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AND RADIATION OUTGASSING

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CRYOPUMP MEASUREMENTS RELATING TO SAFETY, PUMPING SPEED,
AND RADIATION OUTGASSING*

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ABSTRACT

A test cryopump has been constructed to investigate operation in close proximity to a neutral beam, to determine static and dynamic pumping speeds, and to study outgassing such as might be produced by a pulse of nuclear radiation. No difficulty was encountered in operating the cryopump close to a deuterium neutral-beam source suitable for a fusion-reactor injector. Static and dynamic pumping-speed measurements agreed well, but were somewhat lower than expectations, probably due to the unusual method chosen to supply liquid helium. Safety tests showed that hydrogen could not be ignited at any subatmospheric pressure resulting from a leak-up-to-air accident. The possible hazard of liquid-oxygen condensation in such accidents was not explored. Tests made with pulses of neutrons and gamma rays produced by a TRIGA showed that the cryopump could be partially outgassed by radiation pulses of sufficient intensity. However, the effect is ascribed to the gamma-ray component of the TRIGA pulse which is about 10^3 times that expected from a fusion reactor such as TFTR.

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Introduction

Considerable effort is currently being placed on the development of neutral-beam injectors for large-scale fusion reactor experiments. Cryopumping is being incorporated into the beamlines for all such injectors, as well as into the large test stands used in their development. This choice is dictated by the very large pumping speeds required for the quantities of deuterium used in the ion source and neutralizer. For example, the pumping speed necessary for each of the 4 beamlines on TFTR is approximately $2500 \text{ m}^3/\text{s}$. In connection with the design and development of such injectors, the Lawrence Livermore Laboratory constructed a small cryopump to be used by us for some special tests. These tests were intended to determine the ability of the pump to operate in close proximity to a neutral beam, the pumping speed under conditions of both pulsed and steady gas load, and the effect on the pump of large bursts of neutrons and gamma rays such as will be expected from fusion reactors. The radiation tests were to be staged at a pulsed fission reactor of the TRIGA type.

Physical Description

The test cryopump is contained in an aluminum vacuum box to minimize radio-activation. The vacuum box measures approximately 71 cm x 102 cm x 76 cm. The cryopump can be operated as a self-contained vacuum system, or, with the end flange removed from the vacuum box, it can be attached to the LBL Test Stand III beamlines. The design of the test cryopump is similar to that incorporated into TFTR, although the operating scheme of the test cryopump is considerably different. The pump itself consists of a 5-sided copper box cooled with liquid nitrogen, surrounding an inner panel cooled by liquid helium. The remaining side of the copper box faces away from the beam and is closed

off by a liquid-nitrogen cooled panel, similar in design to the interior panel cooled by liquid helium. The cooper box measures 73 cm x 40 cm x 22 cm. The side of the box facing towards the beam is made up of 120° chevrons which are painted black to increase their emissivity. The interior panel is composed of two sheets of quilted stainless-steel, with liquid helium circulating between the sheets. The area corresponding to one side of the quilted surface is 2350 cm^2 . The pump was designed and constructed at the Lawrence Livermore Laboratory, and from previous experience with similar cryopumps, the designers estimated that the pumping speed of the test cryopump for deuterium at 4.3 K would be 18,500 ℓ/s .

Cryopumps for neutral-beam injectors are commonly operated in one of two modes - either being filled from closed-cycle refrigeration systems, or from storage dewars atop the pumps. The test cryopump, however, is operated in a still different mode which maximizes simplicity of design at the expense of operating cost. The test cryopump utilizes once-through feed from pressurized dewars connected to the pump by means of transfer lines. The chief penalty in this mode of operation is the high LHe consumption rate of 17 ℓ/h , consisting primarily of losses in the 1.7 m transfer line. Liquid helium is typically supplied from 50 ℓ dewars pressurized with helium gas to about 10% above atmospheric pressure. An adequate flow of liquid nitrogen is assured by self-pressurization in 250 ℓ dewars. Figure 1 shows the cryopump and its vacuum housing. The flange from which the pump is suspended, also contains the LN and LHe inlet and outlet pipes, as well as the feedthroughs for the temperature sensors. Vacuum monitoring gauges, a gas-inlet connection, and an outlet roughing connection are contained on the opposite flange which is removed when the pump is inserted onto the beamline.

The copper box is instrumented with three thermocouples which span the temperature gradient existing between the LN inlet and outlet. The interior panel is instrumented with three sets of diode-plus-resistor assemblies which span the gradient between LHe inlet and outlet. All six sensors are placed on the side of the panel facing away from the chevrons. Each sensor is a 4-wire device, with the current leads all connected in series and supplied with 10.0 μ A. The diodes are silicon and were obtained commercially. The resistors are 1/4-watt carbon of 330 ohms each, selected for uniformity. The resistors were attached to the stainless panel by first using a copper strap to spot weld the resistor leads to an indium layer which had been spread onto the panel in a local area. The resistor was then covered with a special epoxy, and a copper "hat" was soft-soldered over the whole assembly. In the case of the diodes, a 4-40 nut was soft-soldered onto the indium, and a diode was then screwed into the nut. As in the case of the resistors, a copper "hat" was soft-soldered over the diode assemblies. It was fortunate that the temperature sensing on the LHe panel was made considerably redundant, as several of the sensors failed during the course of the experiments.

Safety Considerations

The explosion potential of the test cryopump became a paramount issue in the safety analysis required for the reactor experiment. The LLL-suggested administrative limit for the loading of a cryopump with normal hydrogen or deuterium is that amount of gas which will produce a partial pressure of 1.7×10^3 Pa at a total pressure of 1×10^5 Pa, i.e. a 1.7% mixture by volume. At atmospheric pressure, combustion can occur for mixtures in the range 4.0-75%¹. It is important to know whether, in a leak-up-to-air accident, when the

partial pressure will range from 100% to 1.7%, an explosion can occur. For the test cryopump (225 l) loaded to the administrative limit, the energy of combustion would amount to about 4.1×10^4 J, or 10g of T.N.T. equivalent.

Experiments by Eseff and Qinlan¹ on the combustion limits of hydrogen in air at various pressures shown that the upper and lower dilution limits draw together as the pressure of the mixture gets lower. Figure 2 reproduces their data, which was taken at ambient temperature, as a dashed line. Everywhere above the line, the mixture is flammable; everywhere below the line, it is not. On the same figure is also shown the leak-up-to-air trajectory as given by the expression $P(\text{Pa} \times 10^{-5}) = 1.7/\%H_2$. It can be seen that the trajectory is everywhere in the non-combustion range.

Wolfe and Yurezyk² have done experiments on the limits of combustibility of H_2 - O_2 mixtures. Figure 2 also shows their data, which was taken at 21°C and at -195°C . It can be seen that the trajectory is even further from the explosive area for gas mixtures at liquid-nitrogen temperatures than it is at ambient temperature.

Although the experiments described above, indicate that the administrative limit suffices to insure that combustion will not take place at any subatmospheric pressure, the paucity of the data and the fact that the experiments were not done with deuterium, both argued for further corroboration of the safety. Hence, we decided to stage two different leak-up-to-air accidents (with the experimenters behind a suitable barricade). In the first, air was admitted to the system with the cryopump loaded to the administrative limit for deuterium. A hot-filament ion gauge was arranged to burn throughout the leak-up-to-air cycle. The liquid nitrogen supply and the pressure to

the helium dewar were then valved off and air admitted to the system. In a 20-minute leak cycle, followed by 10 minutes at atmospheric pressure, nothing occurred to indicate that combustion had taken place. Reassurance was thus obtained for the safety of the reactor experiment. Next, the experiment was repeated with, in addition, a spark gap firing in the vacuum system at approximately 1-second intervals. Again, no combustion occurred during the leak cycle. While these experiments sufficed to satisfy the safety concerns for the reactor experiment, and indeed the cryopump has now been pulsed many times at the reactor, the leak-up-to-air accident which we staged bears only a small resemblance to that envisioned for fusion reactor experiments. The latter has been discussed by Valby³ in the case of TFTR, who reports that because the individual beamlines cannot be isolated rapidly, all 4 will be affected as a result of a leak anywhere in the system. In a worst case analysis, i.e. large leak with maximum deuterium inventory, the total amount of deuterium which would be desorbed, has an energy of combustion amounting to 3.7×10^4 J, or 8.8 kg of T.N.T equivalent. Nevertheless, no combustion can occur, according to our previous arguments, provided that at any subatmospheric pressure, only a gaseous mixture of deuterium and air is present in the vacuum system. We have speculated⁴ that such may not be the case in fusion reactor experiments where continued cooling during a leak-up-to-air accident could allow significant amounts of liquid oxygen to condense.

Pumping Speed Measurements

In order to perform the tests described in this paper it was necessary to make accurate temperature, gas flow rate and gas pressure measurements. The vital temperature measurement was that of the liquid-helium-cooled cryopanel. (A major disadvantage of the present force fed liquid helium system as opposed to the reservoir type is that this temperature is difficult to estimate without a measurement). To insure an accurate measurement, silicon diodes and carbon resistors were embedded in the cryopanel as described earlier. Calibration of the silicon diodes had been done by the suppliers, Lakeshore Electronics, their calibration, limited by our current-source resolution is believed accurate to ± 0.2 K at temperatures in the range 4.2 K to 100 K. The carbon resistors were calibrated by measuring the voltage drop across them when immersed in liquid nitrogen and in liquid helium, and when maintained at room temperature. The three corresponding resistance values were then used to fit the three constants in the expression $\log R = -K/\log R + A + B/T$.

For the static pumping speed measurements, gas flow rate were monitored by a thermal conductivity type flowmeter manufactured by Hastings-Raydist (Model #H-50). The flowmeter was calibrated for H_2 , D_2 and N_2 gases against a mercury bubble-rate apparatus in the range 133-66 Pa/sec. The flowmeter was found to be linear and almost independent of the gas species. As a result of this calibration it is believed that the flow rate could be measured to within $\pm 10\%$.

The pressure in the vacuum system was measured by a glass enclosed and a nude Bayard-Alpert ionization gauge. A calibration of these two gauges and their respective power supplies was made using two Barocel electronic manometers which had in turn been calibrated against an oil manometer. Within the experimental uncertainties the results of the calibration were the same when made both "in situ", on the cryopump vacuum system, and with the same

gauges on a different vacuum system. As can be seen from Table 1, the results obtained were significantly different from the manufacture's recommended correction values, however, the results relative to nitrogen agreed with their values and with theoretical estimates. The reasons for the disagreements are not obvious; however in reporting our results we have used our calibration values.

Measurements of the pumping speed of the test cryopump were made using two techniques. The first was a static pumping speed measurement in which gas is admitted to the vacuum system at a given rate and the equilibrium pressure is measured. The second was a dynamic pumping speed measurement in which a short pulse of gas is admitted to the system and the pumping speed is calculated from the time dependence of the pressure in the system.

These measurements were carried out in two locations, one where the cryopump was contained in its own vacuum vessel and another where the cryopump was attached to the "neutral beam" line. With the cryopanel operating at liquid helium temperature a continuous gas load was admitted into the system through the calibrated Hastings flowmeter. The pressure in the vacuum system was monitored by both of the previously mentioned vacuum gauges. When the pressure reached an equilibrium value (this normally took approximately 30 seconds) the pressure and flow rate were recorded. By plotting the flow rate versus the equilibrium pressure the pumping speed of the cryopump could be calculated from the slope of the curve. All measured values of pressure were first multiplied by the correction factor appropriate to the gas being used.

All the present measurements were made under the same cryopanel temperature conditions. The silicon diodes positioned at the inlet and outlet of the liquid helium circuit for all measurements read 4.35 K and 4.6 K respectively, with no observable change from one measurement to the next.

Typical data for D_2 and H_2 are shown in Figures 3 and 4. As can be seen the pumping speed, given by the slope of the Q versus P curve, is a function of the pressure. For D_2 there is a linear portion over a reasonable pressure range, repeatable from one run to the next. However, for H_2 this linear portion is not as well defined. The results of the static pumping speed measurements at a cryopanel temperature of 4.5 ± 0.4 K are shown in Table 2.

Several factors lead to the uncertainties in the pumping speed measurements. The results with different gauges are quite reproducible from one run to another as shown in Figs. 4 and 5, as is agreement between measurements in different locations. Therefore combining the small uncertainties based on reproducibility with the uncertainties in calibration of the flow meter and the ion gauges, the total uncertainties in these measurements for D_2 and N_2 is estimated to be $\pm 20\%$, while for H_2 where the linear portion of the curve is not so well defined, the total uncertainty is estimated to be $\pm 30\%$.

The dynamic pumping-speed measurements were carried out with the cryopump attached to the neutral beam line. The total volume of the beam line was estimated to be 840 l. With the cryopanel at liquid helium temperature a gas pulse of about 800 Pa/sec lasting 700 msec was introduced into the system which was at a base pressure of about 5×10^{-5} Pa. The pressure rise and fall of each pulse was measured by a nude Bayard-Alpert ion gauge used in conjunction with a fast ion-gauge power supply with a response time of 1 msec. The voltage output of the collector circuit was connected to an oscilloscope and a wave-form digitizer. A typical voltage versus time record is shown in Fig. 5.

The decay portion of the pump down curve is of the form

$$P = P_0 \exp \{ St/V \} \quad (1)$$

where P is the pressure at a time t , P_0 is the initial pressure, S is the pumping speed and V is the volume of the system. A semilog plot of the pressure versus time has a slope $(S/V)\log_{10}e$. Therefore, from the slope and the volume of the system, the pumping speed S can be calculated. A typical plot is shown in Fig. 6, and it can be seen that the data are a good fit to a single exponential for $P < 1.3 \times 10^{-2}$ Pa. Such was the case for both H_2 and D_2 . The results of the dynamic pumping speed measurements at a cryopanel temperature of 4.5 ± 0.4 K are shown in Table 2.

The factors leading to uncertainties in these dynamic measurements are different than for the static measurements. Since the pressure ratio is involved in Eq. 2, an absolute pressure measurement is not required. Instead, the uncertain feature is the volume of the system, and this can be calculated to better than $\pm 5\%$. Considering this uncertainty along with the repeatability of the measurements, the dynamic pumping speed measurements are estimated to be accurate to $\pm 10\%$.

The pumping speed measurements, made using the two different techniques agree within the combined experimental uncertainties. The dynamic method is believed to be the more accurate, largely because it does not involve an absolute measurement of pressure and gas flow, both of which have large uncertainties. The use of the manufacturer's ion-gauge calibration factors would have increased significantly the differences between the static and dynamic pumping speed measurements.

Chubb et al¹⁰ and Benvenuti et al¹¹ have made comprehensive studies of hydrogen and deuterium condensation pumping on to liquid-helium-cooled surfaces. They found that the sticking coefficient, and hence the pumping speed, was a function of the cryosurface vacuum history. In contamination-free

pumping the sticking coefficient increased during the initial coverage of the liquid-helium-cooled condensing surface until it becomes independent of coverage at 10^{16} molecules cm^{-2} .

In the present experiment the cryopump was used in the initial pumping of the vacuum system from air, so before D_2 or H_2 pumping speed measurements were started, the bare metal surface had a substantial coverage of air molecules. The other factors along with the sticking coefficients which affect the pumping speed measurements are the transmission of the liquid nitrogen-cooled chevrons and the temperature of the helium cooled surface. As discussed earlier, since the cryopump used in the present experiment was force fed rather than reservoir fed, the determination of the cryopanel temperature was a major uncertainty.

Several authors have reported pumping speed measurements for cryopanel arrays with liquid nitrogen cooled chevrons. Benvenuti¹² measured pumping speeds of $9 \pm 1 \text{ l s}^{-1} \text{ cm}^{-2}$ for H_2 at 2.3 K with 60° chevrons. Adding a further half chevron reduced this to $6 \pm 1 \text{ l s}^{-1} \text{ cm}^{-2}$. Halama et al¹³ found values of $8.9 \text{ l s}^{-1} \text{ cm}^{-2}$ and $12.2 \text{ l s}^{-1} \text{ cm}^{-2}$ for D_2 and H_2 respectively at 4.2 K, with a 120° chevron. The present measurements from Table 2 are considerably lower than these latter values. In both the previous experiments the pumping speed measurements were made using a constant-gas-flow method with gas pressures measured with ionization gauges. There is no discussion in these papers of ionization gauge calibrations. The calibration factors we applied to our ion gauge measurements substantially decrease the observed pumping speed measurements. We feel the agreement between our dynamic and static pumping speed measurements confirms the need to make accurate ionization gauge calibrations.

It should be noted that some cryopump designers¹⁴ tend to use a value of $8.5 \text{ } \ell\text{s}^{-1} \text{ cm}^{-2}$ for the D_2 pumping speed at 4.5 K based on the sticking coefficient measurements of Chubb et al¹⁰. On surfaces with temperatures between 2.1 K and 3.7 K, the latter reported sticking coefficients of between 0.7 and 0.95 which did not appear to depend upon surface temperature. Later measurements of Benvenuti et al¹¹ confirmed this low temperature dependence but found absorption decreased with increasing surface temperature above about 4 K.

The transmissivity of our 120° chevrons is ~ 0.3 , so from our measured pumping speeds (we will use the more accurate dynamic measurements), sticking coefficients can be calculated from the pumping speed using the equation¹⁴

$$S/A = 11.6 \frac{29T_1}{300M} (t^{-1} + C^{-1} - 1)^{-1} \quad (3)$$

where $S(\ell \text{ s}^{-1})$ is the measured pumping speed, $A(\text{cm}^2)$ is the area of the pumping surface, $T_1(\text{K})$ is the gas temperature in the pumped volume, M is the molecular weight of the gas, t is the chevron transmissivity and C is the sticking coefficient of the panel. We calculate sticking coefficients of 0.29 and 0.20 for D_2 and H_2 , respectively. Using Eq. (3) with the data from Halama et al¹³ would predict sticking coefficients at 4.2 K of the order of 0.85 and 0.78 for D_2 and H_2 , respectively.

Operation in the Presence of a Neutral Beam

One of the primary purposes of the test cryopump was to investigate how it would behave in the presence of an intense neutral beam, similar to those envisaged for use on TFTR. For these purposes the cryopump was mounted on the Test Stand III at LBL. It was positioned downstream of the neutralizer section of the neutral beamline and ahead of the large pumping volume normally used to remove the gas load between pulses. The distance from the center of the neutral beam and the liquid nitrogen cooled chevron of the cryopump was 50 cm. The neutral-beam-source was set to produce 10 amperes-equivalent of neutrals at 115 keV.

A U.T.I. residual gas analyzer was positioned on the beamline directly above the center of the beam. The cryopump was cooled down as described previously and then was partially loaded with D_2 by firing the neutral beam source about 10 times with a D_2 gas supply. During these pulses the mass 4 peak on the residual gas analyzer was seen to rise considerably. The gas supply to the ion source was now switched to H_2 and the pulsing was repeated. During the latter pulses the mass-2 peak showed a considerable increase while the mass-4 peak remained essentially unchanged.

Finally, to ensure abundant D_2 absorption on the cryopanel, D_2 was bled into the system and a pressure of 3×10^{-3} Pa maintained for several minutes. Subsequent pulses again showed no evidence of D_2 desorption from the cryopump.

TABLE 1

Absolute Calibration Factors

	<u>Glass Gauge</u>			<u>Nude Gauge</u>		
	H ₂	D ₂	N ₂	H ₂	D ₂	N ₂
	3.5 ± 0.3	3.6 ± 0.4	1.6 ± 0.2	3.4 ± 0.3	3.6 ± 0.4	1.5 ± 0.2
			<u>Relative to N₂</u>			
Present	2.2 ± 0.3	2.3 ± 0.3		2.3 ± 0.3	2.4 ± 0.3	
Varian ⁶		2.0				
Dushman ⁷ & Young		2.12				
Schulz ⁸		2.38				
Utterback ⁹ Griffith		2.37				

TABLE 2

Pumping Speed Measurements at 4.5 ± 0.4 K for H_2 , D_2 and N_2

STATIC MEASUREMENTS

DYNAMIC MEASUREMENTS

<u>Gas</u>	<u>P(Pa)</u>	<u>S(x 10^{-4} ℓs^{-1})</u>	<u>P(Pa)</u>	<u>S(x 10^{-4} ℓs^{-1})</u>	<u>$\frac{S}{A}(\ell s^{-1} cm^{-2})$</u>
H_2	$4 \times 10^{-3} \leq P \leq 1.3 \times 10^{-2}$	1.76 ± 0.35	$< 1.3 \times 10^{-2}$	1.66 ± 0.17	6.8 ± 0.7
D_2	$1.3 \times 10^{-3} \leq P \leq 1.3 \times 10^{-2}$	1.55 ± 0.31	$< 1.3 \times 10^{-2}$	1.27 ± 0.13	5.4 ± 0.5
N_2	$1.3 \times 10^{-3} \leq P \leq 1.3 \times 10^{-2}$	0.71 ± 0.14			

Radiation Outgassing

Radiation-induced outgassing of metal walls in a vacuum system is a phenomenon which has been studied previously¹⁵⁻¹⁷ in connection with steady-state reactor experiments. The gases observed as being desorbed were H₂, H₂O, CO, and CO₂. The desorption rate, which was linear with reactor power, did not seem to depend on whether or not the system had initially been baked out, thereby suggesting an interior, rather than a surface, origin for the desorbed gas. The desorption effect was ascribed mainly to the gamma ray component of the reactor spectrum, rather than to the fast-neutron component which was estimated as providing an order-of-magnitude lower effect. The measured specific desorption rate ranged up to 5×10^{-9} (Pa · l/cm² · s)/(MR/h) for aluminum, and was 0.5×10^{-9} (Pa · l/cm² · s)/(MR/h) for stainless steel.

The TRIGA Mark III Research Reactor has a dry exposure room, measuring about 4 m on a side, in which large objects may be placed for irradiation by neutrons and gamma rays from the core. The core can be moved in the reactor pool so that a minimum of water intervenes between the core and the exposure room. A drawing of the cryopump placed in the exposure room of the reactor is shown in Fig. 7. The experiment was accessible through several double-L-bend cable pipes, one of which is shown in the Figure. Temperature and vacuum sensing leads were brought out through one such pipe, and a copper sylphon tube as well as 2 nylon tubes were taken in through the same pipe. The sylphon was used to connect the 4.3-litre deuterium reservoir to the cryopump vacuum system, and one of the nylon tubes was used to feed liquid nitrogen to the cryopump LN-inlet connector. It was not possible to feed the doubly-insulated liquid-helium transfer line through a cable pipe, and so the liquid-helium dewar was put in the exposure room with the cryopump as shown in the Figure. The other nylon tube was used to feed gaseous helium

to the liquid-helium dewar in order to maintain a sufficiently positive pressure above the liquid. It was found that once the door to the exposure room was closed with the cryopump operating, the pressure in the system would begin to rise steadily. This pressure rise was finally identified as being due to helium which, on being exhausted into the exposure room, would gradually seep into the vacuum system through gaskets or otherwise tolerable leaks. The remedy consisted in venting the exhaust helium out of the exposure room through one of the cable pipes.

As a fusion-reactor simulator, the TRIGA reactor leaves much to be desired. The TRIGA pulse is a gaussian with a 12-ms FWHM, whereas a 0.5-s pulse is expected from TFTR. Although the fast-neutron fluence roughly matches that expected from TFTR (calculated for the position of the neutral-beam sources), the TRIGA produces a fission spectrum, rather than a degraded 14-MeV spectrum as will be characteristic of a fusion reactor. Finally, the TRIGA produces several orders of magnitude more gamma rays than is expected for TFTR. More quantitative comparisons will be made later.

The logistics for performing an experiment consisted of placing the cryopump in the exposure room, and attaching it to a mechanical pump with an intervening liquid-nitrogen trap. Once a satisfactory forepressure had been achieved, the liquid-nitrogen feed was started to the cryopump. Cool down of the liquid-nitrogen circuit required about 1 1/2 hours. Next, the liquid-helium helium feed was started. Cooldown of the cryopanel required only 3 to 4 minutes, after which the mechanical pump was valved off from the system. The vacuum pressure, which dropped into the high-vacuum range with the cooling of the LHe panel, was then monitored continuously by means of the two ion gauges, as was the LHe-panel temperature by means of the Lakeshore diode. Sometimes, low-frequency

oscillations were observed corresponding to "chugging" in the liquid-helium circuit, but these subsided after 5-10 minutes. Foils and ^7LiF thermoluminescent dosimeters (TLDs) for diagnostics of the neutron and gamma fluences were placed in a polyethylene envelope and suspended on the surface of the cryopanel facing the reactor. The diagnostic envelope was attached to a string which traversed one of the cable pipes, so that the envelope could be withdrawn right after a reactor pulse was fired, and without the necessity of opening the door to the exposure room. A typical experimental sequence consisted of firing a pulse, then admitting 4.3 litres of deuterium to the cryopump over a period of about 25 minutes, and then firing a second pulse with the cryopump then loaded to the administrative limit.

The TLDs were subsequently read using a Harshaw reader. Calibration TLDs were prepared at various doses up to 10 000 R by exposing them to an NBS-certified ^{60}Co source. The neutron diagnostic foils were obtained from Reactor Experiments, Inc. and the characteristic radioactivation gamma rays were counted by means of a Ge(Li) detector which had been calibrated absolutely over a large range of gamma-ray energies. The thermal-neutron contribution was evaluated by means of the difference activity between foils of gold and cadmium-covered gold. The effective threshold energy E_{eff} for the fast-neutron activation foils was assigned according to the prescription cited by Beckurts¹⁸, as were the corresponding effective cross sections σ_{eff} . A summary of these data is shown in Table 3.

Tests were performed at 3 different positions of the core in the reactor pool. The closest position of the core to the exposure room was designated as "0 cm". The 2 other positions were attained by retracting the core 20 cm or 50 cm back into the pool. All pulses were fired with maximum reactivity insertion ($\$2.69$), and the pulse parameters which were monitored consisted

Table 3

Foil-Activation Data

<u>Foil</u>	<u>Radionuclide</u>	<u>E_γ (KeV)</u>	<u>Gammas/Dis.</u>	<u>t_{1/2} (hours)</u>	<u>E_{eff} (MeV)</u>	<u>σ_{eff} (mb)</u>
Au	¹⁹⁸ Au	412	0.99	64.6	thermal	86879
In	^{115m} In	335	0.50	4.50	1.65	350
Al	²⁷ Mg	842	0.70	0.16	5.30	80
Al	²⁴ Na	1370	1.00	15.0	8.15	120

of the peak power P_m and the temperature rise in the fuel ΔT . The latter is proportional to the energy in the pulse, and therefore, to the fluence of neutrons and gamma rays. The cryopump was positioned symmetrically with respect to the midline of the core, and at a position 60 cm from the exposure-room wall surrounding the core. Fast ion-gauge power supplies were arranged to monitor the nude ion gauge and the glass-enclosed ion gauge which were attached to the cryopump. The collector current from the fast power supply was observed by a wave-form digitizer. Two other channels of the digitizer were used to monitor a sealed-off ion gauge, also placed in the exposure room, and a neutron-sensitive ion chamber which observed the reactor pulse.

It was found that an apparent pressure pulse was produced in the sealed-off gauge with the core at 0 cm. As can be seen from Fig. 8, the gauge pulse resembles the reactor pulse, with a full width at half maximum of about 12 ms. The effect was reduced with the core at 20 cm, and practically unmeasurable with the core at 50 cm. In the case of the unloaded cryopump, a similar pressure pulse was produced, as can be seen in Fig. 9. However, the peak pressure change is about 6×10^{-3} Pa, rather than 5×10^{-4} Pa as with the sealed-off gauge. When the cryopump was loaded with deuterium, a dramatic difference resulted in the pressure-time behavior. As shown in Fig. 9, peak pressure changes exceeding 1×10^{-1} Pa were produced, accompanied by a very slow return to the initial pressure. The fact that at least a partial outgassing of the cryopump occurred was further indicated by an accompanying change in the character of the helium exhaust. The latter changed from a steady flow to a chugging which lasted for several seconds, indicating that a boiling of the liquid helium had occurred within the cryopump. A temperature pulse lasting for a few seconds was also observed to occur on the liquid-helium

panel. The pumping speed as deduced from the tail of the pressure pulse, with no temperature corrections, is about 7.8×10^3 l/s, which is considerably less than has been reported above in connection with pulsed-gas measurements. Fig. 10 shows the effect of moving the core back 20 cm, and repeating the experiment. With deuterium in the cryopump, the peak pressure increase is now reduced to about 1×10^{-2} Pa, and the pumpdown is much more rapid. At 50 cm, the effect even in a deuterium-loaded cryopump, was unmeasurably small. A summary of the diagnostic data obtained from the pulses is given in Table 4. The data shown represent averages for several pulses at each core position, and the errors denote the rms deviation for successive pulses which occurred under the same conditions. Also shown in the same table are the corresponding data as predicted to be produced by Refs. 19 and 20 for TFTR. The gamma ray fluence as calculated in Ref. 20, was converted to dose by means of the conversion factor, $1 \text{ rad}/2.78 \times 10^9 \text{ photons cm}^{-2}$, which corresponds to a gamma-ray energy of about 800 keV. The TRIGA reactor pulses were characterized by a peak power of 1080 ± 20 MW and a fuel temperature rise of $335 \pm 5^\circ \text{ C}$.

The apparent pressure pulses shown for the unloaded cryopump are different from those of the deuterium-loaded system in that the former are both much smaller in amplitude and completely lacking in a pumpdown tail. Yet, they are large enough to effectively obscure the radiation-induced outgassing effect discussed previously. For example, using the coefficient previously mentioned for aluminum, and assuming that the effective interior area is 150% of the aluminum-wall area, a pulse with 8450 rads delivered uniformly would produce a pressure burst of 4.1×10^{-5} Pa in the system. The apparent pressure peak observed, however, is about 5×10^{-3} Pa, and we are inclined to interpret this response as mainly due to prompt ionization

Table 4

Radiation Characteristics

<u>Item</u>	<u>ϕt thermal</u>	<u>$\phi t > 1.65$ MeV</u>	<u>$\phi t > 5.30$ MeV</u>	<u>$\phi t > 8.15$ MeV</u>	<u>Gamma Dose (rad)</u>
TRIGA, core at 0 cm	$19 \pm 3 \times 10^{10}$	$825 \pm 50 \times 10^9$	$77 \pm 9 \times 10^9$	$11.4 \pm 0.8 \times 10^9$	8450 ± 2300
TRIGA, core at 20 cm	$2.9 \pm 1.6 \times 10^{10}$	$14.5 \pm 7.3 \times 10^9$	$3.9 \pm 1.7 \times 10^9$	$0.34 \pm 0.09 \times 10^9$	2431 ± 319
TRIGA, core at 50 cm	$1.0 \pm 0.0 \times 10^{10}$	$9.2 \pm 1.8 \times 10^9$	$0.35 \pm 0.20 \times 10^9$	$>0.2 \times 10^9$	994 ± 119
TFTR ¹⁹ , case II	1.9×10^{10}	6.5×10^9	3.5×10^9	2.8×10^9	1.8
TFTR ²⁰	1.8×10^{10}	6.2×10^9	4.4×10^9	2.9×10^9	5.7

Table 5

Calculated Temperature Rise on Vacuum Surface

<u>t(s)</u>	<u>$\Delta T(K)$</u>	<u>T(K) for $T_a = 4.5$ K</u>	<u>$P_{\text{deuterium}}$ (torr) at T(K)</u>
0	0	4.5	1.49×10^{-10}
.002	2.61	7.1	6.23×10^{-5}
.004	4.70	9.2	1.11×10^{-2}
.006	6.19	10.7	1.36×10^{-1}
.008	7.25	11.8	5.76×10^{-1}
.010	8.01	12.5	1.27×10^0
.012	8.55	13.0	2.14×10^0

produced within the gauge. As previously mentioned, the response of the deuterium-loaded system, both at 0-cm and 20-cm core positions, does indicate a partial outgassing of the cryopump, and which of the radiations is (or are) responsible, becomes the next issue of importance.

As can be seen in Table 4, compared to TFTR, the TRIGA core at 0 cm produces considerably more radiation in every category. The radiation produced at 20 cm represents a fairly good match except for the gamma dose, for which the TRIGA exceeds TFTR by about a thousand fold. Since, for TFTR, the gamma dose is similar to the neutron dose, it follows that the gamma dose produced by the TRIGA is the major source of energy absorption due to all radiation incident on the cryopump in our experiment. Using a very approximative model, it can be shown that a gamma dose of 1000 rad suffices to raise the temperature of the helium panel by several degrees Celcius.

Our model consists of an infinite sheet of stainless steel, 1 mm thick, one side of which is bathed in liquid helium at 4.2 K. The other side of the sheet faces into the vacuum, and suffers the maximum rise in temperature during the transient, which is assumed to occur in 12 ms and to deposit 1000 rad uniformly in the stainless-steel sheet. The 1-dimensional heat-conduction equation for this situation has been studied by Pittenger²¹. The solution even in the case of this simple model is difficult to obtain, since at low temperatures the thermal conductivity varies as the temperature, and the heat capacity c_p as the temperature cubed. As an approximation, we have assumed that both are constants with the values normally exhibited at 6 K. The equation to be solved is then

$$\frac{\partial^2 T}{\partial x^2} + \frac{q}{\kappa} = \frac{1}{\alpha^2} \frac{\partial T}{\partial t} \text{ where } \alpha^2 = \frac{\kappa}{\rho c_p}$$

The characteristic response time of the system is

$$\tau = \frac{4a^2}{\pi^2 \alpha} \text{ where } a \text{ is the thickness of the sheet (1 mm)}$$

The solution to the equation is an infinite series, but for $t \geq \tau$, only the first term is significant. Since the maximum temperature rise occurs at the end of the pulse ($t = 12 \text{ ms}$), and since $\tau = 5.9 \text{ ms}$, the approximation is valid for most of the pulse, and is, for $x = 0$,

$$T = T_0 + \frac{a^2 q}{2\kappa} - \frac{16a^2 q}{\kappa \pi^3} \exp \left\{ \frac{-\pi^2 \alpha^2 t}{4a^2} \right\}$$

The temperature rise $\Delta T = T - T_0$ versus time is shown in Table 5, as calculated from the equation above. Also shown is the vapor pressure of deuterium corresponding to the case $T_0 = 4.5 \text{ K}$. It can be seen that the model predicts definite outgassing for the assumptions used. The fact that the outgassing effect is not noticeable at a core position of 50 cm, corresponding to a dose of about 990 rads, indicates that the model overestimates the effect, although it implies that the correct mechanism for the outgassing is being assumed. If such is the case, we have no reason to believe that any outgassing will occur under conditions characteristic of TFTR.

Conclusions

The test-cryopump program has shown that such pumps are capable of operation in close proximity to a neutral beam. The static and dynamic pumping-speed measurements are in good agreement with each other, but somewhat lower than expectations. The difference can be ascribed to the undesirable forced-feed mode of supplying the liquid nitrogen and liquid helium, which probably results in an admixture of 2-phase flow, and consequent higher-than-desired temperatures on the panel. The radiation experiments have brought to light 2 safety questions regarding the leak-up-to-air accident. The first involves subatmospheric ignition of deuterium, which has been shown to be no problem. The second relates to the possibility of condensing appreciable quantities of liquid oxygen during the accident, and presently this possible hazard is unevaluated. TRIGA pulses whose radiation output greatly exceeds that expected from TFTR have resulted in partial outgassing of the deuterium in the cryopump. Under conditions where the TRIGA-produced neutron fluence roughly matches that predicted for TFTR, but the gamma-ray fluence is still about 1000 times too high, a partial outgassing is observed. However, energy considerations and crude heat-transfer calculations, indicate that the gamma-ray component of the TRIGA pulse is responsible for the effect observed, and therefore, that it will not be present in TFTR.

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FIGURE CAPTIONS

- Figure 1: Cryopump Disassembled
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Figure 2

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Figure 3

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Figure 4

Figure 5

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Figure 6

XBL 786-933IA

Figure 7

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Figure 8

XBL 786-1170

Figure 9

XBL7811-12507

Figure 10

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