Vacuum applications for the Tritium Systems Test Assembly

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The Tritium Systems Test Assembly (TSTA) is a facility which will develop and demonstrate the processes for handling the fuel and exhaust from a magnetic fusion reactor using deuterium and tritium as the fuel. The TSTA facility became operational in mid 1982 and will now proceed to test and evaluate the many subsystems required to purify, separate, circulate, and reuse the deuterium/tritium gas recovered from the reactor vacuum system. At TSTA the reactor will be simulated by a large vacuum vessel into which mixtures of deuterium, tritium, and various impurities (He, CH_4, H_2O, NH_3, C_2H_2) are injected. This mixture is then exhausted through the vacuum system, reprocessed and prepared for reinjection into the front end. A fusion reactor must have an enormous vacuum system to remove the mixture of fuel and impurites so that the plasma can be replenished with fresh fuel. At TSTA this evacuation is achieved with "compound" cryopumps. These pumps remove the deuterium and tritium by cryocondensation on a 4-K panel. The helium is removed by cryosorption on a separate refrigerated panel. TSTA will provide the first opportunity to test several models of compound cryopumps with actual mixtures of deuterium, tritium, and helium. This paper will discuss the role TSTA has in the national magnetic fusion energy program with special emphasis on the vacuum system and preliminary experimental results.

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I. INTRODUCTION

The Tritium Systems Test Assembly (TSTA)[1] is a facility which will develop and demonstrate the processes for handling the fuel for, and exhaust from, a magnetic fusion reactor using deuterium and tritium as the fuel. The TSTA, shown in Fig. 1, became operational in 1982 and will now test and evaluate the many subsystems required to purify, separate, circulate, and reuse the deuterium/tritium gas recovered from the reactor. At TSTA the reactor plasma chamber is simulated by a large vacuum chamber into which mixtures of deuterium, tritium, and various impurities (He, CH_4, H_2O, NH_3, C_2H_2) are injected. The mixture is then exhausted through the vacuum system, and transferred with special pumps to the fuel cleanup system. Here, by passing the stream through several chemical process beds, the impurities are removed and either stored in the beds or passed out of the facility after a final processing in the tritium waste treatment system. Some of the beds are periodically replaced as they fill with impurities; others are regenerable. From the fuel-cleanup system the gas stream passes through the isotope-separation system where, by a process of cryogenic distillation in four columns, the hydrogen isotopes are separated into four streams which contain pure tritium, an equimolar mixture of deuterium and tritium, a pure deuterium stream, and a hydrogen stream. The hydrogen stream is removed from the process at this time, and the remaining streams are pumped into holding tanks to await reinjection into the plasma chamber. Supporting the main process systems are environmental and safety systems which assure the safe containment of the tritium gas. Included are the secondary containment features, the tritium waste treatment system, the emergency tritium cleanup system, the building ventilation system, and the computer, which controls the process and safety systems and is backed up by an independent safety computer.

Maintenance of high vacuum plays an important part in the operation of the TSTA fuel loop. The plasma-chamber pumps, mentioned above, are suitable for adaptation to a large, power producing, reactor. Roughing, backing, and transfer pumps are of designs which expose only tritium-compatible metals to the gas stream. The process beds in the fuel-cleanup system have vacuum jackets which perform several functions, and in which vacuum is maintained by nonevaporable getter cartridges. The ability to completely recover pumped tritium from these cartridges assures their continued usefulness in special applications for tritium systems. Vacuum jackets surround cryogenic process beds and the uranium beds designed to store hydrogen isotopes in the event of a rapid fuel-loop shutdown. Finally, the vacuum pumps used primarily for plasma-chamber pumping have secondary maintenance and inventory functions. This paper describes the vacuum systems at TSTA.

II. PLASMA-CHAMBER PUMPING

The TSTA vacuum system comprises a simulated plasma chamber, cryopumps, regeneration pumps, valves, and instrumentation. The system is shown in Fig. 2. Deuterium, tritium, and impurities are injected into the plasma chamber in various amounts and cycles depending upon the experiment. Two cryopumps are connected to the plasma chamber and separated by valves so that one pump is always available for pumping while the other is being regenerated.

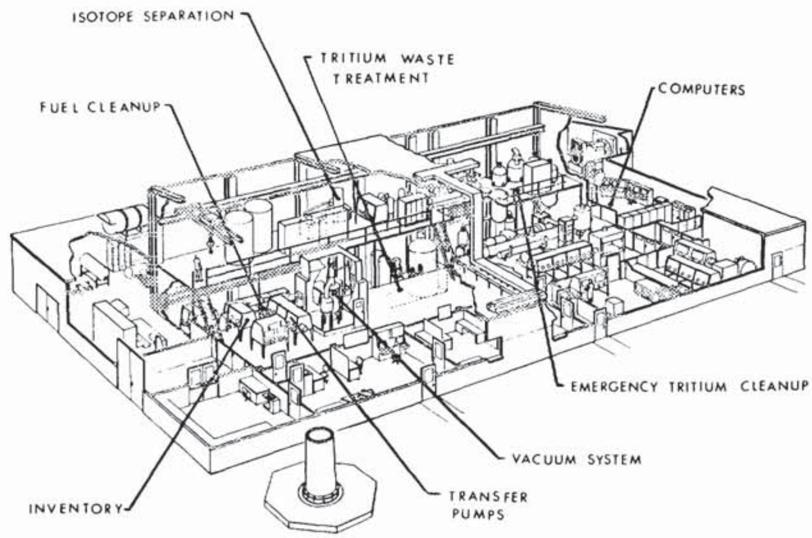

FIG. 1. Artist's concept of the Tritium Systems Test Assembly Facility.

Several options in flow path are available for regeneration of the cryopumps.[2] High vacuum pumping for cryopump startup or controlled pressure helium regeneration is achieved by turbopump, moving-spiral, and metal-bellows pumps in series. For intermediate level vacuum, appropriate for deuterium/tritium (DT) regeneration, the moving-spiral and bellows pumps alone are sufficient. Another choice in flow paths exists after the final metal-bellows stage. Here, the regenerated gas may be returned to the main process stream, to the tritium waste treatment system or back to holding tanks to await reinjection into the plasma chamber. During helium cryosorber regeneration, the helium would normally be passed to the tritium waste treatment system (to remove trace amounts of tritium) and then stacked. Deuterium/tritium would normally be routed back to the main process loop for impurity removal and separation. The other flow path back to tanks for plasma chamber injection is used for closed-loop vacuum system operation.

A. TSTA compound cryopumps

The most promising approach for plasma chamber pumping of large fusion machines is cryopumping. Staged or compound cryopanels can produce high specific speeds for both helium and DT, are clean, and can readily be designed in wall or appendage configurations. One objection to cryopumps has been that, since they are batch pumping devices, there is an undesirable holdup of tritium within the pump. To circumvent this objection, the pump can be designed so that very rapid heating of the panels is possible or that some other means be utilized to shorten the pumping-regeneration cycle. One proposal[3] suggests that mechanical scrapers could be used and thus temperature cycling of the panels could be avoided altogether. Staged cryopumps intrinsically separate the gases they pump, and the fuel cleanup system could be simplified by taking advantage of this feature. For instance, if the panels of a compound cryopump were me-

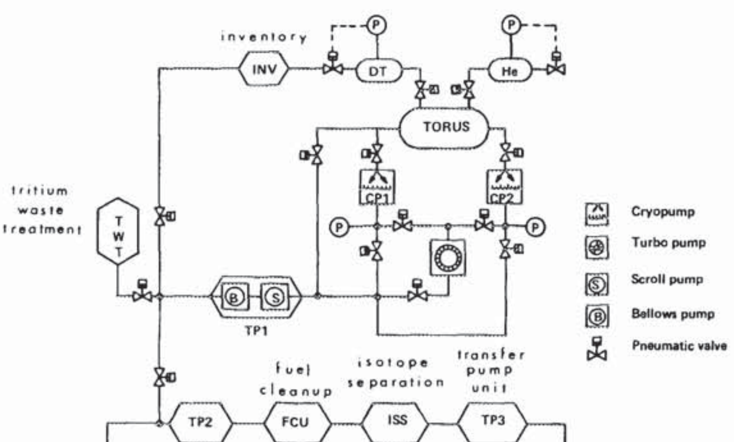

FIG. 2. Vacuum schematical for the Tritium Systems Test Assembly.

chanically separated (conductance limiters) during regeneration, the mix of DT and impurities would be partially separated. From the liquid-nitrogen baffle, tritiated water vapor and ammonia could be routed to the most advantageous process beds; the cryocondensing panel would yield DT plus some hydrocarbons and argon; the cryosorbing panel would give off pure helium.

At TSTA three compound cryopumps of different geometries and having different cryosorbers, have been tested and are ready for long-term tritium pumping experiments. These pumps (Fig. 3) share an arrangement of panels which has been found successful in pumping mixtures of hydrogens and helium, namely the staging of 4-K condensing chevrons in front of 4-K cryosorbers. Most cryosorbers capable of pumping pure helium are quickly fouled by hydrogens, which condense and freeze on their surfaces: The staged or compound arrangement precludes this by intercepting the hydrogens before they reach the cryosorber. This compound arrangement may not be necessary for the argon cryotrapping configuration. The cryosorber for this pump is a continually replenished argon frost, which should be much less sensitive to freezing over than molecular sieve or charcoal.

The three TSTA pumps were designed in general accordance with a requirements specification which fixed the inlet port diameter, minimum speeds for deuterium and helium, and capacities for those gases. Pumps intended to meet these requirements were supplied to TSTA by each of the participating laboratories: Los Alamos National Laboratory (LANL), Brookhaven National Laboratory (BNL), and Lawrence Livermore National Laboratory (LLNL). Briefly the physical characteristics of the three pumps are as follows:

(1) The LANL compound cryopump[4] has outer dimensions of 0.7 m diam[4] by 1.0 m high. Within the outer vacuum jacket and liquid-nitrogen-cooled shields are a copper-chevron cylinder of approximately 2800 cm^2 surrounding a molecular-sieve cyclinder of approximately 1600 cm^2. The ends of both cylinders are closed and both are cooled by continuous two-phase helium flow.

(2) The LLNL cryopump[5] utilizes argon frost at 4 K as the helium cryosorber. The pump measures 1 m in diameter by 1.5 m high. The DT pumping area is approximately 9000 cm^2 of chevrons, which shield the argon-frost sorbing surface. The sorbing surface has an area of 11 000 cm^2 and is the third from the center of the four concentric cylinders making up the cryogenic parts of the pump (liquid-nitrogen baffles, DT-pumping chevrons, helium-pumping argon frost, and liquid-nitrogen heat shield). The argon frost is maintained by continual replenishment in a ratio of 30 times the helium gas load. Twenty-five vertical spray tubes connected to a circular lower manifold are used to distribute the argon gas to the 4-K sorbing surface. The argon gas is maintained at approximately 120 K to prevent condensing within the tubes.

(3) In the BNL pump helium is cryosorbed on coconut charcoal.[6] The pump has outside dimensions of 0.76 m diam by 0.8 m high. The panels are planar and have areas of 2400 cm^2 and 1300 cm^2 for the condensing and sorbing panels, respectively. An innovation in this pump is the method used to bond the charcoal to its heat sink. Epoxy, used on earlier cryosorbers, is not suitable for exposure to tritium, so the charcoal was cast in a low-melting-point alloy and then mechanically attached to the heat sink.

The above pumps have been operated at Los Alamos prior to installation in the TSTA. Table I summarizes some of their pertinent characteristics. The table gives the approximate initial speeds for helium. As helium is accumulated on each of the cryosorbing panels, speed is reduced. This effect is most pronounced on the molecular sieve 5A and least on the charcoal. The reason postulated for the speed reduction is filling of available sites within the sorbent structure. On the argon pump this is not a reasonable explanation since the frost surface is continually being replenished. An explanation for the behavior of the argon pump lies in the insulation effect of the argon frost and consequent increase in surface temperature with increasing frost thickness. Figure 4 compares the reduction in specific speed measured at LANL as a function of total helium sorbed per unit area. From the above it would seem as though charcoal has a distinct advantage over the other cryosorbers because of its greater capacity. There are now strong incentives to limit cryopump tritium inventories by resorting to frequent, fast regenerations. If such cryopump designs prevail, the larger helium capaci-

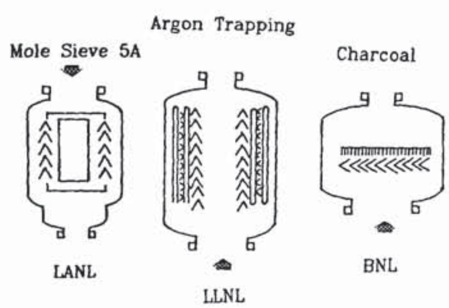

FIG. 3. Tritium Systems Test Assembly cryopumps (77-K panels not shown).

TABLE I. Description of the Tritium Systems Test Assembly cryopumps: Pertinent characteristics.

	Los Alamos	LLL	BNL
Cooling	2 PH. Flow	← He Reservoir →	
DT pump	← 4° Chevrons →		
DT area	0.28 M^2	0.9 m^2	0.24 m^2
He pump	M.S. 5A	Argon Frost	Charcoal
He area	0.16 m^2	1.1 m^2	0.13 m^2
DT speed	8000 ℓ/s	60,000 ℓ/s	16,000 ℓ/s
He speed	1600 ℓ/s	22,000 ℓ/s	3,000 ℓ/s
Specific Sp. for D_2 ℓ/s cm^2	2.85	6.6	6.6
Specific Sp. for He ℓ/s cm^2	1.0	2.0	2.0 +
He capacity Tℓ/cm^2	1.0	1.0	6.0
He capacity Total Tℓ	1.6k	10k	⩾ 10k

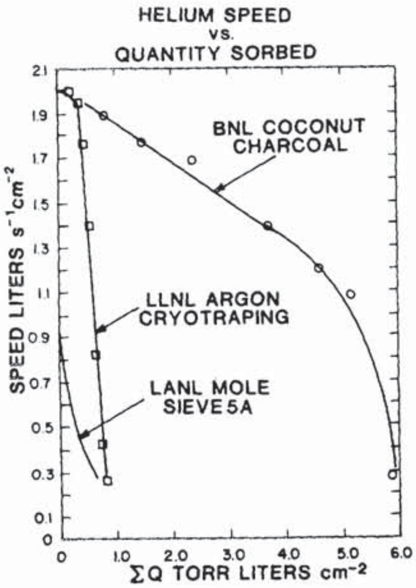

FIG. 4. Speed vs capacity for the three Tritium Systems Test Assembly cryopumps.

ties of charcoal cannot be exploited, and all three cryosorbers are viable for future pumps. Shortcomings of each of the cryosorbers are the following: the molecular sieve 5A requires frequent bakeout to 570 K, argon cryotrapping introduces large quantities of argon into the fuel loop, and the charcoal has a tendency to flake off the cryopanel during temperature cycling.

B. TSTA backing and roughing pumps

The main requirement for roughing and backing pumps is that they not expose organic lubricants, elastomers, or fluorcarbons to the process stream. The reason is twofold: First, degradation of these materials by tritium would impair the pump's function; second, gaseous decomposition products from these materials mix with the process stream and cause problems in other subsystems of the fuel loop. Of the pumps commercially available, only two designs meet the above requirement. These are metal-bellows and moving-spiral-type pumps. Metal-bellows pumps are commercially available and are suitable for general gas transfer. A pump of this type commonly has a compression ratio of 10: With multiple staging, compression to 300 kPa and evacuation to 2 kPa can be achieved. The metal-bellows pumps in use at TSTA are completely hermetic and are of all-metal construction, including static seals and check valves. A booster pump is needed to bridge the gap between a few kilopascal from metal bellows pumps and several pascal needed to back a high-vacuum turbopump. The most promising vacuum boosting device for tritium, and the one selected for TSTA, is the moving-spiral pump. Hermetic sealing of this pump is possible with bellows having small deflections (and hence long life). This pump, described in more detail in Ref. 1, consists of two clock spring spirals; one stationary, the other driven in a small orbit within the first. An inlet port is located near the outer edge of the stationary spiral and the discharge port near its center. The orbital motion first traps and then continuously compresses the gas until it is discharged through the center port. Two pumps of this type have been ordered for TSTA. The first, with a speed of 4 l/s, has been performance tested and reported in Ref. 1; the second, a 5-l/s unit, has spirals machined from aluminum (stainless on the earlier version) and can discharge directly to TSTA processing pressure. Figure 5 shows schematically an arrangement of metal-bellows and spiral pumps in use at TSTA. Line 26, from the vacuum subsystem, is used for initial evacuation of the chamber and regeneration of the cryopumps; a moving-spiral pump in series with two metal-bellows stages is used for DT regeneration directly; to obtain high vacuum, a turbopump is valved into the line between the spiral pump and the simulated plasma chamber.

III. VACUUM DEVICES FOR PROCESS BEDS

It was advantageous to provide vacuum jackets on both high-temperature and cryogenic process beds within the TSTA fuel loop. One reason was that the vacuum annulus combined with multilayer reflective foils provided much more compact envelopes than would have been possible with conventional insulation. Second, the vacuum jacket serves as a high-integrity secondary container and the vacuum annulus will not hold up leaked or permeated tritium. Several approaches were used to maintain vacuum depending upon the temperature of the process beds. At very high temperatures, $\geqslant 700$ K, some loss of tritium by permeation was unavoidable, so getter pumps, from which tritium could be recovered, were used. Also, the high-temperature beds need periodic replacement so the compactness and absence of backing lines is a handling advantage. At intermediate temperatures, a turbopump-vacuum manifold arrangement was found to be the most convenient. For cryogenic devices ion pumps were used. Several examples of pumping arrangements are described below.

A. Fuel-cleanup, hot-metal, and catalyst beds

For impurity removal in the fuel-cleanup subsystem, uranium at 1170 K is used to remove N, C, and O (Figs. 6 and 7). In another bed, titanium at 500 K forms hydrides and passes argon from the system; subsequently, the hydrogens are regenerated by heating to 1170 K. Uranium at 750 K is used to break down tritiated water vapor in another application, forming oxides and liberating the hydrogens. Five beds are used for these three processes; they share space in a single glovebox with a pair of catalytic reactors, four molecular-sieve beds and a heavy water (DTO) freezer. The hot-metal beds have a similar thermal design. Vacuum and multilayer foils are used to reduce heat transfer rates, outer vacuum jacket temperatures, and, consequently, the permeability of the jacket materials to hydrogens. Nonevaporable getters (Zr–Al) at 675 K maintain vacuum for the lifetime of the beds and are regenerated as the bed material is being replenished. The lifetime of these beds varies from several weeks to several months. Figure 8 shows the general location of a

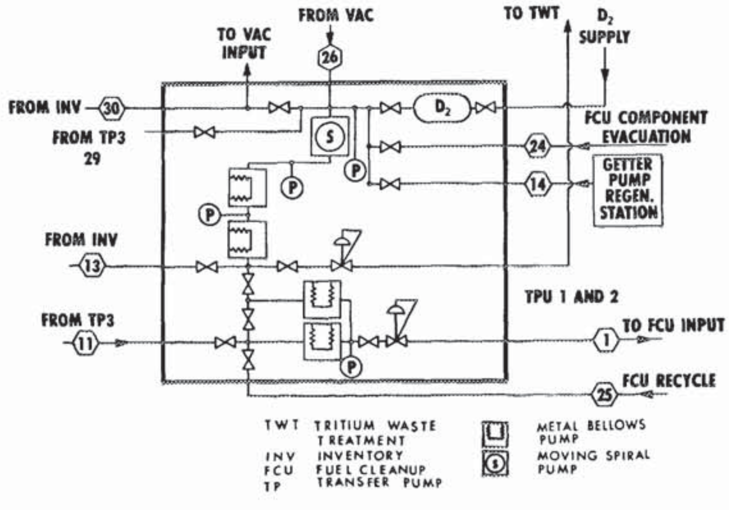

FIG. 5. Flow schematic for regeneration and transfer pumps.

uranium bed within the glovebox. Bed removal from the glovebox for uranium replacement is accomplished by manipulating tools through glove ports to break process connections and maneuver the bed until it is supported by an overhead trolley. The trolley is then slid to the loading tray of the load in–out station. Because this is a difficult process, it is advantageous not to have vacuum manifolds or pumps in the immediate vicinity of the beds. After the bed has been replenished the vacuum jacket is rough pumped by the house vacuum system and then connected to line 14 (Fig. 5) for getter pump regeneration. Hydrogens stored in the getter are returned to the process loop; pumped impurities are retained within the getter. Several catalyst beds (CR-1 and CR-2, Fig. 6) have getter-pumped vacuum jackets and lifetimes exceeding one year. For this application larger cartridges with capacity to match the longer lifetimes are used. In a third application, where a question exists concerning the matchup of getter capacity to bed lifetime, a roughing line has been permanently routed to the bed and provisions added to allow the attachment of a second cartridge for in-place regeneration. The procedure is to activate the second cartridge by heating while under moderate vacuum, then regenerate the primary cartridge while the secondary is pumping.

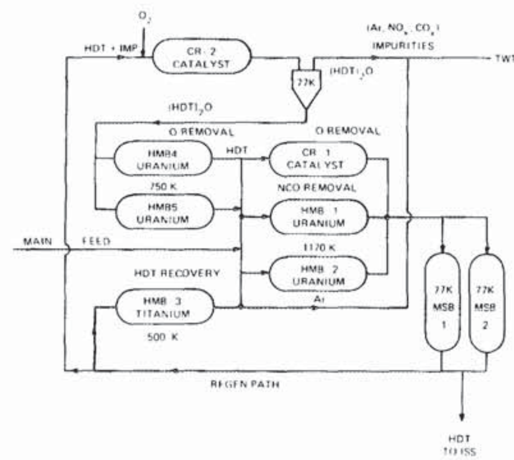

FIG. 6. Tritium Systems Test Assembly fuel cleanup system flowpaths.

B. Cryogenic molecular-sieve beds

Four molecular-sieve beds are operated at 77 K for impurity removal. These beds share the crowding–limited-access problems of the hot-metal beds described above. However, removal is expected to be very infrequent. To avoid large diameter plumbing within the glovebox, a small pump located on each vacuum jacket was chosen. Ion pumps were readily available in various sizes with multiple-unit power supplies and pressure indicators. This approach was more convenient than getter pumps, which would require periodic regeneration. At cryogenic temperatures the permeation losses of tritium are negligible and the main advantage of getters, and the reason for their use in the hot-metal beds is not applicable in this case.

C. Uranium beds for tritium storage

Another approach for maintaining vacuum jackets is used on five uranium beds whose function is to store tritium in the event of a rapid shutdown of the isotope separation system. This system has the largest tritium inventory in the TSTA at 100 g under certain conditions. To provide a place to store this inventory, as well as the deuterium present in the distillation columns, five uranium beds, each containing 6 kg of depleted uranium, are located adjacent to the isotope-separation system. After activation, the uranium is able to getter hydrogen isotopes at room temperature. To restore the hydrogens to the fuel loop requires heating the uranium to approximtely 700 K. The crowding of components, typical

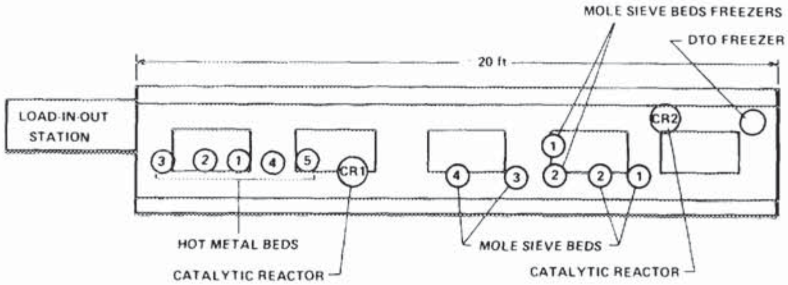

FIG. 7. Arrangement of major components in fuel cleanup glovebox.

the beds in the fuel cleanup subsystem described above, is not a problem with these beds. There is no scheduled removal or replacement, so the goal is to maintain vacuum within the vacuum jackets for the life of the program (approximately 10 yr). Tritium permeation is not a great concern because the uranium is encased in thick-wall copper which only sees elevated temperatures during the relatively brief periods when the hydrogen isotopes are being regenerated back to the fuel loop. For these reasons a conventional vacuum system, comprising a large-diameter (10-cm) manifold, a 100-L/s turbopump, and a helium-tight rotary-vane pump, is installed. This system is expected to be maintenance free for long durations.

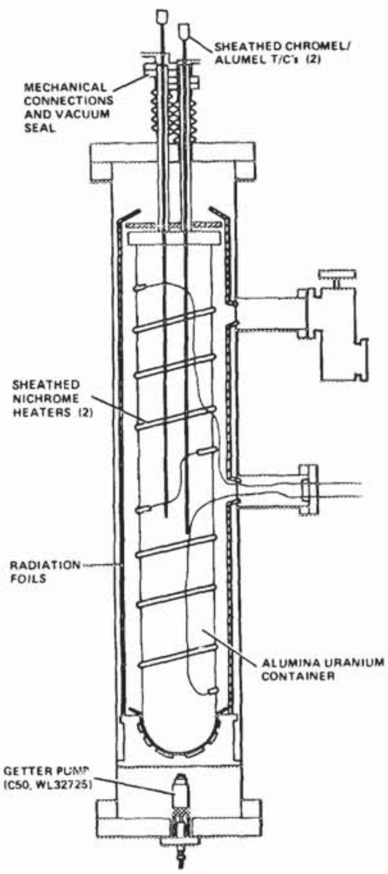

FIG. 8. General configuration of alumina hot-metal bed and vacuum jacket in the Tritium Systems Test Assembly fuel cleanup system.

IV. OTHER VACUUM APPLICATIONS

At TSTA the plasma-chamber pumping system has applications related to other functions and it is expected that this will be found true in future reactor designs. The reason for this is that the combinations of pumps available in the chamber system have inlet pressures which vary from very high vacuum (cryopumps and turbopump) to intermediate (moving spiral) to low vacuum (mechanical bellows), and these pumps are ideally located to admit or readmit gas to the main process loop. At TSTA, the fuel-cleanup process beds are configured so that the beds may be evacuated prior to removal by any combination of the plasma-chamber pumps. Generally, the moving-spiral pump backed by metal-bellows pumps will be satisfactory for this purpose. A five-valve arrangement is used on the beds; two valves at inlet and outlet allow the process lines and the bed to be sealed for removal. A fifth valve is teed between the two exhaust-side valves for evacuation and backfill. This approach reduces tritium loss during component replacement to an absolute minimum. Another use for the plasma-chamber pumping system, mentioned above, involves regeneration of the getter pumps used to maintain vacuum in the insulating jackets of the hot-metal process beds. After replacement of the active metal, the beds are brought to a station adjacent to the vacuum pumps where initial evacuation is accomplished by the house vacuum system. The vacuum jacket is then valved to a moving-spiral pump and the getter pump is heated to approximately 1025 K. During this period active gasses are diffused into the bulk of the getter, and gettered hydrogen isotopes are liberated and readmitted to the process loop. The vacuum jacket is then blanked off, and the entire assembly is reinstalled in the glovebox.

A requirement for periodic physical inventory of the tritium at TSTA is accomplished with the use of the plasma-chamber pumping system. Process lines and components of the TSTA are sequentially evacuated by the backing pumps and transferred to measuring tanks. Here pressure-volumetemperature measurements and chromatographic analysis are used to assay gas content of the system. By using high-vacuum pumps to evacuate DT gas from the large TSTA process system, the quantity of residual unassayed tritium is insignificant compared to other errors inherent in the assay measurements.

V. CONCLUSION

At TSTA, a tritium-compatible combination of cryopumps and backing pumps has been developed for plasma-chamber pumping. It has become apparent that the plasma-chamber evacuation system can influence the design of other fuel-loop systems and may perform functions other than the primary one. In the case of the TSTA compound cryopumps, some separation of the plasma exhaust gases can be attained, so a system approach to the vacuum–fuel cleanup designs should be considered. Also, the vacuum system is well suited to assist in certain maintenance operations, where pump-backfill cycles prior to component removal can reduce tritium loss to inconsequential levels.

At TSTA it has been found necessary to include small separate vacuum systems for specialized applications; in one case where regenerable getters are used, it is desirable to integrate them operationally into the main vacuum system. Finally, the chamber pumping system has been utilized to transfer gases from fuel-system components and lines to calibrated volumes for periodic inventory determination.

ACKNOWLEDGMENT

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