

Performance of BNL-TSTA compound cryopump^{a)}

H. C. Hseuh and H. A. Worwetz

Accelerator Department, Brookhaven National Laboratory, Upton, New York 11973

(Received 5 September 1980; accepted 6 November 1980)

The Tritium Systems Test Assembly Vacuum Facility at Los Alamos Scientific Laboratory is intended to demonstrate realistic fuel supply and cleanup operations similar to those anticipated on fusion devices. The plasma exhaust gases are expected to be mixtures of helium and hydrogen isotopes which can be pumped most efficiently by cryopumping. A compound cryopump for on-line operation at TSTA using cryocondensation for hydrogen isotopes and cryosorption for helium has been designed by BNL and fabricated by Janis Research. The details of this compound cryopump are described in this paper. The performance of the pump during the pre-delivery testing at BNL, such as the heat load during operation and the pumping speed and pump capacity for helium and hydrogen, are also discussed in detail.

PACS numbers: 07.30.Cy, 07.20.Mc, 07.30.Hd

I. INTRODUCTION

In fusion reactors, various pumping systems, with extremely high pumping speed, will be required to evacuate the reactor chamber during and between burns. The plasma exhaust gases are expected to be largely mixtures of helium and hydrogen isotopes, therefore, these pumping systems must be capable of containing and separating, for the recovery, the hydrogen isotopes from helium and other impurities. A vacuum facility using cryopumping can fulfill these requirements. The advantage of cryopumping lies in its ability to achieve very high pumping speeds (proportional to the area of cryosurface) and very low equilibrium pressure while confining the pumped species on the cryosurface. The hydrogen isotopes can be pumped efficiently by either cryocondensation^{1,2} or cryosorption³⁻⁵ at liquid helium temperature. Helium, however, can only be pumped by cryosorption⁶ at low temperature. The two most commonly used adsorbents for cryosorption pumping of helium are activated charcoal and molecular sieves. The cryosorption pumping of helium by coconut charcoal has been studied in detail⁷ and found to have high pumping speed and large adsorption capacity. We have therefore designed a compound cryopump using cryocondensation pumping for hydrogen isotopes and cryosorption pumping with coconut charcoal as the adsorbent for helium. This compound cryopump was subsequently built (by Janis Research, Stoneham, MA) and tested at Brookhaven, fulfilling the design requirements, and has been delivered to the Tritium Systems Test Assembly (TSTA) Vacuum Facility at Los Alamos Scientific Laboratory (LASL) for on-line operations.

The basic construction of this compound cryopump and the results obtained during test runs at Brookhaven are reported below.

II. DESCRIPTION OF SYSTEMS

A. The TSTA vacuum facility

The TSTA Vacuum Facility⁸ at LASL is intended to demonstrate realistic fuel supply and cleanup operations

similar to those anticipated on fusion devices. It has all the elements for the pumping system of a fusion reactor as shown schematically in Fig. 1. The heart of this vacuum facility is the compound cryopump. During the on-line operation, the appropriate gas mix is diverted from the TSTA main stream and injected into a torus simulator, from which it is pumped by the TSTA compound cryopump and then returned to the main loop during the regeneration cycle. The helium is not returned to the main stream during regeneration but is exhausted through Zr-Al getter, turbomolecular pump and rotary vane pump into a stack.

Compound cryopumps which are to be evaluated and accepted by TSTA Vacuum Facility must meet the following requirements:

- (i) provide high pumping speed: 10 000–16 000 l/s for deuterium and tritium, and 1500–3200 l/s for helium.
- (ii) have large capacity: >34 000 Torr l for deuterium and tritium, and >3400 Torr l for helium.
- (iii) be able to pump a mixture of deuterium, tritium, helium (~10%), and other impurities.

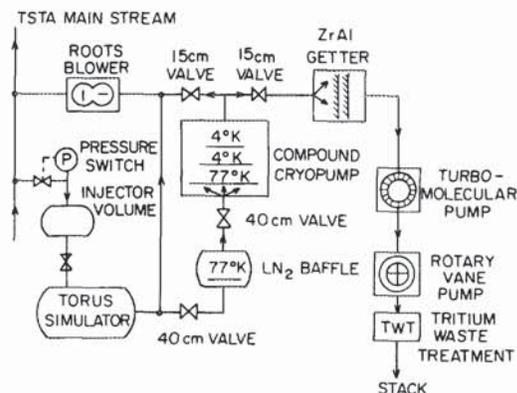


Fig. 1. Systematic drawing of the TSTA vacuum system.

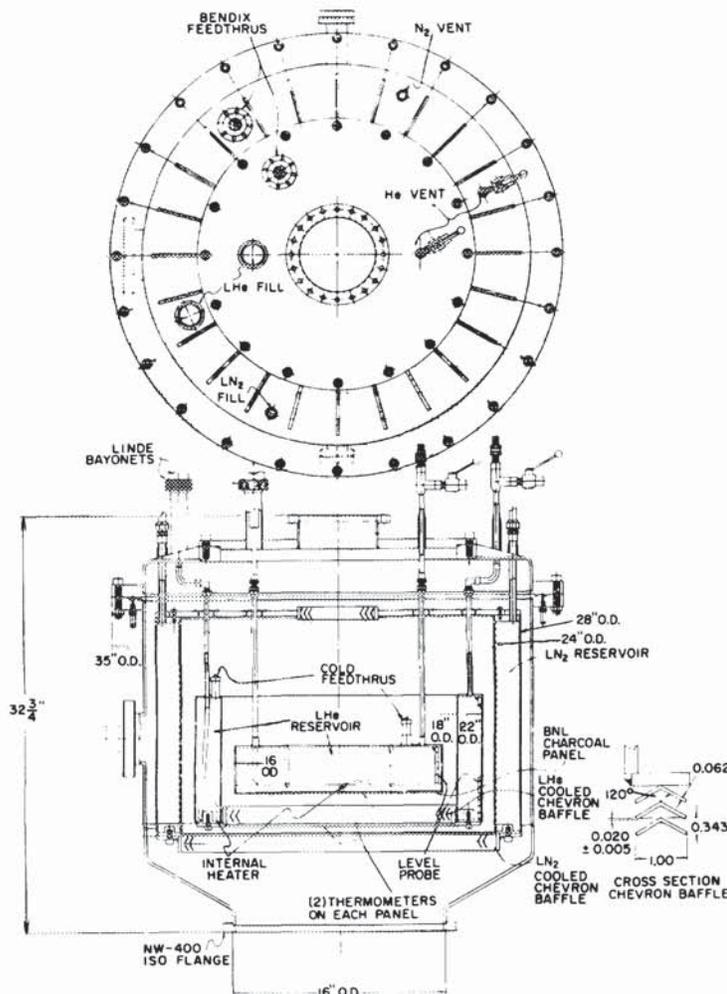


FIG. 2. The BNL-TSTA compound cryopump design.

- (iv) be able to start pumping at an initial torus pressure of $\sim 7.5 \times 10^{-3}$ Torr with an initial flow rate of 52 Torr l/s and be able to achieve a blankoff pressure of $\sim 1 \times 10^{-8}$ Torr.
- (v) be able to regenerate hydrogen isotopes and helium separately.

B. The BNL-TSTA compound cryopump

The designed features of the BNL-TSTA compound cryopump (called the cryopump hereafter) is to demonstrate the feasibility of using cryocondensation pumping for hydrogen isotopes and using cryosorption pumping with coconut charcoal as the adsorbent for helium isotopes. Hydrogen isotopes are pumped by both cryocondensation and cryosorption, therefore, to avoid saturation of the cryosorption panel and to achieve separate regeneration, they should be pumped on the condensation panel first. The BNL compound cryopump

has been designed to meet these features. Figure 2 shows the overall drawing of the cryopump. Except for the chevron baffles and the charcoal panel, this cryopump is constructed entirely from 304 SS. To minimize the conduction heat load to the cryogen reservoirs, all the reservoirs are suspended by thin wall tubes which also serve as transfer and venting lines. The major components of the cryopump are described below:

(i) **Pump body.** The vertically mounted cryopump has 40 cm i.d. bottom inlet port with NW-400 ISO-Pneurop flange, 8 in. o.d. Conflat flange on the top as regeneration port and other Conflat flanges for connecting roughing pumps and monitoring instruments. Indium (with 2% silver) seals are used for the 35 in. o.d. double grooved flanges and the 21 in. o.d. flanges.

(ii) **LN₂ reservoir.** The liquid nitrogen (LN₂) reservoir, the thermal anchor and the chevron baffles serve as radiation shielding, remove the condensables and reduce the temperature of the incoming gases. The cross-sectional view of the

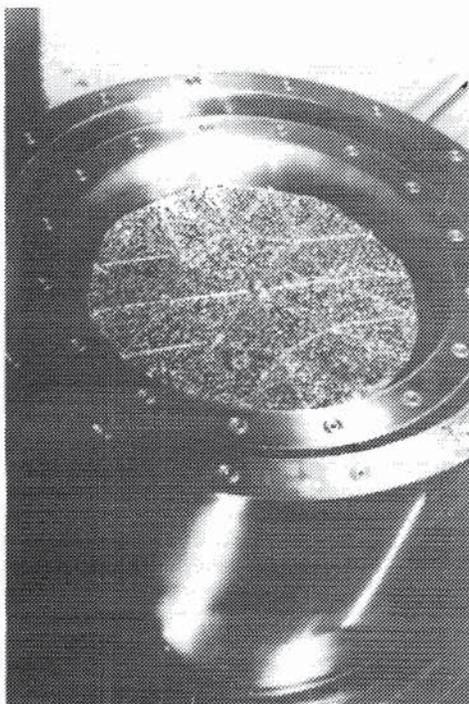


FIG. 3. Cryosorption panel made of metallized coconut charcoal plates. The thermal anchored silicon diodes are shown at center and edge of the panel.

chevron baffle is shown at the right hand corner of Fig. 2. The baffles which are anodized to minimize radiation heat load to inner liquid helium (LHe) reservoir have calculated transmission coefficients of about 27% for molecules and less than 1% for photons when the emissivity is ~ 0.9 .

(iii) **Cryocondensation panel.** The outer LHe reservoir and chevron baffles function as cryocondensation panel for hydrogen isotopes and radiation shielding for inner LHe reservoir. All the hydrogen isotopes are pumped at this stage.

(iv) **Cryosorption panel.** Helium gas is adsorbed on the LHe cooled charcoal panel. The charcoal panel consists of 32 triangularly-shaped ($\sim 40 \text{ cm}^2$ area each) metallized charcoal plates, made of coconut charcoal imbedded in Sn-Ag alloy, bolted to the bottom of the reservoir. Metallized bonding has several advantages over organic adhesive: better thermal conductivity, higher resistance to radiation damage, and nonblocking of the porous path on the surface of charcoal granule. The charcoal panel as well as the bottom of the reservoirs are shown in Fig. 3.

(v) **Instrumentation.** Two heaters, two temperature sensors and one LHe level probe are installed in each LHe reservoir. The heaters are for controlling the temperature of the panels during regeneration. The temperature sensors are the silicon diode type requiring $10 \mu\text{A}$ constant current supply and are installed at the center and edge of each panel. The

voltage response of these sensors ($\Delta V/\Delta T$) is greater than 20 mV/degree when the temperature is less than 20 K.

III. THE PERFORMANCE OF THE CRYOPUMP

To evaluate the performance of the cryopump, several test runs were done at Brookhaven during which the cryopump behaved as expected, however, due to the limitation of equipment at Brookhaven, the capability of this cryopump could not be fully demonstrated. The experimental setup, the test procedures and the obtained results are summarized below.

A. Experimental setup

A setup shown schematically in Fig. 4 was attached to the cryopump to allow a controlled amount of gas or mixture of gases to flow continuously into the system. This was accomplished by using the orifices C (with a known conductance 10 l/s for hydrogen and 7 l/s for helium) between gas inlet chambers and gas mixing chamber and by monitoring the pressures of the gas inlet chambers with Schulz-Pheleps type ionization gauges (operated between 10^{-6} Torr and 1 Torr). The pressures inside the gas inlet chambers were controlled by the Granville-Phillips servodriven bleed valves. Varian quadrupole residual gas analyzer and Bayard Alpert type ionization gauge were installed at the cryopump side to measure the total and partial pressures of gas species. Turbomolecular pumps were attached to the cryopump and gas mixing chamber to evacuate the system initially and during regeneration.

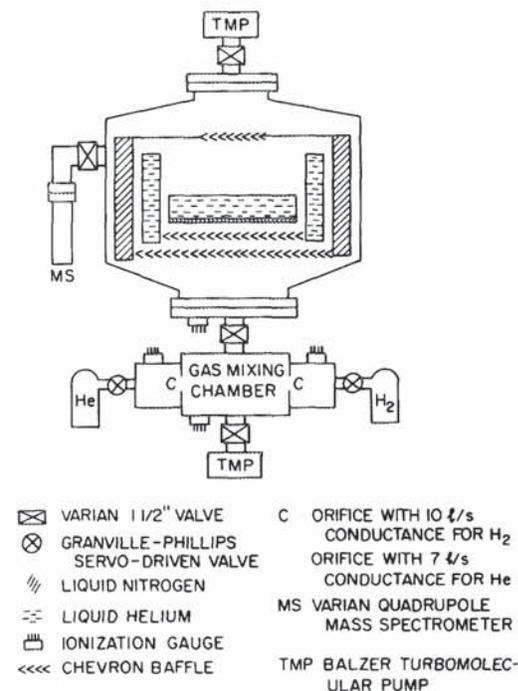


FIG. 4. Setup for testing the cryopump at BNL.

B. Measurement

After the initial evacuation of the system to a pressure $\sim 1 \times 10^{-5}$ Torr (1.33×10^{-3} Pa) by turbomolecular pumps, the reservoirs were filled with LN₂ or LHe. The temperatures of the cryosurface were near 4 K and the background pressure was $\sim 3 \times 10^{-9}$ Torr (3.99×10^{-7} Pa) at this moment. The feeding of the desired amount of gas or gases was started by slowly opening up the servodriven bleed valves and by monitoring pressures inside the gas inlet chambers. During the runs, the flow rates of helium and hydrogen were varied to observe the effect on pumping speeds, and the equilibrium pressures of the cryopump were measured by interrupting the gas flow.

The flow rate Q was calculated from $Q = C(P_1 - P_2)$. Here C is the conductance of the orifices, P_1 the pressure in the gas inlet chambers, and P_2 the pressure at the cryopump. During these runs, P_1 was much greater than P_2 and P_m , where P_m is the pressure in the gas mixing chamber, ($P_1 \gg P_m > P_2$), therefore $Q \approx CP_1$. The pumping speeds of the cryopanel S then could be calculated by $S = Q/P_2$. The surface coverage (the amount of gas pumped at that moment) was calculated by integrating of flow rate versus time. When pumping the mixture of hydrogen and helium, the individual partial pressure and flow rate were used in the calculation.

The cryogen consumption rate and the heat load of each reservoir with and without gas input were determined by the boil-off method. Dry gas flow meters (Singer-American DTM-200) were connected to the exhaust lines of the LN₂ and LHe reservoirs to measure the boil-off rates of the cryogens.

C. Results

(i) **Cryosorption pumping of helium.** The pumping speeds of helium were evaluated as a function of gas flow rate as well as surface coverage on the charcoal panel and are shown in Fig. 5. At a flow rate of 0.7 Torr l/s, the initial pumping speed was $\sim 5,000$ l/s, however, after ~ 200 Torr l of helium was adsorbed, the pumping speed dropped to less than 3000 l/s. Beyond that, it levelled off and decreased slowly with increasing surface coverage. At the same surface coverage, the pumping speed of helium increased with decreasing flow rate. The total adsorption capacity of the charcoal panel for helium is greater than 5000 Torr l, beyond that the pumping speed dropped below 1000 l/s and made it impractical to continue pumping. The decrease of pumping speed with increasing surface coverage and flow rate can be explained by the rate of migration of helium from the surface to the inner bulk of charcoal granule. When the rate of adsorption exceeds the rate of migration (which occurs at higher flow rate and surface coverage), the available area on the outer surface of charcoal granule diminishes which causes a decrease in pumping speed.

(ii) **Cryopumping of a mixture of helium and hydrogen.** A test run was performed by feeding a mixture of 80% hydrogen and 20% helium continuously into the system. The pumping speeds for helium as shown in Fig. 5 were lower than those when pumping pure helium. This decrease ($\sim 30\%$) in pumping speed might be caused by the large uncertainty in

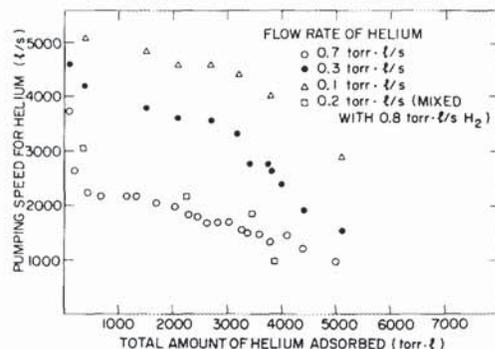


FIG. 5. Helium pumping speed of the charcoal panel at various flow rates and surface coverages.

measuring the helium partial pressure at the cryopump side. As expected the cryocondensation panel produced a far higher pumping speed for hydrogen than the cryosorption panel to which the helium flow was restricted by the chevron baffles. The initial pumping speed for hydrogen was $\sim 16,000$ l/s, as the thickness of the condensed hydrogen reached several monolayers, the vapor pressure of hydrogen increased to $\sim 4 \times 10^{-6}$ Torr (5.32×10^{-4} Pa) (measured by Bayard-Alpert gauge and residual gas analyzer) and made pumping speed measurements rather difficult. This vapor pressure corresponds to a temperature of ~ 4.8 K for the cryocondensation panel. At this temperature, the vapor pressure of the condensed deuterium and tritium film will be less than 1×10^{-8} Torr (1.33×10^{-6} Pa).

(iii) **The cryogen consumption rate and heat load.** The heat load on the LN₂ reservoir/chevron baffles was about 100 W (equivalent to a boil-off rate of 2.5 l/h) and was insensitive to the variation in gas flow rate. The static heat loads (without pumping gas) on the inner LHe reservoir and on the outer LHe reservoir/chevron baffles were ~ 0.2 and ~ 0.8 W, respectively (0.8 W of heat load equals to a LHe boil-off rate of ~ 1 l/h). These heat loads increased proportionally with increasing gas flow rates up to 5 Torr l/s; beyond that the boil-off rate of LHe became excessive and prohibited accurate measurements. The heat content of hydrogen² from 80 to 4 K is ~ 0.2 W/Torr l/s, the heat of adsorption⁷ of helium on charcoal is ~ 800 cal/mole (~ 0.2 W/Torr l/s). The increase in heat load (i.e., ~ 0.3 W when pumping 1 Torr l/s of helium) of the inner LHe reservoir was consistent with the amount caused by the heat of adsorption of helium, however, that of the outer LHe reservoir (i.e., ~ 3.2 W when pumping 1 Torr l/s of 80% hydrogen and 20% helium) was much higher than the amount caused by hydrogen condensation and was attributed to gas convection between LN₂ reservoir and outer LHe reservoir.

IV. CONCLUSION

Based on the performance of this cryopump during the test runs at BNL and on our previous studies on the cryocondensation pumping^{1,2} and cryosorption pumping,⁷ we have reached the following conclusions:

(1) The performance of this cryopump has met the design requirements. The pumping speed and adsorption capacity of the cryosorption panel for helium exceed the TSTA specifications (3000 l/s vs 1500 l/s and >5000 Torr l vs >3400 Torr l) although the actual speed of the pump which could not be measured in the current setup, would be somewhat less due to the conductance limitation. This demonstrates that the compound cryopump is capable of evacuating the fusion reactor and separating helium from hydrogen isotopes.

(2) Using coconut charcoal as adsorbent for cryosorption pumping of helium is superior to using molecular sieves. Unlike molecular sieves, no high-temperature bake will be required to condition the charcoal, and the presence of small amounts of hydrogen and other impurities has little effect on the pumping speed and adsorption capacity of the charcoal.

(3) The cryopump operated well at a pressure as high as 1×10^{-3} Torr (1.33×10^{-1} Pa) with flow rates up to 5 Torr l/s. The LHe boil-off rates were higher than those estimated from heat content and might be caused by gas convection.

ACKNOWLEDGMENTS

The authors would like to thank T. S. Chou, H. Halama, A. Hoffmann, and D. McCafferty for their valuable contributions.

¹Work performed under the auspices of the U.S. Department of Energy under Contract No. DE-AC02-76CF100016.

²H. J. Halama, C. K. Lam, and J. A. Bamberger, *J. Vac. Sci. Technol.* **14**, 1201 (1977).

³T. S. Chou and H. J. Halama, *Proc. 7th Symp. Eng. Problems of Fusion Research*, Knoxville (IEEE, New York, 1977), p. 1790.

⁴S. A. Stern, R. A. Hemstreet, and D. M. Rutenbau, *J. Vac. Sci. Technol.* **3**, 99 (1966).

⁵P. W. Fisher and J. S. Watson, *J. Vac. Sci. Technol.* **15**, 741 (1978).

⁶S. W. Schwenterly, P. M. Ryan, and C. C. Tsai, *Proc. 8th Symp. Eng. Problems of Fusion Research*, San Francisco (IEEE, New York, 1979), p. 1578.

⁷H. J. Halama and J. R. Aggus, *J. Vac. Sci. Technol.* **11**, 333 (1974).

⁸H. C. Hseuh, T. S. Chou, H. A. Worwetz, and H. J. Halama, *Proc. Eighth Symp. Eng. Problems of Fusion Research*, San Francisco (IEEE, New York, 1979), p. 1568.

⁹D. O. Coffin and C. R. Walthers, *Proc. 8th Symp. Eng. Problems of Fusion Research*, San Francisco (IEEE, New York, 1979), p. 513.