Recent developments in cryopumping

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This review covers small cryopumps cooled by refrigerators, sorption pumping of hydrogen and helium, and very large cryopumps for nuclear fusion experiments.

Introduction

Cryopumping—the formation of vacuum by the freezing of gases—has been a recognized technique for a long time and has found use in a wide range of applications. It has of recent years become easier to use for small systems with the development of reliable small refrigerators providing up to a few tens of watts of cooling power at 20 K, and has become an established method for a number of industrial and research applications. At the other end of the scale, the advent of large nuclear fusion experiments has created a demand for pumping speeds of the order of a million litres per second for hydrogen, and has established a renewed interest in basic research.

The principles of cryopumping have been frequently described in detail and will not be repeated here. Only certain points which are particularly relevant to what follows will be discussed.

The partial pressure of a gas in a cryopumped system depends on the vapour pressure of the solidified gas on the cold surface which is doing the pumping. Assuming that a vapour pressure of less than about 10⁻⁶ mbar is required, the surface must be at a temperature of less than about 140 K to cryopump water vapour, at less than 75 K to cryopump carbon dioxide, and at less than 25 K to cryopump nitrogen, oxygen and argon. Hydrogen can only be effectively cryopumped at about 4 K, while helium cannot be cryopumped at all. Frequently sorption pumping is therefore used for hydrogen and helium.

Provided that the vapour pressure of the solidified gas is an order of magnitude or more less than the partial pressure of the gas in the system, the sticking coefficient is equal, or very close, to unity. The pumping speed for a bare cryopump for free molecular flow is then equal to the rate of arrival of molecules at the surface and it is obviously not possible to exceed this figure. In order to express the efficiency of a cryopump, it is convenient to define an overall capture coefficient $C_o$, which is the ratio of the number of molecules actually pumped to the number arriving at the pump inlet.

For an un baffled diffusion pump, $C_o$ usually lies between about 25 and 50% because of reflections from the jet structure and from the oil molecules themselves. Thus a bare cryopump is more efficient than a diffusion pump, but in practice few cryopumps are 'bare', since the low temperature elements have to be shielded from room temperature thermal radiation, thereby reducing the overall capture coefficient to about the same as that of a diffusion pump. Much of current development work is concerned with reducing the effects of the radiation shields on the pumping speed.

What, therefore, are the attractions of cryopumps? Firstly, they are 'clean', that is, no working fluid is in contact with the vacuum space, and hence there are no contamination problems: this is important in many industrial processes, although it should be noted that some modern diffusion pumps claim to be virtually contamination-free, and turbomolecular pumps are also very attractive in this respect. However, in situations where absolutely no oil molecules can be tolerated, the use of cryopumps is probably the best answer. Care must be taken, however, to prevent contamination during the roughing process—an oil-filled roughing pump may not be suitable. The second attraction is that there is virtually no upper limit to the size of a cryopump, so that extremely high pumping speeds can be provided, although, as mentioned above, the pumping speed per unit area will be no higher than that of diffusion pumps. A third attraction is that the geometry can be designed to fit the space available.

Crycondensation pumping

A typical small cryopump is shown in Figure 1. Because this type of pump is usually cooled by a two-stage 'displacer refrigerator' (one which makes use of a displacer and regenerator, with helium as the working gas—for instance, a Stirling cycle), the cold stage cannot be cooled to less than about 15 K. Therefore, the pump is designed so that this stage pumps nitrogen, oxygen and argon by condensation, while sorption pumping is provided for hydrogen and helium. To reduce the heat load due to thermal radiation, a suitable shielding system is attached to the first ('warm') stage of the refrigerator. Historically, this was cooled using liquid nitrogen (and, in the case of large cryopumps, frequently still is). A temperature of around 77 K is in any case convenient, since carbon dioxide and water vapour are both pumped to a low pressure on such surfaces.

Difficulties are occasionally experienced with pumping gases on clean surfaces at pressures near the vapour pressure of the intended cryodeposit. Initially the pump does not appear to function, but if the temperature is lowered or the gas pressure increased, pumping is perfectly normal and continues when the
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Figure 1. Cross-sectional view of a typical cryopump.  

System is returned to its original condition. The explanation for this kind of effect lies in the nucleation characteristics of the cryodeposit. It has been shown that argon and nitrogen will condense on a nominally clean surface whose temperature is at or below the saturation temperature corresponding to the partial pressure of the incident gas. It was also shown that for carbon dioxide the surface must be subcooled by several degrees before formation of the cryodeposit commences, and it is expected that most gases will behave in this way. Roughly speaking, the required subcooling should be higher the higher the triple point of the gas in question, but is small or zero for argon and nitrogen and presumably for oxygen, neon and hydrogen. Once deposition has started, subcooling of the surface is no longer required and the partial pressure of the gas will rapidly decrease to that corresponding to its vapour pressure at the surface temperature.

Because of applications in the generation of electricity using nuclear fusion, where cryopumps will be operated in high fluxes of energetic particles, studies of the effects of energetic particles on both solid gas layers and cryosorbed gases have been undertaken. There seem to be no serious problems: neutrons have little or no effect, and high energy ions are sufficiently accommodated on the radiation shields to produce no desorption when they impinge on the condensed layer. However, some types of particles may interact relatively strongly with the metal from which the cryopump is made, causing a rise in temperature of the surface and hence some evaporation of the cryopumped layer, as well as an increased heat load on the refrigerator. This effect has been observed in some experiments using a combined neutron/gamma ray flux, and was believed to be due primarily to absorption of gamma rays in the stainless steel cryopanels. It is potentially a rather troublesome effect and it may be necessary to construct cryopanels for these applications from materials with a low absorption coefficient for gamma rays and neutrons.

One problem which has not been satisfactorily solved is that of the disposal of the cryopumped layer. Clearly, in order to prevent the build-up of excessive pressure in the system, it is desirable to evaporate the cryodeposit at a controlled rate so that the evaporated gas can be steadily pumped off. It has not yet proved possible to achieve this: on warming up, the cryodeposit evaporates rapidly. Presumably, it first melts, and then runs down onto the warm parts of the pump, where rapid boiling occurs. Thus, in many cases, the interval between regenerations is determined by the maximum pressure which the vacuum vessel can tolerate, rather than by the pump becoming inoperable due to a thick cryodeposit. Such a pressure condition is particularly critical in the case of hydrogen because of the explosion hazard in the presence of any air inleak, and the maximum allowable pressure during regeneration may have to be restricted to around 10 mbar. The conditions for the ignition of hydrogen--air mixtures at low pressures are not well-defined, however, and further study would seem to be desirable.

Sorption studies

With the increased activity in fusion energy research there has been a revival of interest in the cryosorption of hydrogen, deuterium, tritium and helium. These studies are also, of course, relevant to cryopumps for other applications. As a result of work in the early 1960s at the Union Carbide Corporation, in which various sorbents and grades of molecular sieve material were compared, molecular sieve 5A was recommended as the best sorbent for hydrogen, and was also shown to be suitable for helium. However, although the 5A sieve gave the lowest ultimate pressure, coconut charcoal was found to have a greater capacity, and would clearly be useful in some circumstances. Since that time, the 5A sieve and charcoal have been almost exclusively used as sorbents for hydrogen and helium. Recent investigations have repeated much of this work and confirmed the conclusions of the Union Carbide workers: that the 5A sieve gives a lower ultimate pressure than charcoal, but that its ability to cope with a large flow rate is limited by the time taken for the adsorbed molecules to diffuse from the outside to the interior of the sorbent. At high flow rates, charcoal has a higher pumping speed, because the rate of diffusion from the surface into the pores is reasonably fast compared with the sticking probability. The difference can be quite marked; one estimate is that charcoal at 4 K can tolerate a flow rate of helium about 1000 times higher than molecular sieve.

A further advantage of using charcoal is that its pumping ability is less inhibited by impurities than is molecular sieve. It has been suggested that this is due to differences in pore size, but it seems likely that the relative heats of adsorption must also be important. The heat of adsorption of H₂O on molecular sieve, for instance, is about 75 kJ mole⁻¹. Thus at low temperatures, water adsorbing on the surface of molecular sieve will be relatively immobile and will partially block the pores, which are small (30 nm diameter) and uniform in size, thereby inhibiting the diffusion of He and H₂ away from the surface. Charcoal, however, has non-uniform pore sizes ranging up to about 200 nm diameter and this, coupled with a lower heat of adsorption, means that the diffusion paths are not as easily blocked. It is probably for similar reasons that, in contrast to molecular sieve, charcoal can be reactivated without baking.
The conclusion that diffusion is important is supported by some experiments which have been done with the Union Carbide molecular sieve Sodium-Y, which has a larger pore size than the 5A sieve and can tolerate a flow rate about ten times higher. A further parameter which has been investigated is the best granule size for a layer of charcoal sorbent. Since the layer is essentially one granule diameter thick, one might expect the experiments which have been done with the Union Carbide side away from the cold panel to which the charcoal is fixed. The pumping of mixtures of hydrogen and helium has also been investigated. Provided that the hydrogen does not form a condensed layer on the surface of the sorbent, it appears that the presence of hydrogen does not inhibit the sorption of helium, and vice versa. Both compete for the same adsorption sites, so that the total amount of gas adsorbed is the same as for pure helium.

The problem of attaching the sorbent to the cold panel still attracts interest. The adhesive must not block the pores of the sorbent, but at the same time it must be proof against thermal cycling, and provide good thermal contact between the sorbent and the panel. It used to be thought that epoxy resins were not suitable for this purpose because diffusion of the resin components into the sorbent severely reduced the pumping capacity, but nowadays they are used almost universally, the common 'two-tube' variety being favoured by at least one pump manufacturer.

With molecular sieves, methods which involve bonding the material directly to the panel without the use of adhesives are usually used, but much recent experimental work has been with commercially produced panels for which the bonding techniques are not reported. Recently, favourable results have been reported with charcoal bonded using a 3.5% Ag-Sn alloy. The charcoal was mechanically embedded into the molten alloy which was then formed into 3 mm thick plate. This method does not appear to block the channels on the surface of the granules, and provides better cooling of the charcoal than the use of epoxy resin.

**Small cryopumps**

There has been some effort in recent years to promote the use of small cryopumps for industrial processes. This has been led by the manufacturers of small refrigerators rather than by suppliers of vacuum equipment, probably because the greater part of the cost of a small cryopump is attributable to the refrigerator itself.

The cryopump configuration which has become almost a standard design is shown in Figure 1. The first stage of the refrigerator is run at around 70 K, the second stage at around 15 K. The rear of the colder cryopanel is covered with sorbent (usually charcoal), which is thus shielded from gases which are condensable at 15 K, that is, from all except hydrogen and helium.

One problem in designing such a pump is to properly balance the heat loads on the two stages. Since they form part of the same refrigerator, an increased heat load on one causes the other to rise in temperature, and until very recently information about the interaction was often difficult to obtain, so that the refrigerator could not be used to maximum capacity. However, such data are now being produced by more manufacturers. A particularly complete example is given in Figure 3. In a typical cryopump for atmospheric air, the second stage would be run at about 20 K, which means that the first stage heat load on this particular refrigerator must be restricted to less than about 100 W. However, for other applications, it may be advantageous to run the stages at...
higher heat loads and temperatures, and the availability of the complete refrigerator characteristics enables this to be done.

Two novel panel configurations have recently been described. Workers at Philips Laboratories have developed a pump in which more effective use is made of the charcoal used for sorption\(^{13,16}\). A flat chevron baffle is attached to the second stage of the refrigerator to pump those gases condensable at 20 K (Figures 4 and 5). Behind the baffle, a radial panel arrangement covered with charcoal provides a large sorbent area whilst giving good access for hydrogen and helium molecules. It is claimed that the radial arrangement of fins, together with the star-shaped scattering surface, gives a reasonably uniform distribution of gas molecules over the surface so that the capacity of the pump is not restricted by saturation of one part of the sorbent.

Longsworth addressed himself to the problem of cool-down time. It had been noted at Air Products and Chemicals that while the pumping speed and heat load of the type of cryopump shown in Figure 1 increase with the square of the aperture diameter, the mass of the panels increases approximately as the diameter cubed, resulting in an undesirably long cool-down time—as much as 5.5 h for a 0.5 m aperture pump. To reduce this time, a new configuration was evolved\(^{17}\) (Figure 6) which resulted in a smaller mass. The main feature is the orientation of the refrigerator expander, which is placed parallel to the inlet flange, so that the first stage of the refrigerator is close to the inlet louvre, in contrast to the geometry of Figure 1. The panel at 20 K consists of three cups facing away from the inlet port and which are lined inside with charcoal. These are surrounded by a radiation shield which is attached at its centre to the first stage of the refrigerator and at its edge to the baffle. The baffle and shield are designed to have minimum mass consistent with a temperature of less than 145 K at

Figure 4. A cryopump design by Philips Research Laboratories. The baffles A and B are attached to the first stage of the refrigerator at 80 K, while C and D are attached to the second stage at 20 K. The panels D are covered on both sides with charcoal. The lower diagram is a cross-section through the dashed line\(^1\,2\). (Reproduced with the courtesy of Philips Technical Review.)

Figure 5. The cryopump of Figure 4. Left: the baffle C. Right: the panels D before coating with charcoal\(^1\,2\). (Reproduced with the courtesy of Philips Technical Review.)
the edges so that water can be pumped to less than $10^{-8}$ mbar. Argon, nitrogen and oxygen are cryopumped on the cups, which presumably also pump carbon dioxide, although the efficiency of pumping of this gas was apparently not investigated. It is also worthy of note that, as a consequence of the cup geometry used, some molecules which penetrate the baffle are reflected from the rear radiation shield, and are cryopumped on to the charcoal, thereby reducing its capacity for hydrogen and helium. A reduction of 25% in some circumstances has been noted.

Besides their use in attaining very low pressures, applications for small cryopumps have been found at higher pressures. Scheer and Visser have successfully used a cryopump in a magnetron sputtering system, in which a pressure of argon of about $4 \times 10^{-3}$ mbar must be maintained, but impurities such as hydrogen, water and hydrocarbons must be removed. The 20 K surface of the pump was carefully dimensioned so that the pumping speed for argon was not too large, while as much area as possible was coated with charcoal to provide maximum pumping speed for hydrogen (Figure 7). This capability of cryopumps of generating different pumping speeds for different gases is perhaps an area which would repay further exploitation.

A rather different application, which makes full use of the flexibility of geometry possible with a cryopump, is in pumping the stripper gas in the accelerator at the Daresbury Laboratory, England. The accelerator is of the tandem type, in which negative ions are first accelerated by a positive electric field gradient to the 'centre terminal', where electrons are stripped off so that the ions become positively charged. They are then further accelerated by the negative field gradient between the centre terminal and ground potential. One method of achieving stripping is to pass the ions through a low density gas, when electrons are lost by collision processes. The stripping gas is at a pressure of about 0.1–1 mbar, whereas the rest of the system must be at a pressure of less than $10^{-7}$ mbar.

Differential pumping is clearly necessary and the arrangement used at Daresbury is shown in Figure 8. The stripping gas region is separated from the high vacuum region by a chamber containing a cylindrical cryopump 10 cm in diameter and 8 cm long. A tube projects into the centre of the pump to provide a path for the ion beam and the stripper gas. Since nitrogen is used, the inner cylinder is cooled to about 20 K with a displacer refrigerator developing about 1 W at this temperature; the outer cylinder is attached to the first stage of the refrigerator and forms a radiation shield at about 70 K. To enhance the differential pumping effect, a low conductance path is provided between the chamber and the rest of the system. At a nitrogen flow rate of $1.6 \times 10^{-2}$ mbar l s$^{-1}$, an average running time of about 1700 h was achieved before warming-up and vaporization of the cryodeposit became necessary.

Two further features are of interest: by making the cryopump of thin (1 mm) high purity aluminium (Figure 9), the cool-down time was reduced to 90 min; and the refrigerator and its associated compressor were operated satisfactorily in SF$_6$ at 8 bar, the only modification necessary being the replacement of capacitors by a type with reinforced cases to withstand the high pressures.
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Figure 9. The radiation shield of the Daresbury cryopump. The large cylinder is 12.5 cm diameter and 12 cm long when the two halves are put together. It was made from 1 mm thick high purity aluminium sheet. The bottom end of the smaller diameter cylinder is clamped round the first stage of the refrigerator.

Compound cryopumps

The pumping requirements of nuclear fusion reactors have generated some new problems. The plasma in a nuclear fusion machine may be formed from hydrogen, deuterium or tritium, or some combination of these, depending on the particular reaction being studied. The reaction product is mainly helium. Thus it is anticipated that large cryopumps capable of pumping mixtures of hydrogen isotopes and helium will be required. It is clear that a cryopanel at 4 K backed by a sorbent material would be suitable, provided that the hydrogen isotopes were prevented from reaching the sorbent and building up a cryocondensed layer, which would prevent the access of helium to the pores. Such a geometry is clearly not difficult to arrange. However, an additional requirement is that the helium must be desorbed separately from the hydrogen isotopes to allow independent recovery, and this clearly implies a separation of the helium and hydrogen pumping panels.

Three designs of such 'compound' cryopumps are shown in Figure 10. Two of these (a and b) use charcoal or molecular sieve 5A surrounded by a chevron baffle at 4 K to condense hydrogen isotopes. The third design (c) uses solid argon as the sorbent; it has been known for a long time that argon deposited at less than about 6 K has a reasonable capacity for adsorbing both hydrogen and helium. In the Lawrence Livermore Laboratory design, argon gas at about 120 K is continuously sprayed onto a panel at 4.2 K, where it solidifies. By this method, diffusion problems are eliminated, since the helium is being adsorbed concurrently with the deposition of the argon layer, and no doubt pumping is assisted by cryotrapping. Further, there are no problems with cryocondensed hydrogen. There is a penalty, however, of a greatly increased heat load on the helium refrigerator due to the latent heat of condensation of argon, since about 30 argon atoms have to be deposited for each helium atom adsorbed, and a further disadvantage that a large quantity of gas has to be handled during regeneration.

The design shown in Figure 10(d) incorporates a valve. Closure of this during regeneration enables sorbent regeneration to take place simultaneously with vaporization of the cryodeposit on the chevron baffle, thus increasing the pump duty cycle by as much as 50%.

Large cryopumps

A number of very large cryopumps have been, or are being, constructed for various applications in connection with nuclear fusion. These are all required to pump hydrogen (and eventually deuterium and tritium); in the future, there will also be a requirement for helium pumping.

The pumps all use liquid helium as coolant for the hydrogen pumping stage, which must therefore be carefully protected from ambient temperature thermal radiation by shields cooled with liquid nitrogen and by blackening or polishing the various pump surfaces as appropriate. Pumping speeds of up to around $10^7$ s$^{-1}$ are called for in some cases, with a heat load of around 1 kW on the helium-cooled system. Since this involves a power input to the refrigerator of several megawatts, it is clearly important to provide highly efficient radiation shielding whilst maximizing the transmission of gas molecules.

Whilst several of the pumps use 'conventional' chevron baffles or Santeler arrays, some new, more efficient configurations have been devised. The chevron type has the advantage that with careful design, the thermal radiation reaching the helium panel...
can be reduced to a very low level\textsuperscript{23}. The other designs tend to be more 'open' in that they have a somewhat higher transmission for thermal radiation, but this disadvantage is outweighed in many cases by a much higher transmission coefficient for gas molecules.

One such design has been developed for the neutral injector boxes of the Joint European Torus (JET) nuclear fusion experiment at Culham in England. A neutral injector is a device which fires a beam of high energy neutral hydrogen atoms into the circulating plasma of the fusion machine, thereby increasing the plasma energy. It consists essentially of an ionizer, acceleration potential and a neutralizer of low density hydrogen gas. Un-neutralized ions are deflected by an electromagnet onto a water-cooled copper block to dissipate their energy, while the neutralized beam passes straight into the plasma. In order to prevent reionization of the neutral atoms, the pressure remote from the neutralising region must be less than about $3 \times 10^{-5}$ mbar although hydrogen is being injected into the box at the rate of 200 mbar s$^{-1}$. Unfortunately, the constraints of the system components meant that use could not be made of the flexibility of cryopump geometry, and the cryopanels had to be restricted to each side of the neutralizer box (Figure 11).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{cryopump_module.png}
\caption{Cryopump module (10 per assembly).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{cryopump_module_support.png}
\caption{Figure 11. The neutral injector box for the JET nuclear fusion experiment. Dimensions are in mm\textsuperscript{23}.}
\end{figure}

An investigation of a number of different types of arrays suitable for the flat panel type of geometry was undertaken, and that shown in Figure 12(a) appeared particularly interesting. The overall capture coefficient of this type of array can be optimized only to about 20\%\textsuperscript{24}, but this low figure is mostly due to the molecules reflected from the front radiation shield; between a third and a half of those which pass through the two apertures are in fact captured by the helium panel, depending on the depth of the array. However, if a number of arrays similar in geometry but successively smaller in size are stacked in series, as indicated in Figure 12(b), it is clear that the overall capture coefficient can be considerably increased. From this idea\textsuperscript{25} evolved the final design (Figure 13)\textsuperscript{25}, which was optimized to produce an overall capture coefficient of about 49\%\textsuperscript{24}. (These capture coefficients are all for an infinitely long cryopanel with no location plates, but take into account panel thickness and cooling tubes).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{cryopump_module_pressure.png}
\caption{Figure 12. (a) Cross-section of an open-structure cryopump. (b) A simple method of enhancing the capture coefficient.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{cryopump_module_fusion.png}
\caption{Figure 13. The JET 'serial open structure' cryopanel\textsuperscript{25}.}
\end{figure}

The array shown in Figure 13 forms a 'module', is 6m in length and is oriented vertically. The panels are aluminium extrusions. Ten modules are joined side by side to form an assembly 3.5 m wide. The various cooling channels are manifolded together above and below this assembly, so that overall the unit is just under 7 m
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high. The complete unit has a theoretical pumping speed of about $4.5 \times 10^8 \text{ s}^{-1}$ for room temperature hydrogen and weighs about 2 tonnes. The estimated refrigeration requirements are not more than 40 W for the helium panels, and not more than 10 kW for the liquid nitrogen panels. Two units are required for each neutral injector box.

Another large fusion experiment for which novel cryopump arrays have been developed is the Mirror Fusion Test Facility (MFTF) which is under construction at the Lawrence Livermore Laboratory in California. Whereas the JET specification called for a flat panel geometry, the MFTF problems were rather different.

The MFTF consists basically of two large superconductive magnets forming an approximate sphere 9 m in diameter and containing the plasma, situated in the middle of a vacuum vessel 10 m in diameter and 20 m long. Thus the cryopumps have to be sited in each end region, but part of this is reserved for the plasma itself. The magnetic field is arranged so that the plasma leaks out of the magnets towards both ends of the vacuum vessel, where it is neutralized and reduced in energy. The same path is used to inject neutral hydrogen atoms into the centre of the magnet, the neutral injectors being sited on the end domes of the vacuum vessel. The net result is that the area available for the cryopumps is reduced by perhaps 30%.

The initial calculations showed that a minimum pumping speed of $3.4 \times 10^7 \text{ s}^{-1}$ was required. If chevron baffled cryopumps were to be used, placed against the chamber walls, it was quite clear that there was not enough space available to achieve the specification. The panels would therefore have to be suspended within the available volume, and both sides of each panel used for pumping.

The obvious solution was to use a panel with a chevron baffle on each side (Figure 14(a)), but a higher pumping speed was obtained with a 'Z' configuration (Figure 14(b)), which also satisfied the condition that both sides of the helium panel were to be used. Monte Carlo calculations showed that the Z configuration could be designed to have a capture coefficient about 30% higher than the chevron baffled type. In the final design, D/S was chosen to be 1.5 and the angle $\theta$ to be 45°.

The optimum configuration of panels was next determined. Placing them parallel to each other allowed a significant fraction of molecules to pass between them without being pumped; a better arrangement was the 'accordion' design shown in Figure 15. No molecules can now pass through the pump, while the 'V's enhance the probability of capture because of the 'black hole' effect. A capture coefficient of between two and three times that for a single panel can be achieved, depending on the angle of the V, which was selected in this case to be 20°. It is interesting that the low transmission coefficient of a baffle can be enhanced in this way—an effect which has also been utilized in an array design with a capture coefficient of 0.4 which has been proposed by Schwenterly.

One other variable to be considered is that the Z configuration is to some extent directional because molecules are more easily captured if they are travelling parallel to the arrow in Figure 14(b), rather than perpendicular to it. A 50% increase in capture coefficient is obtained if this can be arranged, and it is clear that with the accordion array it is easy to do, and will apply to both sides of the Z (Figure 15).

Figure 16 shows the constructional details of the Z array. This gave a computed capture coefficient of 0.25 for molecules incident on one side and 0.27 for those incident on the other, the difference being due to asymmetry of the detailed design. The overall capture

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**Figure 14.** Cross-sections of chevron and Z arrays considered for the MFTF nuclear fusion experiment.

**Figure 15.** The cryopump arrangement at each end of the MFTF vacuum vessel.

**Figure 16.** The Z panel design showing some constructional details. The right-hand side will be at the end of a V, and has a small open structure array incorporated.
 coefficient for the inside of each V is 0.67. However, the edges of the V are less efficient, being a simple ‘open structure’ pump (compare Figures 12(a) and 16), and this reduces the overall capture coefficient based on projected area to about 42%.23

As with the JET design, the panels are made from aluminium extrusions. The overall pumping speed is $4.6 \times 10^7$ l s$^{-1}$ for 300 K hydrogen, and the total weight is 66 tonnes. The estimated refrigeration requirements are 1200 W for the helium panels and 60 kW for the nitrogen panels.

Some comparative figures for pumps which have been, or are being, built for nuclear fusion experiments are given in Table 1. These are all for neutral injector systems except for the MFTF pumps. The Doublet III experiment, operated by General Atomic at San Diego, California, uses a cylindrical pump covered with Santeler arrays running in an axial direction along the cylinder.28 One end of the cylinder is closed with chevron baffle arrays; the other is open. The pumps of the Tokomak Fusion Test Reactor (TFTR) at Princeton, New Jersey, are of the flat panel type: large flat panels cooled with liquid helium are protected by chevron baffles.29,30 The JET design would appear to have some advantages over the others in terms of weight and heat load per unit pumping speed, but it should be said that the heat loads in the table are estimated rather than measured. Such calculations depend critically on the emissivities of the cryopanels, which are notoriously difficult to predict. Also, the measured heat loads will depend on the final surface finishes achieved on these very large

### Table 1. Comparison of some large cryopumps for fusion experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Baffle design</th>
<th>Pumping speed: hydrogen at 300 K (l s$^{-1}$)</th>
<th>Weight (tonnes)</th>
<th>Estimated helium panel heat load (W)</th>
<th>Estimated nitrogen panel heat load (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doublet III</td>
<td>Santeler and chevron</td>
<td>$1.4 \times 10^6$</td>
<td>—</td>
<td>23</td>
<td>—</td>
</tr>
<tr>
<td>TFTR</td>
<td>Chevron</td>
<td>$3.5 \times 10^6$</td>
<td>5.5</td>
<td>45</td>
<td>4.7</td>
</tr>
<tr>
<td>JET</td>
<td>Open structure</td>
<td>$9 \times 10^6$</td>
<td>4</td>
<td>&lt;80</td>
<td>&lt;20</td>
</tr>
<tr>
<td>MFTF</td>
<td>Z</td>
<td>$4.6 \times 10^7$</td>
<td>66</td>
<td>1200</td>
<td>60</td>
</tr>
</tbody>
</table>

Note that the estimated heat loads may not correspond to those achieved in practice—see text.

Figure 17. The MFTF cryopanels during manufacture. The large circular pipe at the near end of the panels is part of the helium manifold, and is the only part of the helium system visible. (Reproduced with the courtesy of CVI Inc.)
structures, and may reflect such factors as cleanliness during assembly rather than the ingenuity of the design.

Conclusion

This paper has described a selection of the developments in cryopumping which have been published during the past few years. It has been a period of detailed development and consolidation rather than of spectacular advance, of an increased sophistication in cryocondensation pumps, and of an increased understanding of cryosorption pumping. We may look forward to a wider use of small cryopumps cooled by displacer-cycle refrigerators in industry and research, and to an era of very large cryopumps for nuclear fusion studies.

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