pump body. This assumption was needed to establish an ion gage sensitivity and was, in turn, based upon the relative measured pumping speeds of the two cryopanels. In spite of the cumulative error in these estimations of pumping speed, the observed performance agrees with expectations based upon pure gas behavior of the individual panels. The degree of helium separation attained during operation and regeneration was measured and found satisfactory to qualify the pump as the TSTA helium remover. The pump was operated normally with a 90/10 mixture of H_2/He, and again with a 90/5/5 mixture of D_2/He/Ar. After a suitable period the feed gas supply was shut off and a controlled pressure regeneration of the helium cryosorber was performed, as previously described. Then the pump body was sealed and allowed to warm to room temperature. The gases thus evolved from the cryocondenser were then analyzed for helium. The helium mole fractions appearing in the regenerated H_2 and D_2/Ar mix respectively were 2.7×10^{-4} and 1.4×10^{-5}, which agrees with data reported by Chou and Halama.[4] The DT stream can therefore be passed back to the main fuel loop without further helium removal.

Conclusions

Vacuum pumps for the first DT-burning fusion machine will have been operated at the TSTA under realistic conditions in advance of hardware commitments. Compound cryopumps are the present front runners for high vacuum fusion applications, and the first 3 pumps to be tested at TSTA are variations of this design approach. The first of these designs, a cryopump designed at LASL, is operational and has pumped mixtures of deuterium, hydrogen, and helium. The concept of using a compound cryopump as the fuel system helium ash separator has been successfully demonstrated. All the auxiliary tritium-compatible vacuum components for the TSTA vacuum system have been procured, and these will be exposed to realistic tritium concentrations over the long period of TSTA operation. The resulting data base will be of considerable value to designers of DT-burning fusion devices.

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