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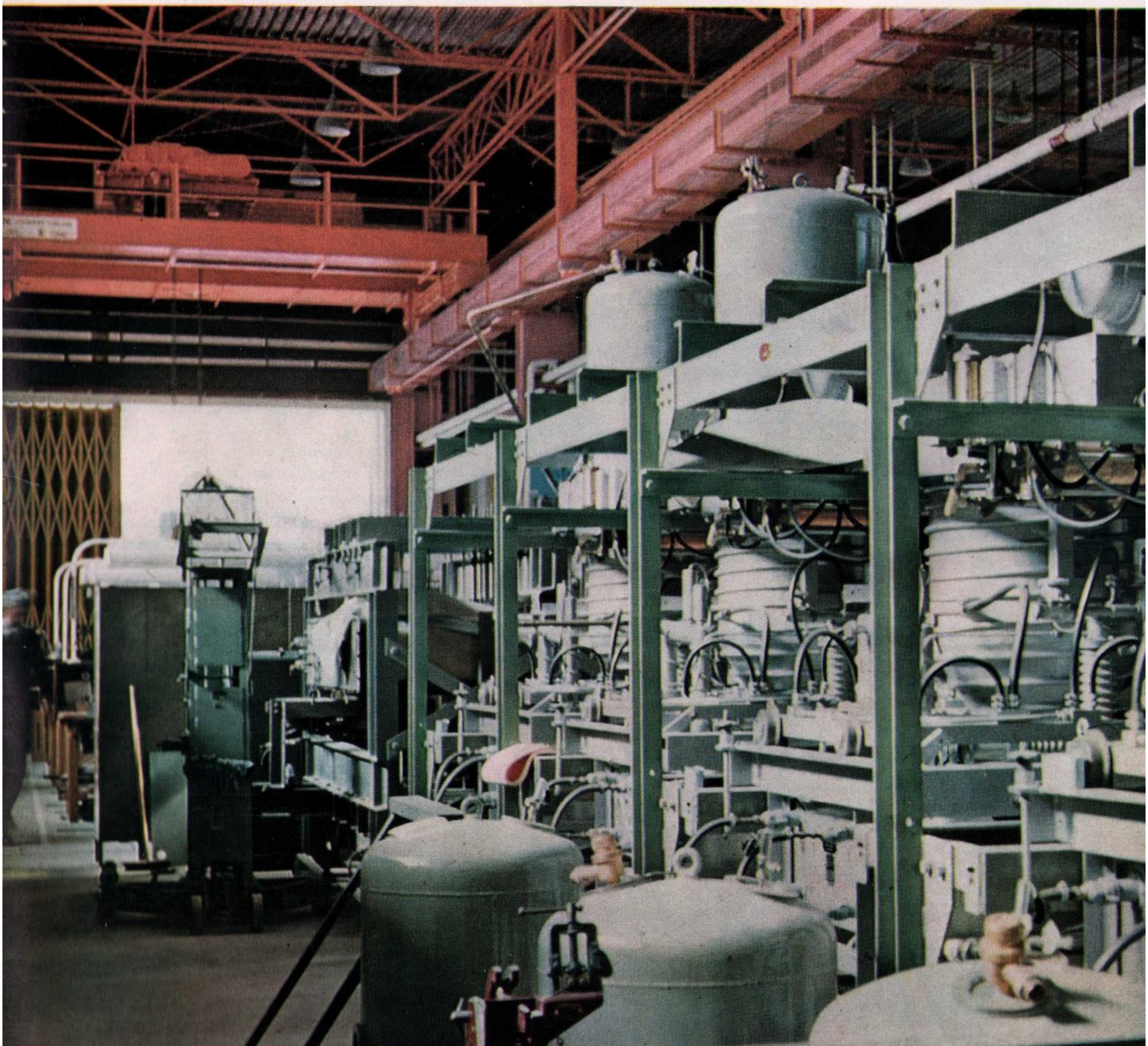
JULY 1962

Special Nimrod Issue

VACNIQUE

A "SPEEDIVAC" view of a low pressure world



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IN THIS ISSUE

The Nimrod project and the N.I.R.N.S. *T. G. Pickavance, B.Sc., Ph.D.*	..	page 3
Pumping Equipment for Nimrod *N. T. M. Dennis, B.Sc., A.Inst.P.*	.. ..	page 4
Control Units for the Nimrod Proton Synchrotron High Vacuum System *W. Steckelmacher, B.Sc., F.Inst.P.*	.. ..	page 11
Liquid Air Supply for Mercury Diffusion Pumping Stations for Nimrod *T. A. Heppell, B.Sc.*	..	page 16

THE FRONT COVER PICTURE

The vacuum equipment assembly area at the National Institute for Research in Nuclear Science, showing several torus oil diffusion pump stations under test.

Why this special issue. . . .?

There could be no better reason to break with the normal pattern of '*Vacnique*' than NIMROD, a project involving the construction of a particle accelerator for the National Institute for Research in Nuclear Science at Harwell. As main contractors for the high vacuum pumping system, we have carried out a great deal of research and design work in connection with this proton synchrotron and this issue of '*Vacnique*' is an attempt to make known some of the results.

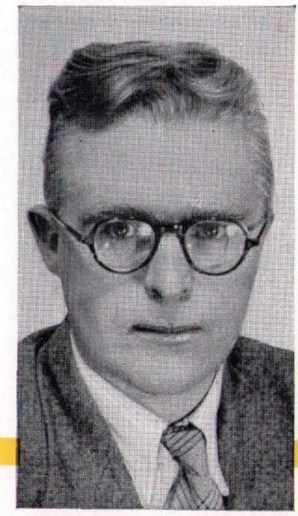
The final pumping system for NIMROD was very complex and was honeycombed with controls and safety devices so that in the event of a failure in service or an operating fault, the vacuum chamber was instantly sealed off under high vacuum.

Our equipment therefore, had to be capable of:

1. **Evacuating and maintaining a vacuum of 10^{-6} torr in a large vacuum chamber.**
2. **Ensuring absolute freedom from contamination.**
3. **Providing complete protection for the vacuum chamber with fully automatic controls and facilities for remote control.**

Similar conditions exist, either separately or together in many other research projects and industrial processes for example:—Space Simulation—electron optics—study of surface phenomenon—solid state physics—remote handling of dangerous materials—production of semi-conductors, etc. The experience we have gained with NIMROD has enabled us to produce standard pumping systems for this type of work.

Dr. T. G. Pickavance, Director of the Rutherford Laboratory, kindly consented to provide our introduction to NIMROD, and the remainder of this issue consists of papers by our research staff dealing with (a) The pumping stations; (b) The gauges and controls; and (c) The liquid air transfer equipment.



THE NIMROD PROJECT AND THE N.I.R.N.S.

The National Institute for Research in Nuclear Science was set up in 1957 with the general object of providing and operating nuclear research facilities for co-operative use by universities and other bodies. Universities are, of course, vitally concerned with fundamental research, and would soon die if cut off from it, but the biggest accelerators needed for nuclear and elementary particle research are too costly to be duplicated in individual universities, and require too large a staff for operation, maintenance and development to fit well into the environment of a single university.

The Rutherford High Energy Laboratory at Harwell is the first laboratory of the N.I.R.N.S., and contains two accelerators. The smaller machine, a 50 MeV proton linear accelerator, has been operating for two years and is being used by over 60 graduate physicists, of whom two-thirds are visitors from several universities. The visitors include research students, and spend an average of perhaps a quarter of their time at the Rutherford Laboratory; they are therefore able to continue with their normal university activities. This has set the pattern which we hope to follow with Nimrod, a much bigger machine. Nimrod is a synchrotron, still under construction, which will accelerate protons to a maximum energy of 7 GeV (7,000 MeV, or 7.10^9 electron volts). Protons of this energy will produce, in collisions with targets placed in the machine, beams of the many types of "elementary" particles which have been discovered in high energy experiments. The field of research is the study of the properties and mutual interactions of these particles and, therefore, the ultimate structure of matter; it has been, and promises to continue to be, one of the most challenging and exciting frontiers of science.

Construction of Nimrod was begun in 1957, and is scheduled to be completed in the latter half of 1963. It will be the biggest accelerator in Britain, although the CERN proton synchrotron in Geneva which produces 28 GeV is shared by physicists from 14 states of Western Europe, including Great Britain.

T G Pickavance

PUMPING EQUIPMENT FOR NIMROD

by

N. T. M. DENNIS, B.Sc., A.Inst.P.

Pumping Equipment Research Division

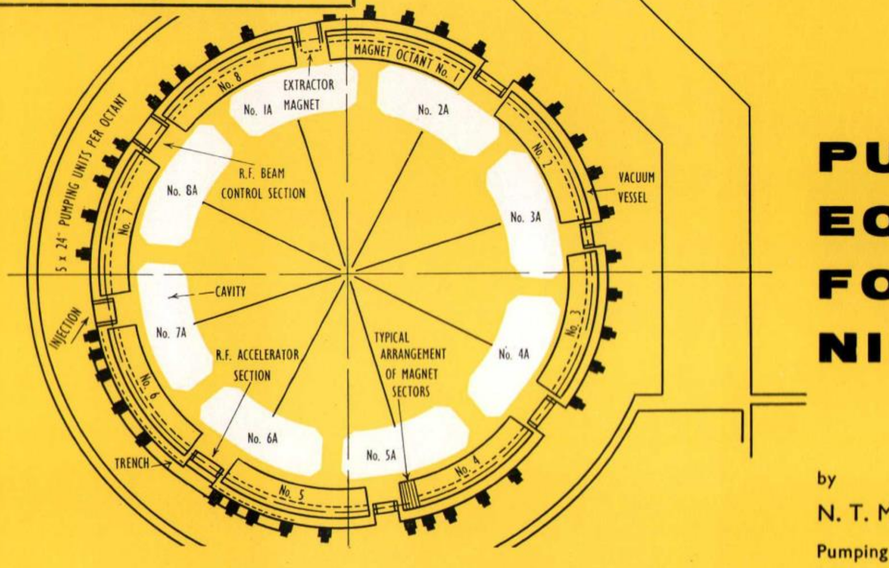


Fig. 1. *Plan view of synchrotron torus.*

Nimrod consists primarily of two units, the linear accelerator injector which, with its associated apparatus, is about 120 ft long and a torus which is some 150 ft in diameter. The linear accelerator accelerates the protons to 15 MeV before they are injected into the torus.

In the torus the protons are made to describe a circular path some 90 000 miles long by means of a magnetic field, and in an acceleration time of about 0.7 seconds they reach an energy of 7 GeV before being ejected.[1] The magnet assembly, which is used to maintain a constant orbital radius in the torus, uses some 7 000 tons of special magnet steel. The torus vacuum vessel is placed between the pole pieces of the magnet and because of the intense and varying magnetic field, is constructed mainly of glass reinforced epoxy resin. Forty oil diffusion pump stations with a total pumping speed in excess of 200 000 litre/sec are provided to obtain an ultimate vacuum in the vessel of less than 10^{-6} torr.

The linear accelerator and its associated apparatus are constructed mainly from metal and with the electrode assemblies in the vacuum chamber present a very extended surface to be pumped. An added complication is that, due to the large potential gradient existing in the linear accelerator, the vessel must be kept free of any traces of organic material. The pumping system therefore consists of a number of mercury diffusion pump stations giving a total baffled speed of some 10 000 litre/sec, with which an ultimate vacuum of less than 10^{-6} torr has been reached.

SYNCHROTRON TORUS

The synchrotron torus is divided into octants each subtending 45°. Between these curved sections are eight straight sections, made mainly of steel, which are utilised by devices for the injection, acceleration, control and ejection of the protons, a plan view of the torus is shown in Fig. 1. The curved sections have to work in an intense and varying magnetic field. So that the power dissipated and the field distortion are not substantial, each curved section has to be built mainly from non-conducting material and the chamber wall has to be kept as thin as possible so as to make full use of the magnet gap. To achieve this, the curved sections consist of inner, outer and header vessels, all constructed in glass reinforced epoxy resin, the inner chamber being lined with thin stainless steel to prevent electrostatic charge accumulation. The inner chamber walls are about $\frac{1}{4}$in thick and they form a vessel approximately 10in high by 40in wide. As this chamber is of such light construction it cannot withstand atmospheric pressure when under vacuum, so it is surrounded by an outer chamber which is held at a vacuum of about 1 torr. The inner chamber is able to stand a pressure differential of about 8 torr and there are safety devices, so that if a large leak occurs, and this pressure differential is likely to be exceeded, then the pressure in the inner and outer chambers is equalised.

The outer chambers are placed between the magnetic sectors and the pole pieces, this means that they can be of relatively light construction as the atmospheric loading on them is effectively transferred to the pole piece support. A cross-section of the inner and outer chambers with their header vessel is shown in Fig. 2. The header chamber, constructed in the same manner as the other chambers, has much thicker walls so that it can support atmospheric loading. It is connected to the outside of the torus, and it is to this header chamber that the high vacuum pumping units are connected.

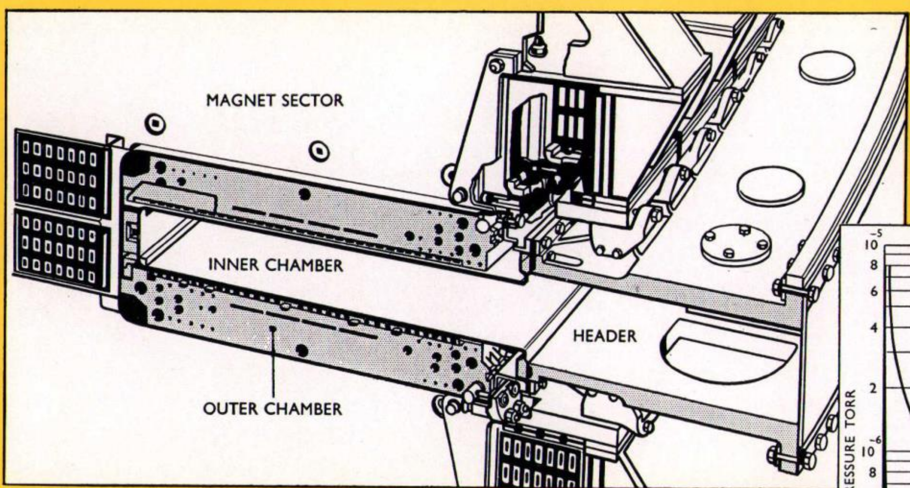
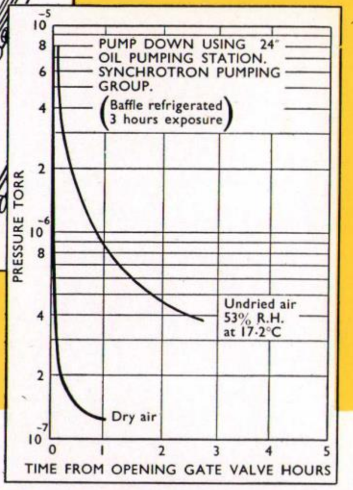


Fig. 2. *Cross sectional view of inner, outer and header chambers.*

Fig. 3. *A comparison of pump down curves after exposure to undried and dried air for large test chamber using 24in oil diffusion pumping group.*



HIGH VACUUM PUMPING REQUIREMENTS

As the path travelled by the proton is of considerable length it is necessary to keep the pressure of the inner chamber to as low a value as possible. It has been estimated that to keep the loss of beam energy to less than 10% the chamber pressure should not exceed 10^{-6} torr.[2] Work has been carried out to find the best type of epoxy resin to use so that the degassing rate of the chamber is low enough to enable this pressure to be reached with a reasonable pumping speed.[3] The pumping arrangement arrived at was 40 pumping stations[4]; five to each octant of the machine as shown in Fig. 1. Each pumping station was to have a pumping speed, above the high vacuum valve, of between 5 000 and 6 000 litre/sec, for air, making a total speed for all the units of at least 200 000 litre/sec. The stations were each to be capable of reaching an ultimate vacuum with valve and baffle, of less than 5×10^{-7} torr.

The pump down time required on a chamber of this type depends primarily on the degassing from the chamber. It has been proved that a large proportion of the degassing is due to water vapour, and considerably improved pump down time can be achieved if the chamber is let up to atmospheric pressure with dry air.[5] An example of this effect on a metal header is shown in Fig. 3. To improve the pump down cycle on the torus, facilities have been made to let the inner chamber up to atmosphere with dry air and then to pass warm dry air through it, this will considerably reduce the time required to pump down to 10^{-6} torr.

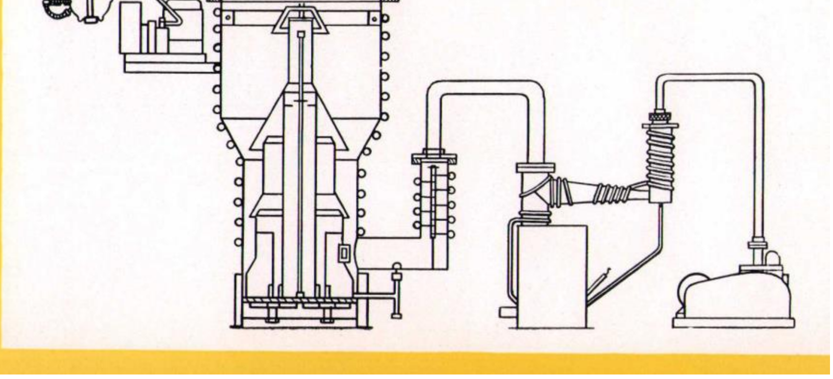
ROUGH PUMPING REQUIREMENTS

The roughing system consists of eight mechanical booster (Roots) pumps with a peak speed of 230 ft^3/min, and in parallel with these are eight large rotary pumps. During rough pumping the inner and outer vessels are connected by a large number of 4in bore quarter swing valves until a pressure of 1 torr is reached, then the inner vessel is isolated from the outer vessel leaving the large rotary pumps to hold the outer vessel at 1 torr or below. The Roots pumps continue to pump the inner vessel until 10^{-2} torr is reached when the high vacuum units take over. To protect the inner vessel during the roughing cycle from the rotary pump oil vapour existing above the mechanical pumps, refrigerated baffles are interposed between the mechanical pumps and the inner chamber.

HIGH VACUUM PUMPING STATIONS FOR THE TORUS

The pumping station finally decided upon for

Fig. 4. *Diagram of torus 24in diffusion pumping group.*



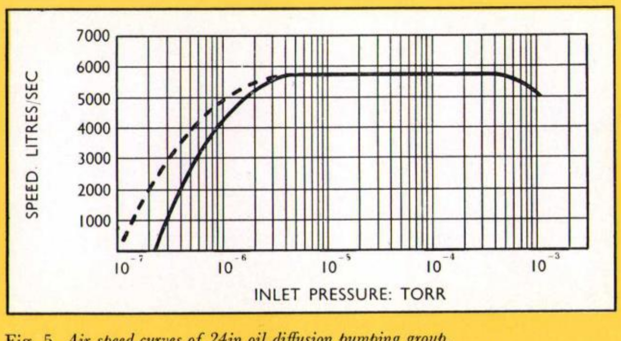


Fig. 5. *Air speed curves of 24in oil diffusion pumping group. The dotted curve corresponds to the baffle being refrigerated.*

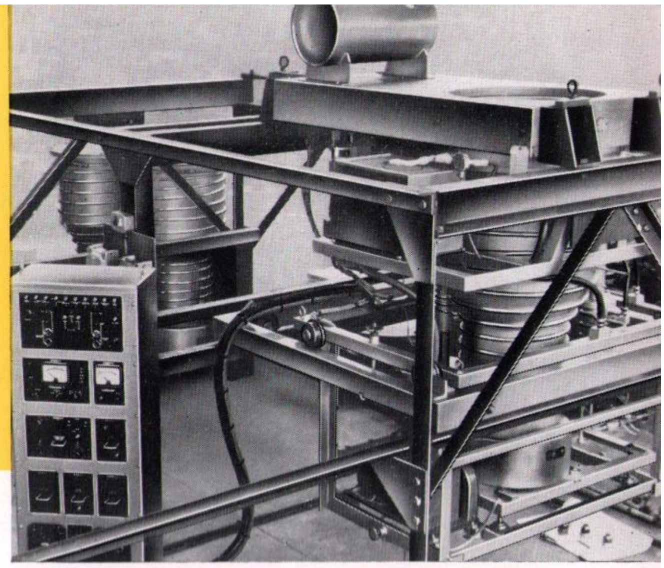


Fig. 6. *24in oil diffusion pumping group in specially constructed test frame work.*

pumping the torus is shown diagrammatically in Fig. 4. It consists of a 24in bore gate valve (GV24), refrigerated chevron baffle (CB24), a 24in bore fractionating oil diffusion pump (F2404) backed by vapour booster pump (9B1) which, in its turn, is backed by a 150 litre per minute rotary pump (1SC150). The overall pumping speed of this high vacuum station is shown in Fig. 5.

The pumping group has been designed for ease of removal from the gate valve, which is supported from the magnet sectors, and replacement by another group. This is achieved by the use of two carriages which can be moved at right angles to each other for positioning the pumping group under the gate valve and an internal jack operated from one point to bring the unit up to the gate valve. The unit in its framework is shown in Fig. 6.

The control system is completely automatic, the pumping station being started by a single push button. When the pressure reaches 5×10^{-6} torr it is possible, by operation of a further push button, to open the gate valve. The control and safety devices are fully described in a later article on page 11.

GATE VALVE

The GV24 gate valve gives a clear bore of 24in diameter. The body consists of six steel plates which are sealed together with indium wire, so reducing the elastomer material in the valve to that in the valve plate and in the rotary seal through which the operating shaft enters the valve. The valve mechanism is operated pneumatically and is such that the plate is moved into the closed position, then pressed on to its seating with the mechanism locking at the same time. When in this position the valve can resist atmospheric pressure in either direction. In this type of valve it is normal for the valve plate to seat against the top cover so that when the chamber is brought up to atmosphere the valve mechanism is kept at high vacuum as it is on the diffusion pump side of the valve plate. When the vessel is again pumped down the only outgassing that arises from the valve is that due to the valve plate and sealing ring that have "seen" the atmosphere. The speed of operation of the pneumatic mechanism is controlled by an oil damping cylinder. This is arranged so that the valve takes about 30 minutes to open fully but closes in less than 10 seconds. The slow opening of the valve is required in order that the gas load from the chamber is not too large for the diffusion pump during the initial pumping period.

CHEVRON BAFFLE

The 24in bore baffle below the valve is of a compact chevron type having a height of only $2\frac{3}{8}$ in. This type of baffle is preferred due to the small distance between the baffle elements as this reduces the probability of inter-molecular collision within the baffle, and so improves its baffling efficiency. The baffle element is cooled by means of direct expansion of a refrigerant in its cooling coils and, with the compressor used, a temperature of about $-25°C$ is reached. The angle of the chevron has been chosen to give optimum conductance, the conductance of the baffle for air being about

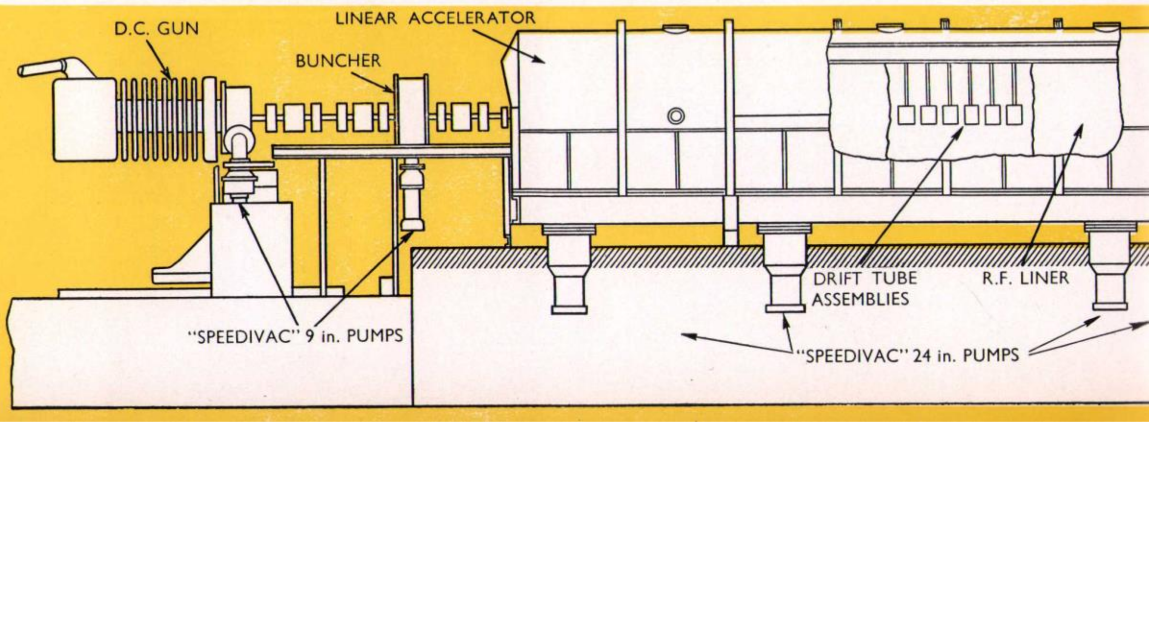


Fig. 7. *Diagram of linear accelerator injector system showing position of pumping units.*

the same as the speed of the diffusion pump so reducing the overall pumping speed by only about 50%.

OIL DIFFUSION PUMP

The diffusion pump is a four stage fractionating oil diffusion pump of 24in mouth diameter and a pumping speed of about 11 000 litre/sec. The pump is fitted with a "guard ring"[6] over the top jet cap which reduces the backstreaming rate of the pump to the very low value of less than 5 micro grams/cm^2/min.[7] The side stage of the pump besides giving the pump a high critical backing pressure of 0.35 torr, also has a purifying action.[8] This is because oil condensed from this stage has to flow back past the vapour jet, on the bottom of the hot side tube, with the result that the more volatile fractions of oil re-evaporate and do not return to the pump boiler. This purifying action, together with fractionating arrangements in the boiler of the diffusion pump, ensures that with the best diffusion pump fluids, it is possible with a water-cooled baffle to get an ultimate of less than 5×10^{-8} torr. The pressure is measured by a fully immersed ion gauge calibrated for air. If the baffle is refrigerated and a metal gasket used, a pressure of about 2 to 3×10^{-8} torr can be reached, almost the whole of this pressure being due to outgassing from the chevron baffle and the test header.[9] The fluid chosen for this particular application was Apiezon C so that if any breakdown products of the oil are formed due to the proton beam then these products are likely to be of a conducting carboneous nature and electrostatic accumulation of charge will not occur. A thermal switch, fitted on the lower side of the side stage vapour tube, is used in the automatic control system to indicate when the pump is working. The top stage cooling coils of the pump and the connection between diffusion and booster pumps are cooled by chilled water at about 5 to 10°C, while the cooling coils on the lower stages are cooled by water from a cooling tower, the temperature of which could reach 30°C during warm weather. This has reduced the cost of the equipment required in the water recirculating system, as only 36 kW is handled by the chilled water, while approximately 180 kW is handled by water from the cooling tower.

BACKING PUMPS

The single stage vapour booster pump which backs the diffusion pump was primarily used so that a full speed curve of the diffusion pump could be maintained while using a very small rotary mechanical pump, so reducing vibration, noise, and weight. The critical backing pressure of the combination of vapour pumps is about 5 torr and to keep the backing pressure lower than this at full throughput requires only a single stage 150 litre/min rotary pump, which can be on full gas ballast if required. If the vapour booster pump had not been used, a rotary pump of about 1 500 litre/min would have been needed. The vapour booster pump has at the lower end of its condenser a thermal switch, this being used in the control circuit to indicate that the pump is working satisfactorily.

LINEAR ACCELERATOR INJECTOR

The injector is illustrated diagrammatically in Fig. 7, and consists of an electron gun, linear accelerator assembly, "buncher", "de-buncher", and flight tube, these forming a series of inter-connected metal chambers. The main requirements of the pumping systems on these chambers were that a vacuum of about 10^{-6} torr should be achieved and that there should be freedom from organic contamination, as this can lead to difficulties with the high potential gradients encountered in this type of accelerator. It was therefore decided to use mercury vapour pumps with liquid air cooled traps. The linear accelerator chamber is approximately 50 ft long with a volume of 2 500 ft^3 and with the assemblies inside, has a surface area of some 4 000 ft^2.

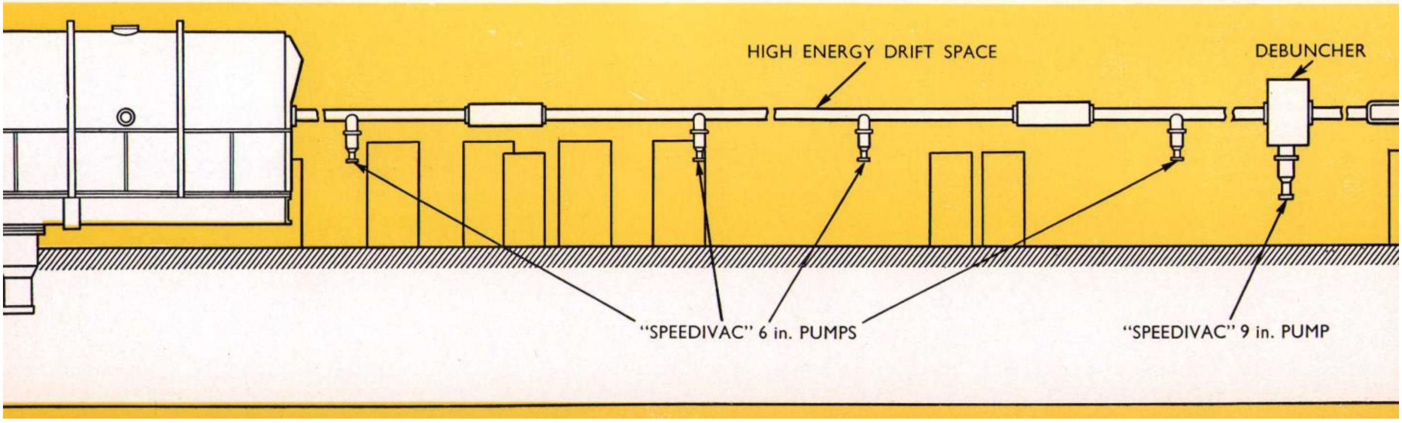
The rough pumping of the injector to 10^{-2} torr is carried out by a number of mechanical booster pumps as on the synchrotron torus.

PUMPING STATIONS FOR THE LINEAR ACCELERATOR

It was decided that on this chamber four pumping stations should be used, each with a speed of 2 000 litre/sec. The electron gun, "buncher" and "de-buncher" required pumping stations with speeds of 400 litre/sec while on the flight tube a number of units of 150 litre/sec were required. The ultimate vacuum obtained by all these units has to be less than 5×10^{-7} torr so that an appreciable speed must be reached at 10^{-6} torr. To achieve these pumping speeds groups were designed based on a 24in, a 9in and a

TABLE 1

Type of station	No. of such station used	Total liquid air consumption of these stations
2 000 litre/sec	4	4 litre/hour
400 litre/sec	4	1.8 litre/hour
150 litre/sec	4	1.2 litre/hour



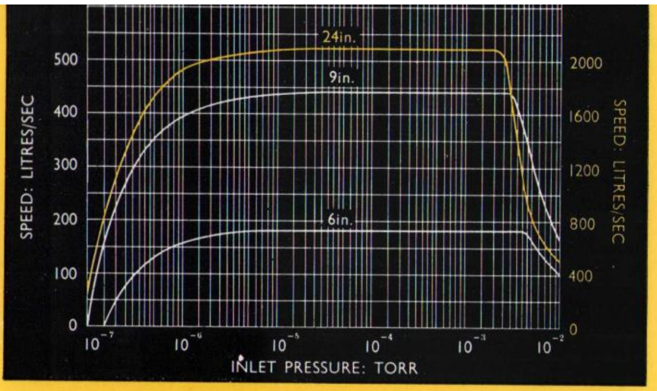


Fig. 8. *Air speed curves of 6in, 9in and 24in mercury diffusion pumping groups.*

TABLE 2

Pump type	Mercury charge	Time for all the pump charge to be transferred to trap at the measured transfer rate	
		without baffle	with baffle
24M4 24 in. mouth pump	2 000 ml	1 day	160 days
9M3 9 in. mouth pump	500 ml	6½ days	1 000 days
6M3 6 in. mouth pump	200 ml	8½ days	1 300 days

6in mercury vapour pump respectively. Typical speed curves for these units are shown in Fig. 8. The control requirements were the same as those on the oil diffusion pump stations on the synchrotron torus but with the complication of automatic maintenance of all the liquid air cooled vapour traps. This is dealt with in a further article on page 16.

All the stations consisted of a valve, vapour trap, refrigerated chevron baffle, mercury diffusion pump and a rotary backing pump; diagrams of these pumping groups are shown in Figs. 10a and 10b.

INLET VALVE

The inlet valves on the two larger stations were gate valves, similar to those used on the oil diffusion pump stations but of 16in (GV16) and 9in (GV9) bore. The

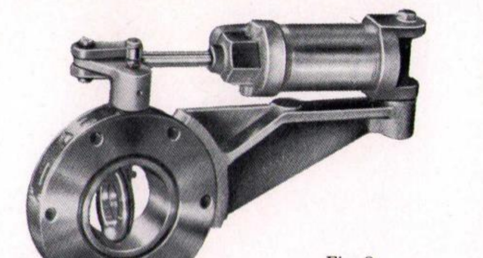


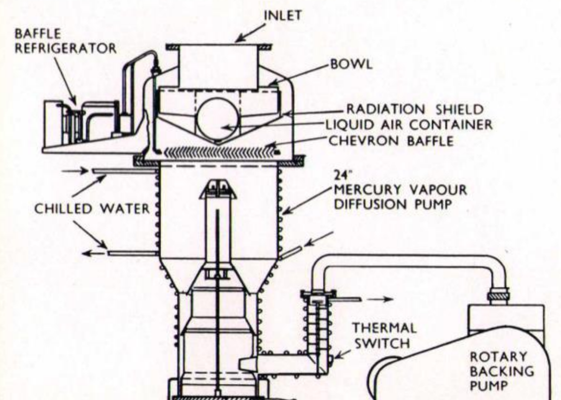
Fig. 9
Quarter swing butterfly valve.

valves on the smaller 6in stations were 6in quarter swing valves (QSB6) similar to those used for connecting the inner and outer chambers on the torus during rough pumping; a QSB valve is shown in Fig. 9. This type of valve will, like the gate valve, resist atmospheric pressure in either direction. All the valves were controlled to open slowly and close as fast as possible.

COLD TRAPS AND CHEVRON BAFFLES

The larger stations correspond to Fig. 10a, and here the vapour trap and chevron baffle are assembled in one body. The vapour trap consists of a horizontal cylindrical stainless steel container, supported by two filling tubes, to which is clamped a bright nickel-plated copper bowl. This copper bowl overlaps a 16in bore tube coming down from the top flange of the trap and unless there is an intermolecular collision, the mercury vapour cannot get past without hitting the cold bowl. To the outside of the bowl is attached a thin highly polished stainless steel radiation shield. When clean the liquid air consumption of this trap is about 1 litre per hour. The trap shown in Fig. 10b is the type used on the 9in and 6in stations and is constructed entirely from stainless steel and highly polished on all internal surfaces. The inner liquid air container is extended at its lower end so that it overlaps a tube coming from the pump end of the trap and, therefore, mercury vapour molecules must hit a liquid air cooled surface, provided no intermolecular collision occurs. The liquid air consumption of these traps under clean conditions is shown in table 1, the total liquid air consumption of all the traps on the accelerator being 7 litre/hour.

Below the traps are mounted chevron baffles which are refrigerated by direct expansion of a refrigerant to −25°C to −30°C at which temperature the con-



densed mercury is still a liquid and can run back into the pump. The main purpose of these chevron baffles is to reduce the vapour pressure of the mercury so that the vapour trap captures it at a very low rate. The trap is a very good pump for mercury vapour, the rate at which mercury is removed from the pump depending primarily on the wall temperature of the pump body above the top stage and the molecular conductance for mercury vapour between the top stage and the cooled surface.[10] With increasing size of pump this factor becomes of greater importance as the molecular conductance between the pump and trap increases at a much faster rate than the increase in the size of the mercury charge in the pump. Table 2 indicates the time required for the whole pump charge to solidify on the trap with and without a refrigerated chevron baffle, and with a wall temperature above the top stage of about 15°C.

MERCURY DIFFUSION PUMPS

The mercury diffusion pumps are constructed entirely of polished stainless steel and electro-polished to give a clean surface. The pumps are then cleaned very carefully with a solvent to remove any trace of organic content. It has been shown[10] that any slight organic contamination of a mercury diffusion pump considerably affects both the speed and the back migration rate of the mercury from the pump. Typical pump bodies and interiors are shown in Fig. 11. Chilled water at about 5°C is used for cooling the top stage cooling coils and backing condensers on all the diffusion pumps, this improves the speed performance of the pumps, reduces the amount of back migration to the chevron baffles, and reduces mercury loss to the backing system. The change of pump speed with the temperature of the condensing surface of the top stage is very noticeable in mercury diffusion pumps and

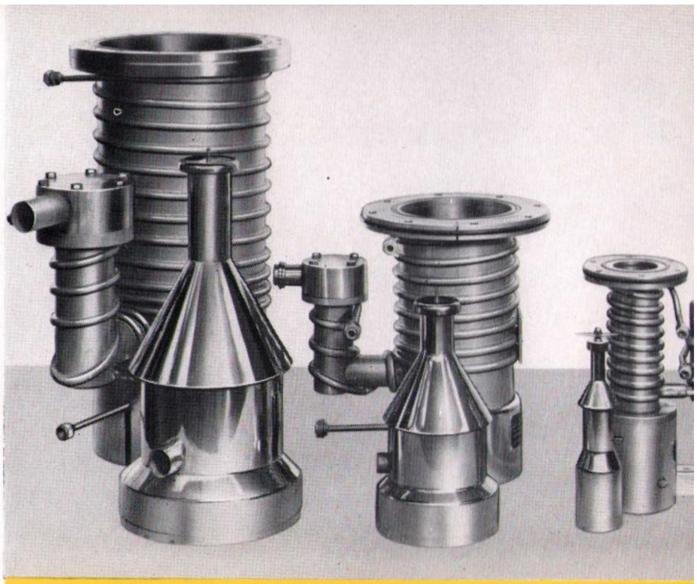


Fig. 11. *Stainless steel mercury diffusion pumps with interiors removed showing highly polished stainless steel construction.*

Fig. 12. *24in mercury diffusion pumping group installed below linear accelerator.*
(Photograph by courtesy of N.I.R.N.S.)

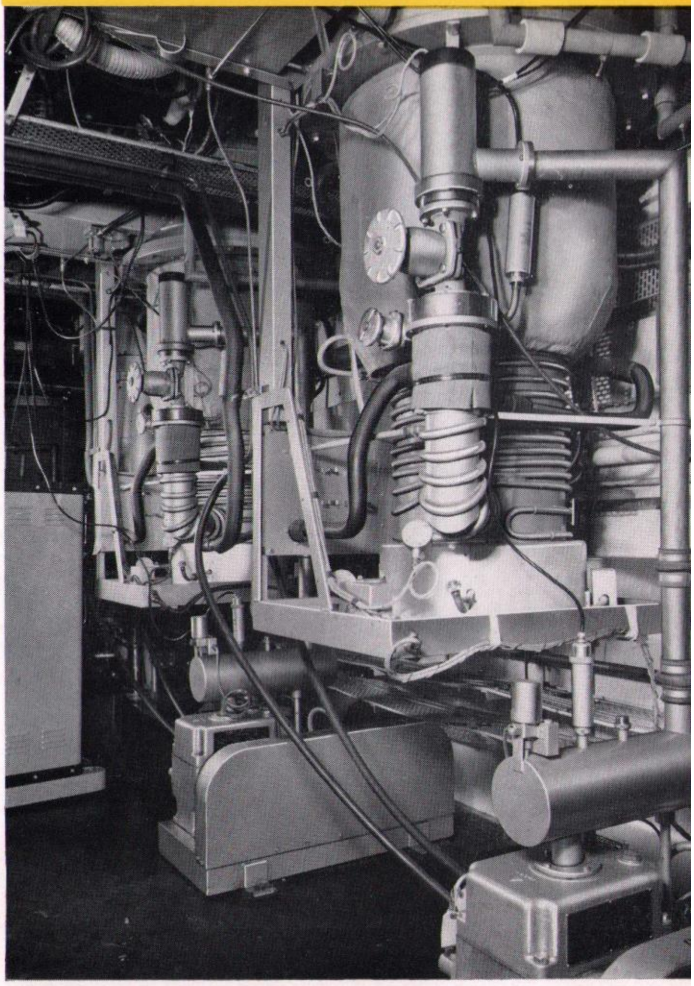
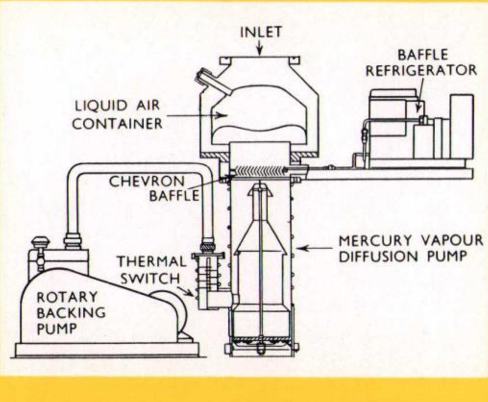


Fig. 10a. *Diagram of linear accelerator 24in mercury diffusion pumping group.*

Fig. 10b. *Diagram of linear accelerator 9in and 6in mercury diffusion pumping group.*



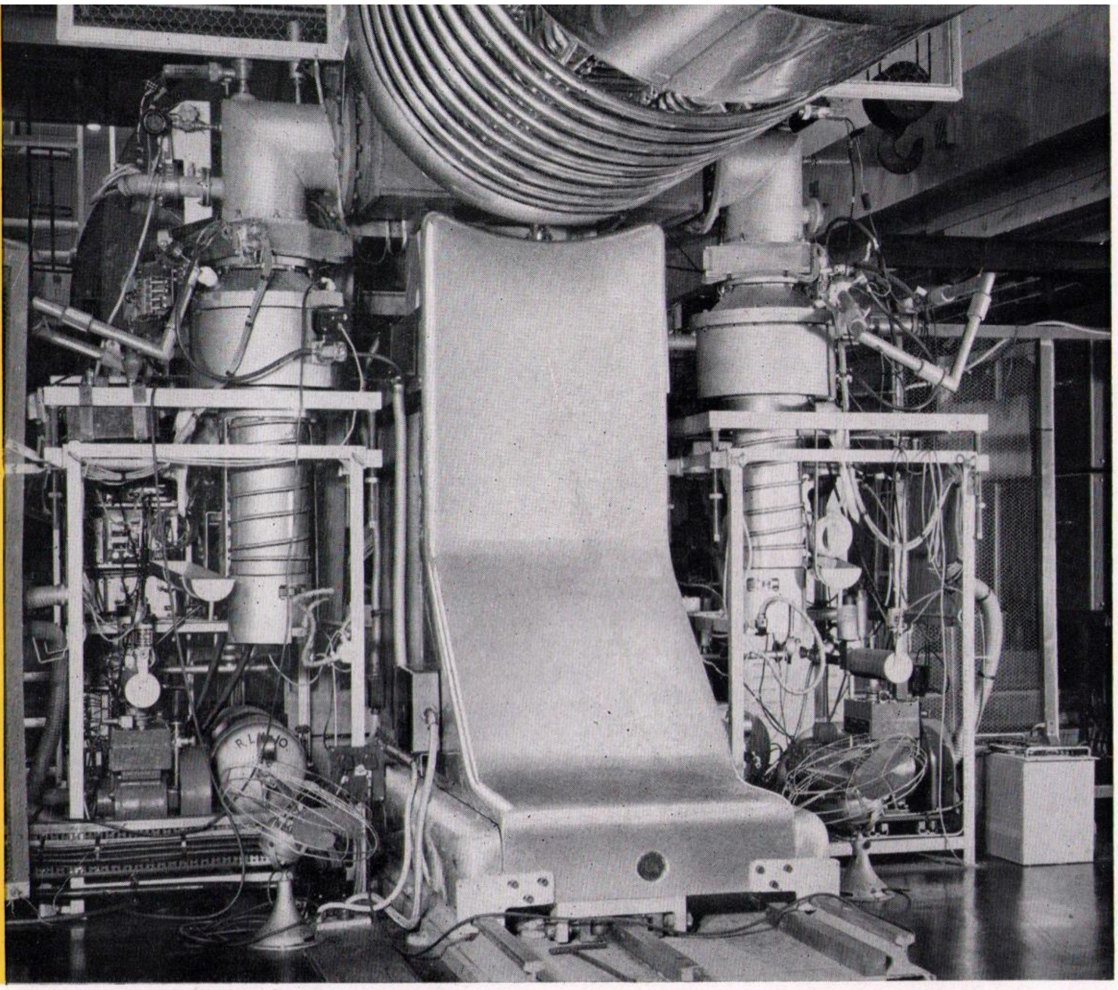


Fig. 13.
9in mercury diffusion pumping group installed below d.c. gun.
(Photograph by courtesy of N.I.R.N.S.)

becomes especially important in the larger size pumps. An example of this effect on speed is that with a 24in pump the change in speed at the pump mouth is from 9 000 litre/sec at 19°C to 15 000 litre/sec at 5°C condensing wall temperature.[10] To reduce the load on the chilled water supply the cooling coils for the lower stages are cooled, as on the oil pumps, by re-circulated water from a cooling tower. All the pumps have thermal switches on the lower side of the backing condenser which when the pump is working get warm due to the vapour stream from the side stage and this indication is used in the automatic control system.

BACKING PUMPS

The 24in, 9in and 6in stations are backed by 900 litre/min, 450 litre/min, and 150 litre/min pumps respectively. The 24in stations attached to the linear accelerator chamber are shown in Fig. 12, the 9in stations on the electron gun in Fig. 13.

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CONTROL UNITS FOR THE NIMROD PROTON SYNCHROTRON HIGH VACUUM SYSTEM

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Head of Instrument Research Division

INTRODUCTION

In this project each of the 40 pumping stations on the main toroidal chamber and each of the special pumping stations on the injection system is controlled by an individual local unit. These are separate rack mounting electrical units which look after the complete functioning of the pumping station. They provide appropriate electrical controls to the pumping station, indicate pressure, carry monitoring lamps indicating the state of the equipment and contain all subsidiary power units.

The control system allows the control of the pumping station to be switched from each local control panel sited near the pumps to a corresponding remote unit situated in the control room. A selector switch on each remote panel enables control to be transferred to a master panel on the control desk so as to have simultaneous control over all selected pumping stations. Clearly therefore the system must provide automatic operation of each pumping station such that each event is sequentially controlled to avoid mal-operation of the station. The local control units were therefore designed to contain a number of protective devices, sequence controls and timing devices with associated indicators including vacuum gauges to show the condition and correct operation of the various components.

CONTROLS FOR TORUS PUMPING STATIONS

In any vacuum system, the most important parameter is the pressure level at different points in the system as a function of time. Each pumping station was therefore provided with vacuum gauges at three positions and vacuum switching devices at four positions as shown in the schematic diagram in Fig. 1.

Diffusion Pump Entry. The pressure in the high vacuum part of the pumping station below the high vacuum valve is continuously indicated by a Penning type vacuum gauge having two pressure ranges. The low pressure range indicates 10^{-4} torr for full scale deflection and the high pressure range goes up to 10^{-2} torr as seen from Fig. 2A. Range changing is by push button, biased to the high pressure range. The two interspace pressure conditions are indicated by a two range (atmospherically balanced) Pirani type gauge using two gauge heads covering the ranges 10 torr to 0.5 torr and 0.5 torr to 5×10^{-3} torr as shown in Fig. 2B.

The vacuum switch in the high vacuum part of the pumping station is used in conjunction with the Penning indicating gauge. Above 10^{-3} torr the ionisation current from the Penning gauge could be used to operate a sensitive relay directly, but below 10^{-3} torr the currents are too small. A preferable arrangement is to pass the ionisation current through a series resistance, the voltage developed being used to operate a voltage discriminating switching circuit. As these gauges operate at a high voltage, the loss of several volts for control purposes does not affect their calibration. The Penning gauge switching unit circuit is shown schematically in Fig. 3. The cold cathode tube V_2 is fired by the biasing voltage E_1 from a cold cathode voltage reference tube. The

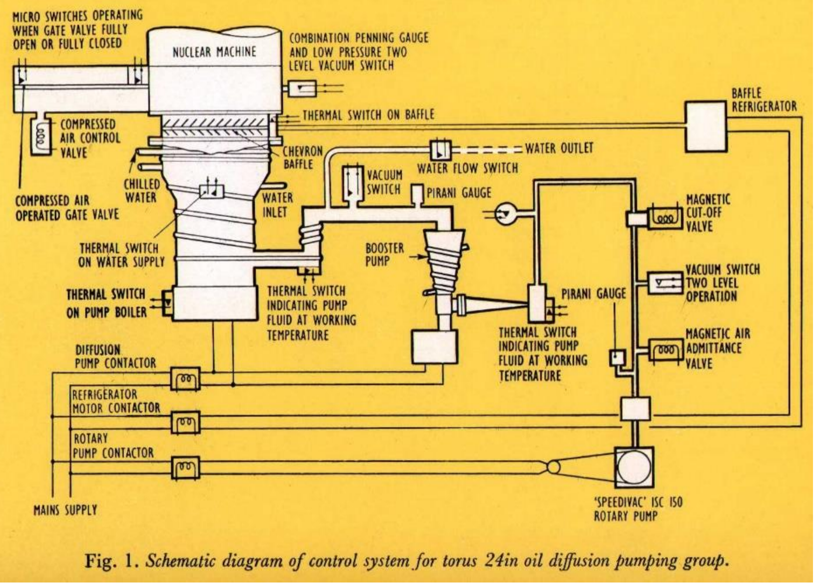

Fig. 1. *Schematic diagram of control system for torus 24in oil diffusion pumping group.*

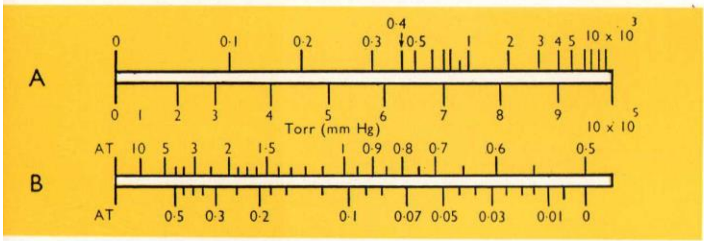

Fig. 2. (*A*) *Meter calibration for Penning gauge.*
(*B*) *Meter calibration for Pirani gauge.*

ionisation current from the gauge is used to overcome the bias by developing the voltage E_2 across the resistance R. As the Penning gauge pressure is increased, the current I rises until the voltage difference E_1-E_2 falls below the critical trigger voltage of V_2 and the tube is extinguished. A suitable silicon diode D is inserted as overload protection to prevent appreciable negative voltages from being developed as the current through R is increased.

A rather simpler arrangement would be direct triggering without biasing but the present arrangement ensures that any of the more likely failures of the switching unit (e.g. H.T. supply, relay failure or trigger tube failure) corresponds to a high pressure condition as far as external circuits are concerned.

The operating pressure of 10^{-6} torr is selected by the resistance R. In this application a second alternative higher pressure operating point, adjustable between 10^{-3} and 10^{-4} torr was obtained by switching a shunting resistance across R at the appropriate time in the control sequence.

Booster Pump Entry. Between the diffusion pump and booster pump a discharge switch is provided. The collapse of current, when a simple high voltage glow discharge blacks out, changes the state of a relay circuit. To ensure long life, the discharge current was kept at a low level and a cold cathode trigger circuit similar to the one described for the Penning gauge is used. The discharge tube is shown diagrammatically in Fig. 4.

The H.T. voltage is obtained from the Penning gauge power supply and the black-out point is selected over the range 500 to 5×10^{-2} torr by adjusting the discharge tube gap from 1 to 30 mm. In this application the gap was set to operate at 0.23 torr.

A fundamental difficulty in the use of the otherwise simple discharge tube for this purpose is that a second black-out point occurs at higher pressures between, say, 10 torr and atmospheric pressure. This was overcome by combining an arc discharge with the glow discharge, the arc being established at atmospheric pressure and remaining until the glow discharge takes over at approximately 1 torr.

To give protection against possible failure of the common high voltage supply for both Penning and discharge switches the bias voltage E_1 required in the case of the discharge switch trigger circuit (analogous to that shown in Fig. 3) was derived from the Penning gauge H.T. supply.

Mechanical Pump Entry. Between the backing valve and mechanical rotary backing pump a hot wire vacuum switch is fitted. The change in length of an electrically heated wire with changing pressure is used to open and close contacts as shown in Fig. 5. Wire length depends on wire temperature and this varies with the pressure-dependent thermal conductivity of the surrounding gas as in the Pirani gauge. With a fixed gap the operating pressure can be varied by varying the power supplied to heat the wire. As relatively delicate contacts are required to operate under varying pressure conditions, the contact loading of both open circuit voltage and closed circuit current are kept low and hence any gas discharge and associated contact fouling effects are prevented. To this end, the contacts control the grid circuit of a thyratron trigger valve with an electromagnetic relay having heavy duty contacts in the anode circuit. The hot wire is supplied from a constant voltage supply with a variable series resistance, the setting of which is calibrated in terms of pressure. A second series resistance set to a different level can be switched in and out by the relay to provide an adjustable differential.

For the synchrotron pumping stations the pressure settings were adjusted to 0.07 torr and 1.2 torr respectively so that on pump down the switch first operated at 0.07 torr, but on increasing pressure from less than 0.07 torr it did not again operate until a pressure of 1.2 torr was reached.

Between the backing valve and booster type vapour pump a simple capsule switch is fitted. This consists of a pressure sensitive capsule connected to the

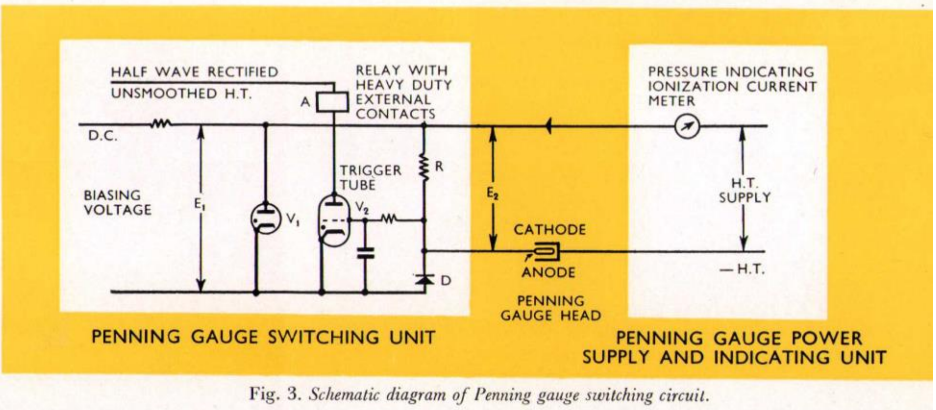

Fig. 3. *Schematic diagram of Penning gauge switching circuit.*

vacuum system. The switching pressure is set (to 20 torr in this case) by adjusting the position of a spring loaded so-called "microswitch".

Thermal Control Switches. In a pumping system involving vapour pumps, cooled baffles, cooling water, etc. the second most important parameter available for control purposes is the operating temperature at different points in the system. A number of thermal switches, generally of the bimetal type are therefore provided as indicated in Fig. 1.

(*a*) baffle switch to indicate that the baffle is cooled below −15°C

(*b*) vapour pump body switches to indicate water cooling of the pumps is satisfactory

(*c*) vapour pump boiler switch to indicate pump boilers are near operating temperature

(*d*) vapour pumps backing stage switches: the correct operating temperature at this point is a good indication that pump fluid at working temperature is reaching the high pressure stages of the vapour pumps.

Other Control Switches. The pumping station shown in Fig. 1 also contains water flow switches for each cooling circuit, and microswitches to indicate that the high vacuum gate valve is either fully open or fully closed. Power is supplied to pumps and refrigerators via contactors incorporating their own overload protection.

THE CONTROL SEQUENCE FOR THE TORUS PUMPING STATIONS

The control sequence of the pumping station can now be briefly considered. It should be noted that a separate rough pumping system is provided to evacuate the synchrotron chamber from atmospheric pressure to below 0.01 torr which is not controlled by these units. However, when a chamber pressure of 0.01 torr is obtained, a signal is available for interlocking purposes.

One of the most common failures of automatic plant is due to the possibility of mains interruption. Every part of the control scheme was therefore designed to operate under conditions of failing "safe" with an interruption of mains supplies, so that on mains failure each pumping station would automatically shut down in a safe manner, particularly with regard to pressure conditions and any possible contamination of the vacuum system. Mains failures are often of only very short duration, for example when transferring from one generator to another or remaking an overload trip. In this case it would be a nuisance to have to wait for an operator to have to start up the pumping stations. Provision was therefore made for a timer to be initiated by a failure of the mains supply. This timer is external to the control system but interlocked with it in such a way that any selected local control units would restart automatically after a mains failure, provided that the mains supply returned before the timing cycle was complete. Restarting in this way occurs sequentially in a safe manner as when units are initially started. On the other hand there may be some local control units and associated pumping stations purposely not in commission (for instance while being serviced). To avoid the unpremeditated start-up of such units each local control unit is fitted with a three position selector switch for:

(i) local operation only, without automatic restart in the event of a temporary mains failure

(ii) local operation only, with automatic restart in the correct sequence on the return of a temporary failure of the main supply

(iii) remote operation only with mains fail protection as in (ii).

Pumping stations are started by pressing a single starting push button type starting switch either at the local control unit or remotely depending on the position of the selector switch. Assuming that cooling water is flowing the normal sequence of operations

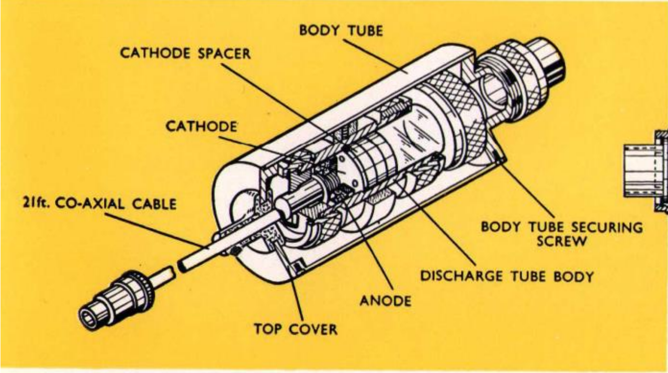

Fig. 4. *Diagram of discharge pressure switch head.*

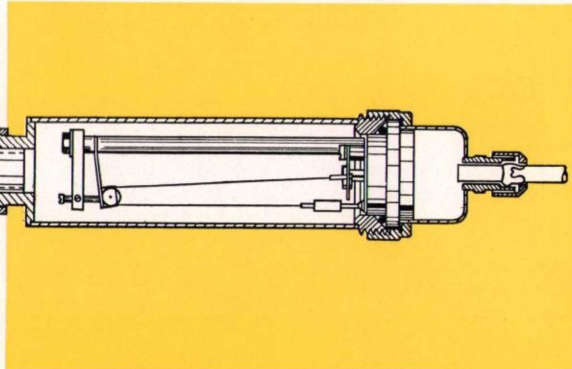

Fig. 5. *Diagram of VS4 hot wire switch head.*

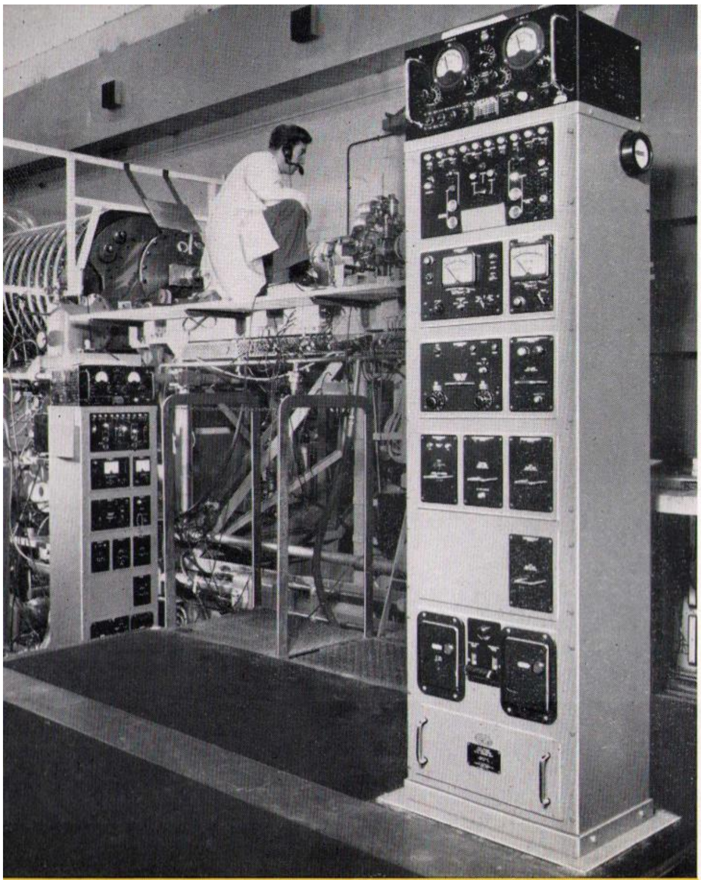

Fig. 6. *Local control unit for torus 24in oil diffusion pumping group.*
(Photograph by courtesy of N.I.R.N.S.)

for starting a pumping station involves the following main steps:

Mechanical pumps only, backing valve open, vapour pump heaters warming up, baffle cooling and finally the whole unit is ready for the high vacuum valve to open.

The control sequence is such that each step is safeguarded. For example the pump heaters cannot be energised unless there is cooling water flowing and the pressure in the vapour pumps is low enough to prevent oil decomposition.

Vacuum systems required to operate at very low pressures may become contaminated if they are exposed to the oil-sealed mechanical rotary pump for excessively long periods especially when these pumps are operating near their ultimate vacuum. Such conditions could arise in an automatic control system if there were a fault which prevented the vapour pump heaters coming on while allowing the backing valve to remain open. This condition has been foreseen by ensuring that the pumping station will shut down if a predetermined roughing period has been exceeded.

The unit is finally ready for the high vacuum valve to open if the following conditions are fulfilled:

(*a*) vapour pump boilers are at operating temperature

(*b*) backing pressure of vapour pumps is sufficiently low

(*c*) water is flowing in the cooling system

(*d*) vapour jets are operating

(*e*) cooled baffle is at a low enough temperature ($-15°C$)

(*f*) pressure on the high vacuum side of pump up to baffle is sufficiently low (less than 10^{-6} torr)

(*g*) pressure in the synchrotron vacuum chamber is less than 10^{-2} torr.

The actual opening of the high vacuum valve is the second manual operation required (except in the case of automatic restart after a short period mains failure) before pumping stations can perform their pumping duties on the synchrotron. The high vacuum valve is opened and closed by push button switches either remotely or locally. A key switch is interlocked in such a way that only an operator who possesses the key can open the valve by operating the local push button.

An important feature of automatic control units of this type is the provision made for indicating the condition of the unit at any time.

The indications required are of two types:

(1) Main controls and indicators to show at a glance the overall satisfactory operation of the unit, and

(2) Subsidiary controls and indicators which serve quickly to locate the cause of any faults if they should arise.

It is important to be able to discriminate between a faulty indicator and a fault on a component. The main controls and indicators are separated from the subsidiary controls and indicators. The main indicators consist of filament lamps showing both the *ON* and the *OFF* condition. These are duplicated in the remote control room.

Subsidiary indicators use gas discharge lamps arranged to indicate almost every step of the control sequence. Test points are incorporated for independent checking of each position in case of maloperation or failure of the subsidiary indicator. The actual control and indicator panel is shown in Fig. 6.

CONTROLS FOR THE INJECTION SYSTEM PUMPING STATIONS

The pumping stations for the linear accelerator and d.c. gun are based on mercury vapour pumps. Associated with these pumps are refrigerated baffles and liquid air cooled vapour traps; on the other hand the mercury diffusion pumps are backed directly by an oil sealed mechanical pump without the need for a vapour booster pump. The pumping station is shown in the schematic diagram in Fig. 7 which may be compared with Fig. 1 showing the pumping stations of the main chamber. The requirements for automatic control are essentially the same.

Referring to Fig. 7 each pumping station is provided with vacuum gauges at two positions and vacuum switching devices at three positions—one less in either case because of the absence of the booster backing pump. Pressure control and indication are otherwise no different from the oil pumped systems.

Controlling the Supply of Liquid Air. The other main difference here is due to the need to provide for the correct phasing of the supply of liquid air to the trap and the associated interlocks to safeguard the pumping station if the trap should warm up.

It is essential that liquid air should not be supplied to the trap at too early a point in the start-up sequence or it will collect unnecessary quantities of vapour. On the other hand mercury must be prevented from contaminating the low pressure side of the vacuum system. Similarly, conflicting considerations apply in deciding on the correct time at which to cool the refrigerated baffle. For this part of the control system the following operating sequence has therefore been selected:

(i) backing pressure sufficiently low

(ii) diffusion pump and refrigerated baffle come into operation together

(iii) provided that both the *cooled baffle* is at a low enough temperature *and* the *vapour jets* of the diffusion pump are operating in a *set time* they are allowed to continue to operate

(iv) at the *end* of this set time, provided condition (iii) is satisfactory, the liquid air supply to the trap is actuated.

Liquid Air Switches. The remaining requirement is to sense the presence of a satisfactory supply of liquid air in the trap. To this end a liquid air switch was designed which can distinguish between the two states of immersion in the liquid and being suspended in the cold air just above the liquid level. This was based on the use of resistance thermometer elements operating in a d.c. low voltage wheatstone bridge network with electromagnetic relays to detect the out-of-balance conditions. The operation is based on the latent heat of liquid air. Enough power was supplied to the resistance element to cause its temperature to rise appreciably when surrounded by cold air immediately above the liquid air level, but this power was not enough to cause any appreciable boiling of the liquid while the element was immersed.

Each trap is supplied with two switch elements as indicated in Fig. 7.

The upper element is interlocked with the liquid air supply valve and indicates that the trap is full. The lower element is interlocked with the pumping station control sequence ensuring that the pumping station is not ready for the high vacuum valve to open unless the trap is cold.

The main and subsidiary controls and indicators of the mercury pump stations are in all other respects similar to those of the other main pumping stations described.

FAULT SIMULATOR

To check correct functioning of the local control units a simulator was constructed. The purpose of this was to replace the pumping unit and associated services and to supply signals to the local control unit corresponding to the effect of water supplies, pumps, pressure conditions, etc. The simulator was used to operate the control unit in correct sequence from start-up as well as to simulate any faults, for example by simulating pressure conditions other than would be expected under correct operation.

Acknowledgments *are made for help received in early developments in this laboratory by J. M. Parisot and R. Brymner and correspondence and discussions on the control system with S. H. Cross, J. H. Major and G. S. Grossart of the Rutherford Nuclear Energy Laboratory, Harwell.*

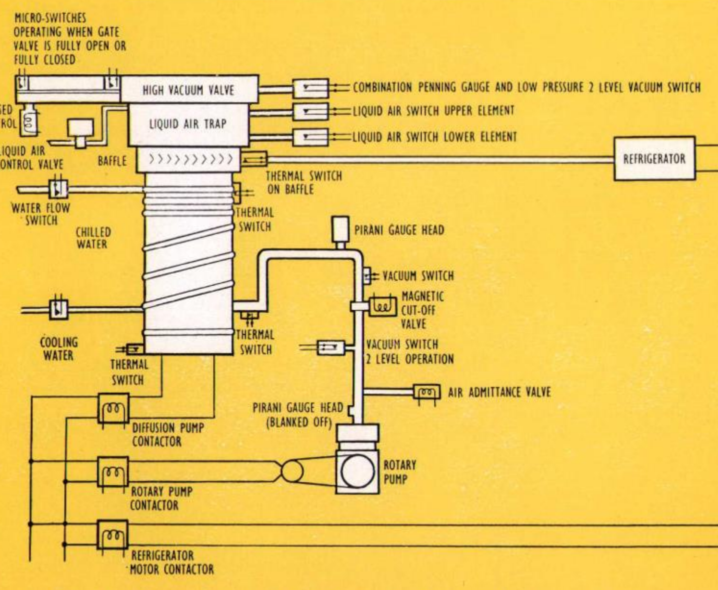

Fig. 7. *Schematic diagram of control system for linear accelerator 24in mercury diffusion pumping group.*

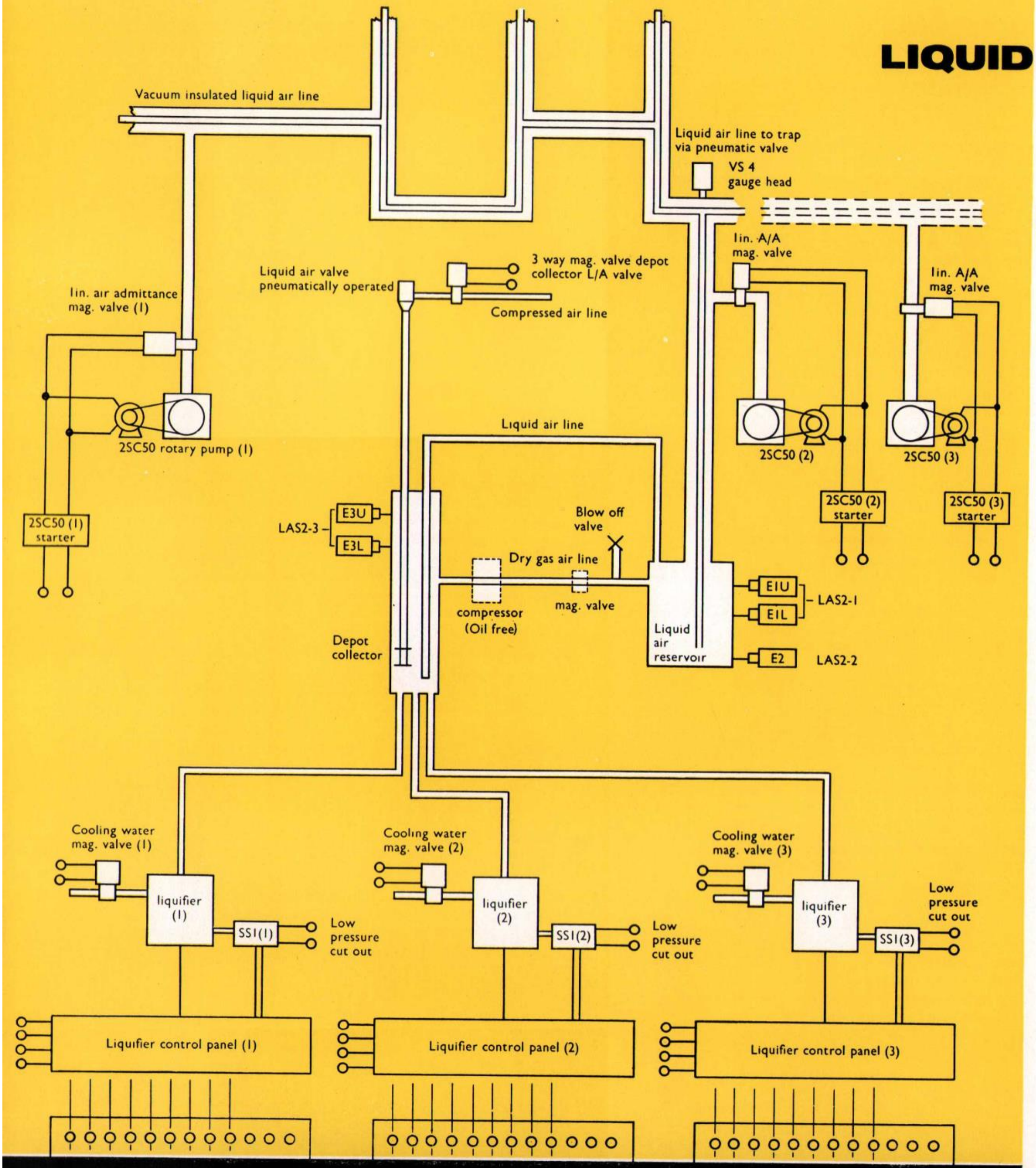

Fig. 1. *Diagram of System*

SUPPLY FOR MERCURY DIFFUSION PUMPING STATIONS FOR NIMROD

by T. A. HEPPEL, B.Sc.

Pumping Equipment Research Division

GENERAL REQUIREMENTS

This entails the on-site production of liquid air from three Philips air liquefiers, the collection and storage in a main reservoir, distribution to the traps along a pipe line, constructed on-site to run the entire length of the injector—some 120 feet, and the controlled transfer into the liquid air traps by means of a liquid air switch and valve.

An installation of this complexity presents many problems apart from those strictly cryogenic in nature. For example:

Cryogenic

Cryogenic problems include thermal contraction of materials, liquid air valving, insulation (particularly important in dealing with comparatively small quantities of liquid air) and icing.

Space

Three liquid air machines must be accessibly located amongst the other multitudinous equipment associated with a large linear accelerator. The liquid air equipment must be assembled beneath the raft of the accelerator, which would rate high in a list of regions of man-made congestion.

Automation

The systems must operate unattended when the accelerator is working, because the radiation level is lethal.

Liquid Air Transfer

Liquid air produced on site at atmospheric pressure must be transferred into a pressurized reservoir from which it can be pushed along the main line.

A MAJOR PROBLEM—PRESSURIZATION OF THE SUPPLY

Pumping means. The design of suitable pumping equipment for liquid air transfer proved to be a major

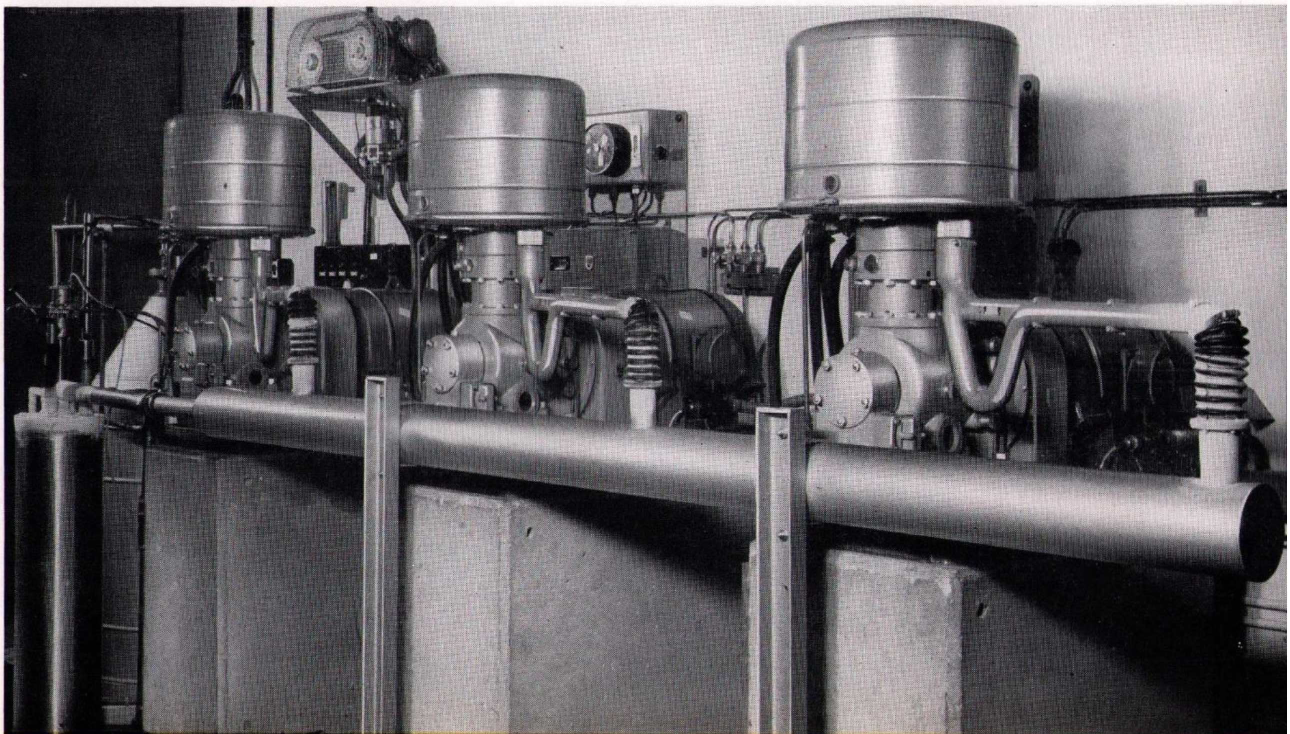

Fig. 2. *Three Philips air liquefiers feeding liquid air to the depot collector via a vacuum insulated manifold.*
(Photograph by courtesy of N.I.R.N.S.)

problem and it was decided to adopt a gas pressurization method utilising a device known as a depot collector (more fully described later) which would transfer its contents to a pressurized liquid air reservoir which in turn would feed the pipeline. The depot collector is expected to work from some 18 hours per day for periods of about a week, and for such working conditions involving almost continuous operation, the transfer of liquid by pressurization with dry gas is thought to be preferable to the use of a mechanical pump. We have built prototype liquid air pumps in the laboratory but their realm of usefulness tends to be for applications requiring short fast transfers of liquid air against small back pressures.

Condensation effects. When liquid air is being transferred by gas pressurization however, due consideration must be given to the effects caused by the elevation of the boiling point of a liquid when the pressure of the vapour above it, with which it is in thermal equilibrium, is increased. For liquid air the elevation of the boiling point amounts to about 2°K per lb/in^2 increase in pressure. Hence the liquid air in the main reservoir, in equilibrium with an over pressure of 8 lb/in^2 is some 16°K hotter than that produced by the liquefiers. This phenomenon produces effects which complicate the transfer of liquid air from the depot collector to the pressurized main reservoir. When the transfer is initiated, the gas spaces of the reservoir and depot collector are connected together through a compressor. The pressure in the depot collector rises to about 15 lb/in^2 and the pressurizing gas begins to condense on what appears to be a super-cooled liquid surface. Therefore, in order to obtain a sufficiently rapid pressure build-up in the depot collector and a correspondingly rapid transfer time, the pumping speed of the compressor and its associated pipework must be fast enough to compensate for this condensation rate. Further, in order that the condensation rate be held to a minimum, the pressurizing gas must be applied uniformly through a diffuser to prevent disturbance of the liquid surface, which would accelerate heat transfer and condensation rates.

It is worthwhile to illustrate these effects by two examples of pressurizing 25 litre liquid air dewar flasks.

(i) If a 25 litre dewar is pressurized to 5 lb/in^2 by means of a small compressor in order that liquid air be blown out of a delivery pipe, then there is a continuous gas flow into the dewar of about 15 litre/min even after the 5 lb/in^2 has been established. This is the rate at which air is condensing within the dewar flask. The importance of this example is that the compressor is generally drawing in moist air from the atmosphere, and consequently the formation of ice in the neck of the dewar is far greater than might at first be imagined.

(ii) If a dewar is sealed and allowed to pressurize by consequence of its own boil-off, then the time required to reach a given pressure becomes greater as the dewar contents increase and not as is sometimes thought as the volume of the gas space increases. This is because an increase in gas pressure must be accompanied by the necessary temperature rise of the bulk of liquid, and the more liquid there is the longer it takes to establish thermal equilibrium.

For example, a dewar containing 6 litres of liquid air takes about four hours to build up a pressure of 10 lb/in^2 whereas the same dewar containing 16 litres takes about 10 hours.

GENERAL DESCRIPTION OF INSTALLATION

Liquid Air Production, Pressurization and Storage. The complete system prepared for NIMROD is shown in the diagrammatic sketch Fig. 1. Three Philips PW 7 000 liquid air machines, each having a capacity of 5 litres per hour and operating on a closed circuit chilled water supply, produce the liquid air which is fed through a three-way manifold connecting each machine to the depot collector. The depot collector is essentially a pump which transfers liquid air at atmospheric pressure into a reservoir maintained

Fig. 3. *Depot collector surmounted with pneumatic gun assembly, liquid air feed pipe to main reservoir liquid air feed pipe to main line assembly (with rotary pump belt guard just visible in bottom left hand corner), and wall mounted compressor to pressurize depot collector.*

(Photograph by courtesy of N.I.R.N.S.)

at 8 lb/in^2 gauge. It is a batch transfer device which when full, discharges its contents by pressurization, allowing the liquid air produced during the discharge period to collect in a valved off compartment at atmospheric pressure. The pressurization of the depot collector is accomplished by means of an oil free compressor whose intake is connected to the main liquid air reservoir, hence perfectly dry air (boiled off liquid air) is used and ice formation within the depot collector is prevented.

The main reservoir is a vacuum insulated vessel of 150 litre capacity, and liquid air is delivered from this reservoir to the middle of the main line under a pressure of 8 lb/in^2 gauge.

Pipeline Arrangements. For comparatively small installations—here the liquid air production rate was only 15 litres per hour—the conservation of liquid air is of primary importance. Vacuum insulation of liquid air lines is the most compact and efficient system when the lines carry liquid air continuously.

The number of joints on a transfer line should be held to a minimum, particularly on the inner line since the throughput of a leak in contact with liquid air is some 100 or 200 times greater than that of the same leak in contact with atmospheric pressure. Such lines should be continuously pumped, or have the facility for repumping, since the volume of the vacuum interspace is generally so small that a guaranteed 'life' of about one month is optimistic. In the Nimrod installation the liquefier manifold and transfer lines connecting the depot collector to reservoir and reservoir to main line were all coupled to the three 'Speedivac' two-stage rotary pumps which evacuate the main liquid air line. The interspace pressure was 10^{-3} torr or better as measured on a McLeod gauge.

The main pipeline was constructed from stainless steel on site using compression couplings on the inner line and 'O' rings on the outer vacuum jacket. A castellated method of construction was employed with the main pipeline which provides strain relief when the inner line contracts and the outer jacket remains unaltered. Stainless steel contracts about 0.003in per inch when cooled from room to liquid air temperature, and this amounts to more than 4$\frac{1}{2}$in over a 120 ft length. The line was "teed" off close to each trap and the final side arm into the trap was completed by permanently sealed transfer tubing.

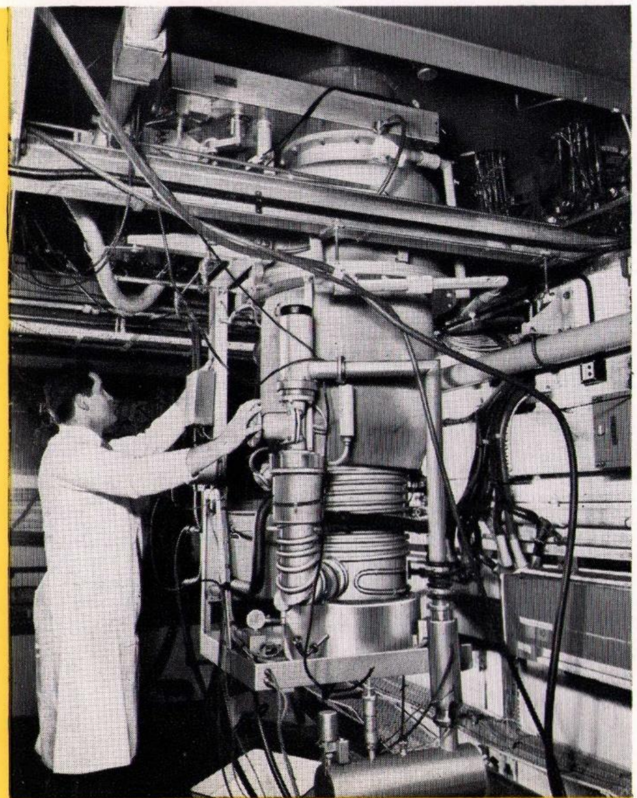

Fig. 4. *24in pumping group beneath accelerator raft showing: 24in gate valve, 24in liquid air trap, main liquid air line (top left hand), liquid air line to trap and liquid air flap valve in trap port, 24in diffusion pump and backing line.*

(Photograph by courtesy of N.I.R.N.S.)

Trap Feed and Level Control. Liquid air is fed into the trap through a pneumatically operated flap valve which is fitted to the end of the side arm and situated within the trap to prevent ice formation on the sealing surfaces.

Liquid air levels are sensed by small resistive elements which are associated with a power and switching unit. These were described in detail in the preceding article. Each trap is fitted with such a liquid air switch to control compressed air feed to the pneumatic flap valve and hence controls liquid air flow into the trap. The depot collector is fitted with a double element switch to start and stop the discharge of liquid air from itself to the reservoir via a pneumatically operated plate valve. The main reservoir is also fitted with a double element switch to automatically start the liquefiers when the liquid air reserve falls below the lower element, and to stop the liquefiers when the level reaches the upper element.

A compressed air supply was conveniently available on site and had the advantage of being able to break down ice formation on the flap valve if it should occur, and in the depot collector a plate valve had the advantage of offering very little impedance to liquid flow in the open position.

CONCLUSION

Although the problems involved in this installation have only been briefly discussed it is possible to gain some idea of the engineering and design difficulties which had to be overcome. Obviously much experience has been gained from this project and it is important to remember that the original design was conceived nearly three years ago. A similar project designed now would not necessarily employ all the same ideas and in addition there is the choice of more varied and improved equipment, which has become available in this comparatively short time.

As we hope that readers of this issue of '*Vacnique*' will agree, the interest of Nimrod from the vacuum point of view is not so esoteric as might be imagined. The project provides an excellent example of the extent and quality of the research, design and manufacturing resources available at Edwards to meet the most exacting and unusual requirements. But yesterday's "unusual" is today's orthodox, and Edwards can now offer standard pumping and control systems for many special requirements.

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