SECTION 8

VACUUM SYSTEM

8.1. Introduction

The design of the Nimrod vacuum system presented problems peculiar to accelerators. The vacuum vessel had to meet special environmental requirements and it had to allow a sufficiently low pressure to be achieved to keep the loss of particles, due to scattering by residual gas molecules, down to an acceptable level. The particles travel a distance of about 100,000 miles within the vacuum vessel while being accelerated to the full energy of the machine and this distance is far in excess of the mean free path, even in ultra high vacuum conditions (mean free path at 10^{-9} torr is about 30 miles), so that collision between the accelerating particles and residual gas molecules is inevitable. The scattering effect is greatest at injection and it has been shown(1) that to keep the particle loss below 10%, a pressure of not more than 10^{-6} torr is required. This pressure is readily achieved in small laboratory apparatus but presented problems on equipment of the size and complexity of the Nimrod vacuum system.

The vacuum vessel was designed with the following requirements in mind:-

(i) It must take up as little of the magnet aperture as possible. The horizontal walls of the vessel must be as thin as possible since, with a known vertical aperture required for the beam, the gap between the polepieces is decided by the vessel thickness.

(ii) The material used in the construction of the vessel must be non-magnetic and sufficiently non-conducting to avoid influencing the magnetic field by eddy-current effects.

(iii) Since a high level of radiation is inevitable, the vessel must be made from materials which would remain structurally sound after exposure to a radiation dose of at least 10^9 rads. (2),(3).

(iv) It should be possible to remove and replace vessels easily.

(v) The interior of the vacuum vessel should be readily accessible for experimental devices and it must be possible to extract beams past the outer edge of the vessels.

(vi) To avoid charge build-up affecting the beam, it must not be possible for electrostatic charge to accumulate on the surface of the vessel.

(vii) The vacuum properties must allow the operating pressure to be achieved with a reasonable pumping speed in a reasonable time and these properties must not be readily degraded by irradiation.

(viii) Manufacturing feasibility, must obviously be taken into account bearing in mind the vessel dimensions, (approximately 7 ft by 1 ft in cross section in the form of a torus with a mean diameter of 155 ft).

8.2. Vacuum Vessel Design

8.2.1. Choice of Material

The search for the most suitable material for the construction of the vacuum vessels proceeded in parallel with the study of the mechanical design. Several materials, such as glass, ceramics and stainless steel, possess excellent vacuum properties but their use is prohibited by one or more of the above requirements. The material which most nearly fulfilled all the requirements was considered to be one of the glass fibre reinforced resins and many varieties of laminate were evaluated for vacuum properties and irradiation resistance. The types of resin included phenolics, polyesters, melamine formaldehydes, silicones and epoxies. Other properties such as shrinkage on curing were weighed against ease of manufacture and epoxy resin was finally chosen.(4)

Although this material was not ideal in every respect it had the advantage that the vacuum vessel could be constructed by a matched metal moulding process to the required engineering tolerances, while retaining acceptable vacuum properties and irradiation resistance. The reinforcing glass cloth was, in general, a 0.006 in plain weave cloth with a general purpose silane finish but a heavier fabric was used as a coring material on the thicker header vessels.

The resin system finally chosen consisted of a bisphenol 'A' diglycidylether cured with methyl 'Nadic' anhydride. This formulation is stable at room temperatures for periods of 12 to 15 weeks and even when suitably catalysed with a tertiary aromatic amine, considerable stability is retained at room temperature while a reasonable cure takes place at higher temperatures. The catalyst chosen (5) was a proprietary material known as 33/1266 (an aromatic amine salt) and this gave the best cure consistant with the longest stability at room temperature to allow the vessels to be handled for long periods during fabrication.

A satisfactory laminate may be obtained with this formulation after a cure time of 2 hours at 150 C. It was found that irradiation resistance and mechanical strength were only slightly affected by varying the catalyst. The considerations which dictated the final choice of material have been recorded in greater detail elsewhere (6) (7) (8).

Laboratory tests indicated that an ultimate flexural bending stress of 100,000 lb/in^2 was possible while under production conditions ultimate stresses of 40,000 to 50,000 lb/in^2 would be achieved for large panels and joints.

8.2.2. Choice of Design

Many designs were considered (9) in one or other of the following categories:

(i) Using the magnet as the walls of the vessel.

With this type of construction the pole pieces are inside the vacuum region and the problem arose of finding an adhesive for the laminations in the pole pieces compatible with high vacuum. The scheme was rejected because of the possibility of long pump down times to reach the required operating pressure.

(ii) Using self supporting vessels.

These could be manufactured from:-

(a) Insulating materials - a moulded ceramic section joined by rubber gaskets was considered but because of the large magnet aperture the construction was beyond the

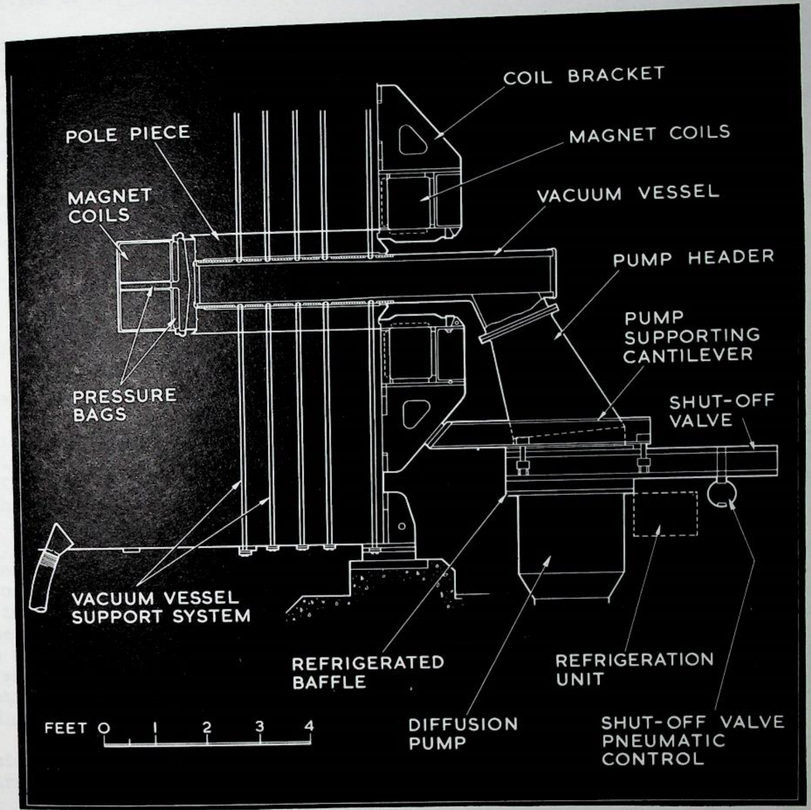


Fig. 8.2.2(i) Design of externally supported vessel.

capabilities of the ceramic ware manufacturers (in 1958) and was eliminated.

(b) Metal laminations bonded together with insulating materials - tests carried out with adhesives which had suitable vacuum properties showed that existing knowledge of this type of construction was not adequate. (A satisfactory vessel of this type might have been developed in time.) The difference in the thermal and mechanical properties of the metal and the bonding materials made the structure susceptible to mechanical failures, to short circuiting between adjacent metal laminations and to gaseous leaks.

(c) Discontinuous metal reinforcement moulded in an insulating material - this was rejected because of the amount of space which would be taken up in the magnet aperture.

(d) Metal framework clad with an insulating material - this was also rejected because it consumed several inches of magnet aperture.

(iii) Using externally supported vessels.

The design of an externally supported vessel which permitted the use of a thinner walled vessel seemed very promising and a prototype vessel 6 ft long was manufactured. This design (Fig. 8.2.2(i)) was a single wall construction of epoxy glass fibre resin laminate, externally supported by ties to the magnet sectors. The main difficulty in structural design was the high stress concentration at the point where the supporting tie secured to the inserts in the laminate. Another uncertainty was the effect of the stainless steel inserts in the laminate (to which the ties were secured) on the magnetic field. The 6 ft prototype vessel was manufactured from a laminate chosen for its vacuum and mechanical properties and its radiation resistance. The pole face windings were secured to the outer skin of the vessel and it was intended to coat the inner surface of the vessel with a metallic film which would serve to conduct away static charge and to screen 99% of the epoxy resin surface from the vacuum. The vessel extended beyond the poles of the magnet forming a duct which enabled the vessel to be pumped from below. This left the periphery of the machine free for beam extraction. The loss of magnet aperture due to the pole face windings and the vessel was less than 2 in.

This design was eventually rejected as it was considered that the expected life under irradiation would be inadequate (10),(11).

(iv) Using a double walled vessel.

A double walled vacuum vessel manufactured from thin stainless steel sheet was rejected because of the excessive heat which would be generated by eddy currents. A complete design study considered using epoxy glass fibre laminate, moulded into a double walled type of construction using thin sections of laminate. The inner vessel, which is subjected to a high level of radiation, which will in time degrade the mechanical properties of the material, was surrounded by an outer vessel. This outer vessel could be evacuated so that the inner vessel was stressed to a minimum, allowing the inner vessel to be much thinner and to have a longer life. The gain in aperture and the elimination of external ties were the main advantage of this scheme. Its disadvantages were its complexity and the close dimensional tolerances which were required.

This design was selected and manufactured in epoxy resin glass fibre. It was not an ideal solution but the one which best met most of the requirements.

8.2.3. Design Details

The vacuum chamber consists of eight curved sections approximately 54 ft long which correspond to the magnet octants. Each section comprises an outer, inner and header vessel joined together at a common radius (Fig. 8.2.3(i)). The header vessel provides a means for attaching the vacuum pumps, while leaving the outer periphery of the machine clear for beam extraction.

8.2.4. Outer Vessel

The internal working pressure is required to be below 1 torr.

The outer vessel is nominally $\frac{1}{8}$ in thick on the horizontal surfaces. The back is 3/16 in thick and the flanges, at the edge of the pole pieces, are $\frac{1}{4}$ in thick. The vessel is supported between the pole pieces and the magnet sector on the horizontal surfaces and by the pole piece jack shims on the back face. It is stiffened sufficiently in this way to withstand atmospheric pressure. The external front flange is supported from the front of the pole piece by a shim formed by a resin filled bag, which is cured in situ, and by shims from the header vessel flange. 24 in at the end of each vessel extends beyond the magnet octant and is thickened up to 1 in and supported on sliding faces by bolster pads and a rigid beam. Since the end sectors and pole pieces move at each magnet pulse, the whole of the vessel in this area is supported on rubbing surfaces; the horizontal faces are supported by the underside of the pole pieces and by the bolster plates. To prevent trapping the outer vessel between the end pole piece and the magnet face when the magnet is pulsing, the end pole piece (see Fig. 8.2.4(i)) is stood off the magnet sector by four pillars which pass through holes in the outer vessel. These holes are sealed by a special triplicate seal which allows movement of the pole piece and the sector relative to the vacuum vessel.

The general stress level throughout the vessel due to atmospheric pressure is less than 2000 lb/in^2 but additional stresses are introduced in the re-entrant corner (See Fig. 8.2.5(i)) during installation, since the vessel tolerances are adjusted to allow clearance for insertion of the vessel in the throat of the magnet. The theoretical maximum clearance is 0.036 in top and bottom. When the pole pieces are drawn up hard this clearance is eliminated by distortion of the vessel and stresses of approximately 5000 lb/in^2 were indicated. When the outer vessel is clamped in position by the pole pieces an additional stress between 2,000 and 6,500 lb/in^2 may be introduced because of the different heights between adjacent magnet sectors. Pole piece retaining studs pass through the front vertical faces and the front horizontal surfaces. The horizontal studs are sealed with 'O' ring seals (Fig. 8.2.4(ii)) and the vertical pole piece bolts are sealed by a special external seal. The pole face windings are individually brought through the outer vessel and sealed at the end of each octant (Fig. 8.2.4(iii)).

8.2.5. Inner Vessel

The internal working pressure is required to be below 10^{-6} torr.

The crowned inner high vacuum vessel has a thickness of $\frac{1}{4}$ in except at the flanges and inner corners. The vessel is an interference fit between the pole face windings. This is achieved by crowning the vessel so that contact is maintained with the pole face windings under the vessel's own weight and 1 torr of external pressure. The tolerances are such that with the smallest vessel placed in the largest aperture there is a minimum interference of approximately $\frac{1}{4}$ in while the maximum interference is

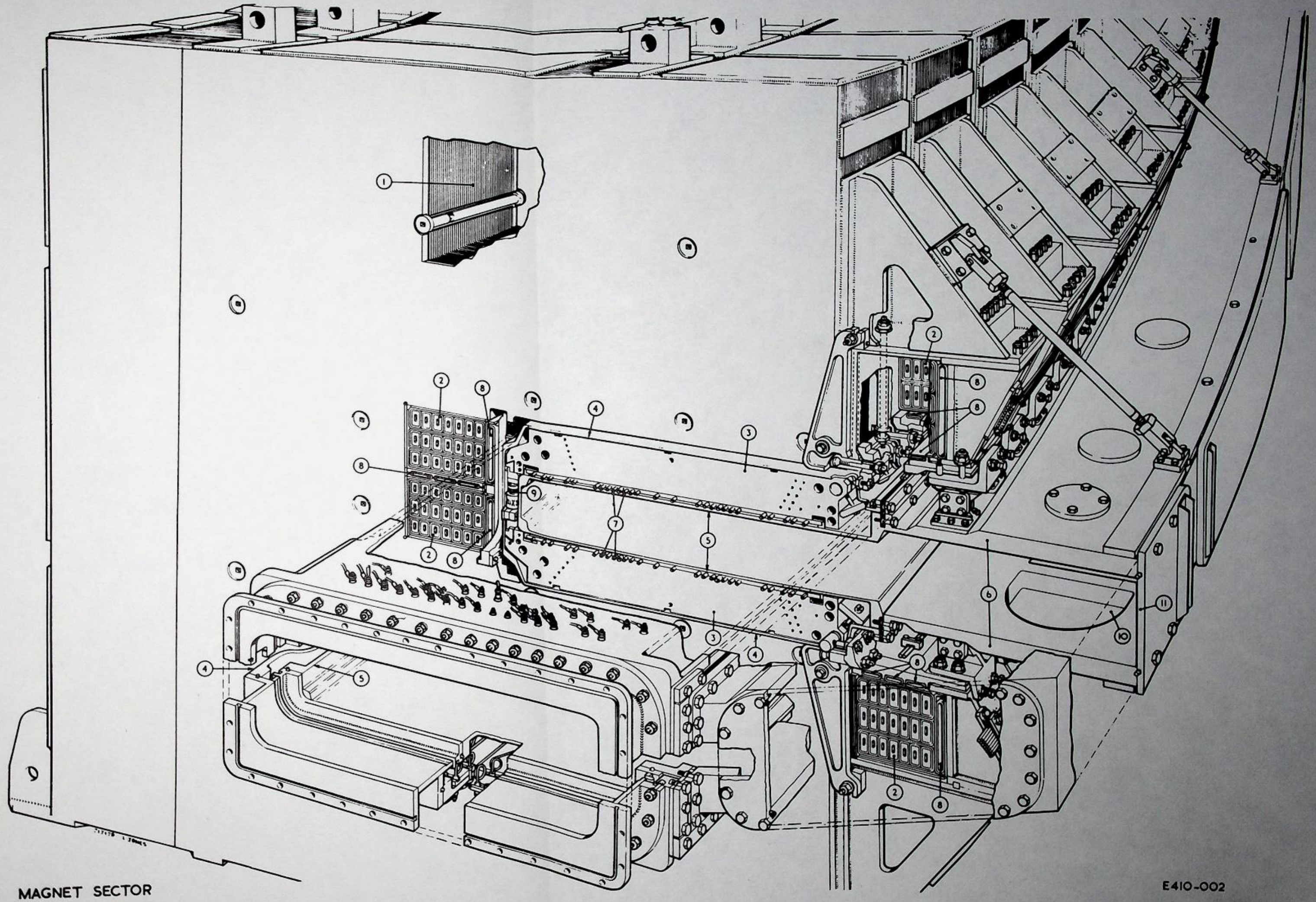


Fig. 8.2.3(i) Isometric cross section of an octant.

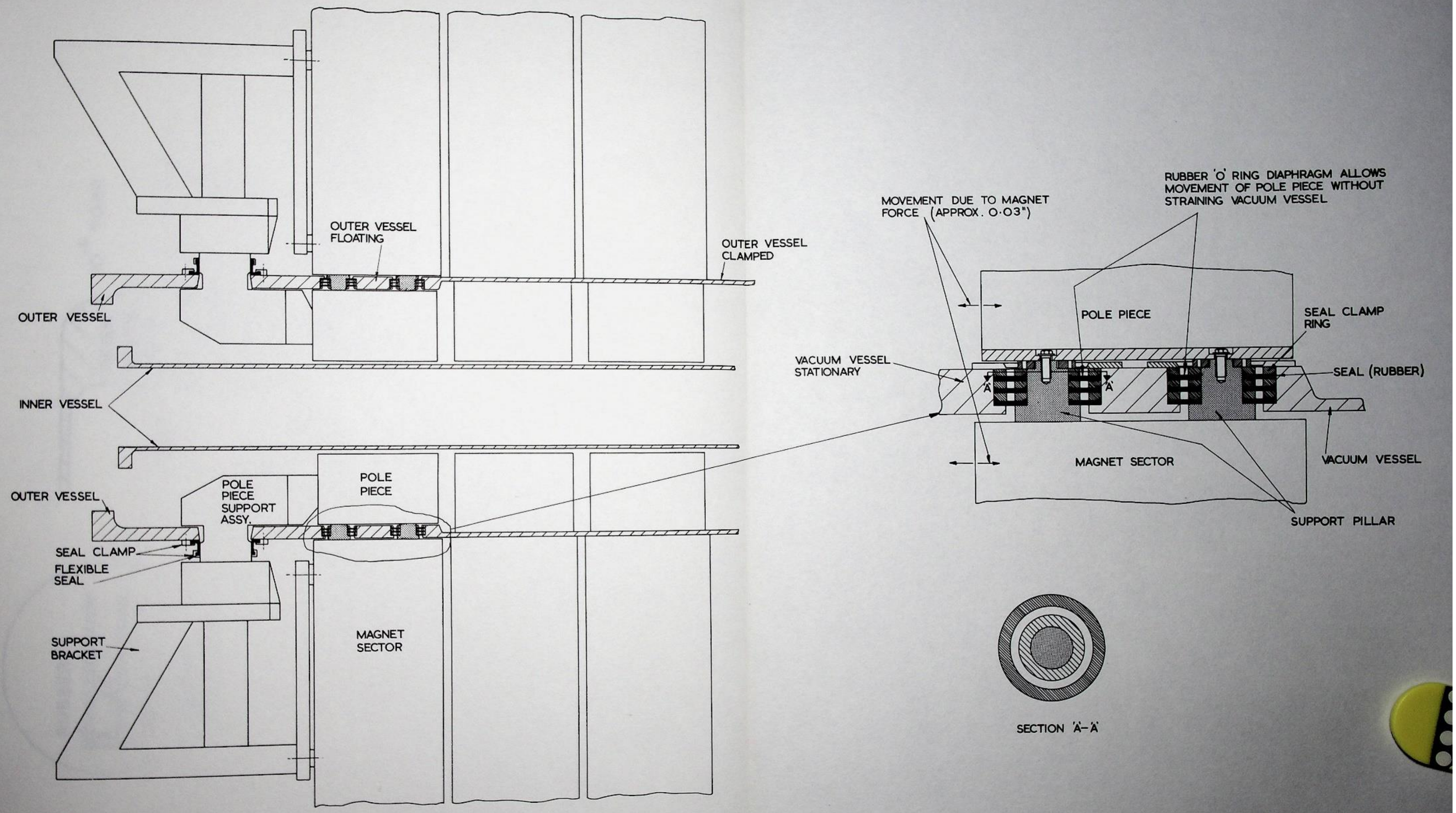


Fig. 8.2.4(i) End pole piece assembly.

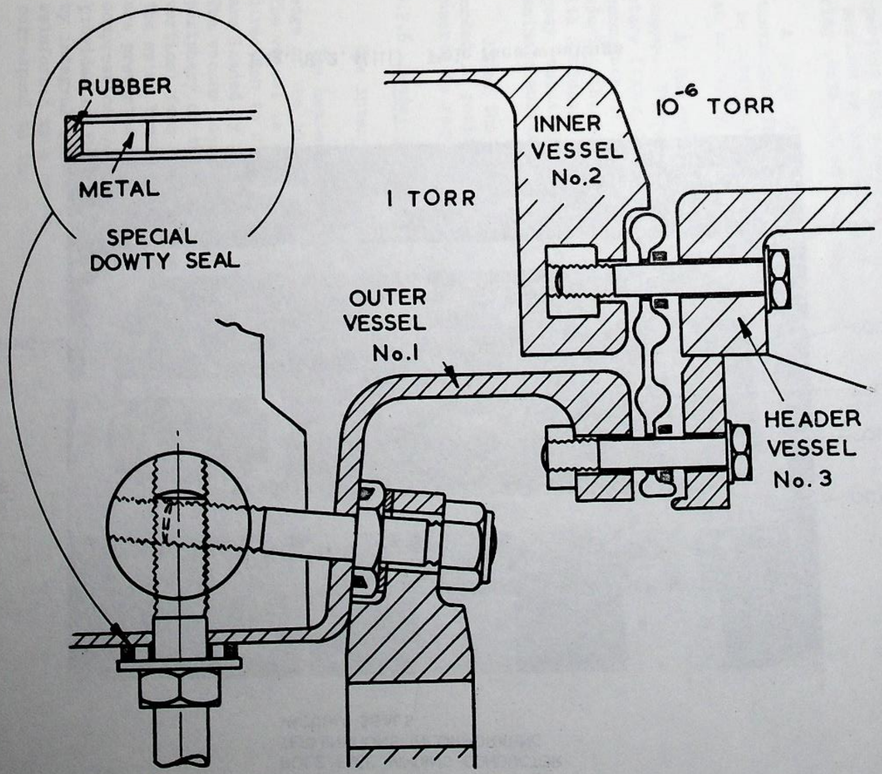


Fig. 8.2.4(ii) Vacuum vessel sealing arrangement.

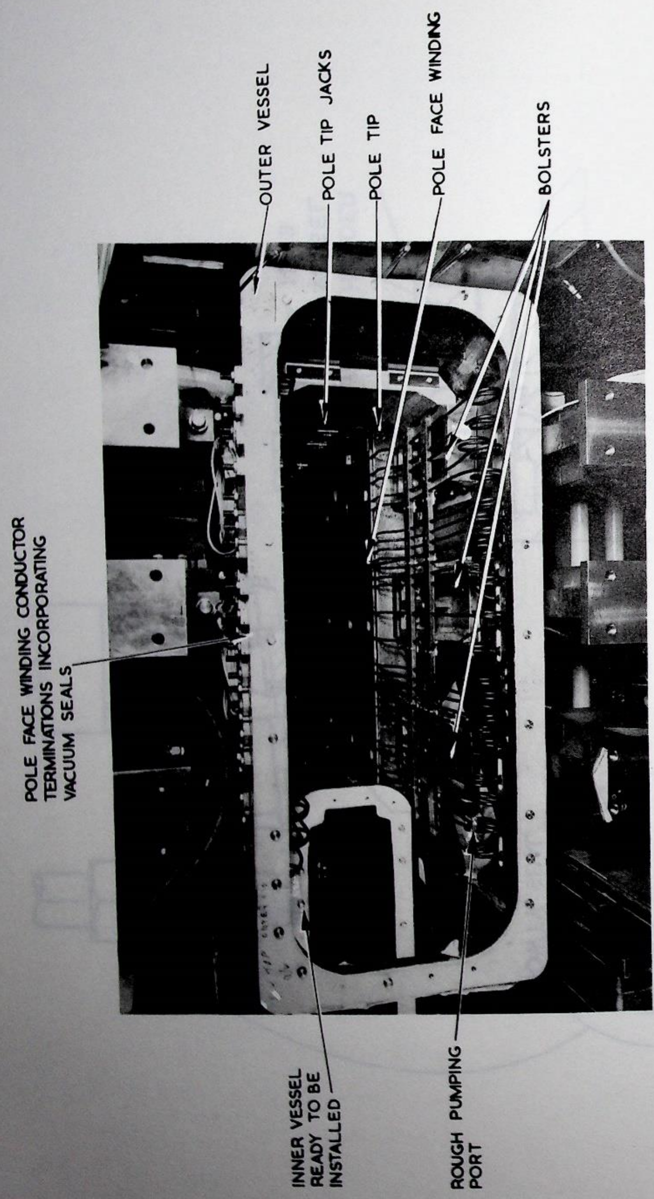


Fig. 8.2.4(iii) Pole face windings

of the order of $\frac{3}{8}$ in. The crowning shape consists of flat sides with a 10 in wide flat top (Fig. 8.2.5(i)).

One of the main features of the design of the double walled chamber is that if the outer vessel is pumped to approximately the same pressure as the inner vessel, there are negligible stresses on the inner vessel. The resin for the inner vessel could therefore be selected chiefly for its vacuum and radiation resistance properties and also, the degradation of mechanical properties by irradiation are not as serious as they would be if the chamber were highly stressed. Stresses introduced during installation were approximately 2000 lb/in^2.

A large pressure difference between the inner and outer vessels would cause catastrophic failure of the inner vessel and the pumping systems for each vessel need to be interlocked. In the event of failure of the interlocking devices, a bursting disc collapses and equalises the pressure in the two vessels (section 8.10.4).

At the ends of the vessels the crowning is tapered off to meet the rigid end flanges. Tapped inserts are secured to the back wall of the inner vessel for the future fixing of targets, etc. To conduct away the electrostatic charge, which would accumulate on the surface, and to minimise the resin area exposed to the vacuum (hence reducing the effect of the outgassing of the resin), the inside surfaces are lined with stainless steel foil 0.002 in thick and 4 in wide. The foil is bonded to the epoxy laminate, with small gaps between adjacent strips, and covers 99% of the laminate surface.

After the flange is manufactured, it is drilled and serrated metal inserts are bonded in position with an epoxy adhesive. The minimum pull out load for these inserts is required to be 3 tons.

8.2.6. Header Vessel

The internal working pressure is required to be below 10^{-6} torr.

The header vessel completes the vacuum enclosure at the outer circumferential edge of the inner vessel and varies in thickness from $\frac{1}{2}$ in to 2 in epoxy laminate. The vessel is supported from swinging brackets which give freedom in a tangential direction to allow the vessel to expand (Fig. 8.2.3(i)). The supports for the vessel are loaded by full atmospheric pressure acting on the whole surface of the vessel. The vacuum loads on the horizontal faces are taken by posts around the outer periphery of the vessel and by the swing bracket supports. Vacuum loads on the outer vertical face are transmitted through the horizontal faces of the vessel and taken at the swing brackets. At the outer periphery, the top and bottom horizontal surfaces are prevented from closing together by posts approximately 22 in apart. The compression load on each post is approximately 4000 lb. Five pumping ports are provided on the underside of each header vessel; each port is bridged in two places by integral struts to prevent radial collapse of the vessel. The struts are reinforced by a short, stainless steel, upper pump header with deep webs, which correspond to the integral struts in the header vessel to which they are clamped.

The maximum stress in the vessel is approximately 5000 lb/in^2.

The outlet windows on the header vessel are aluminium $\frac{7}{8}$ in thick and are stressed at 3500 lb/in^2. They are secured back to anchor bars which are in turn secured to the top and bottom faces of the vessel.

The header vessel (for the same reasons as the inner vessel) is lined with stainless steel foil. Inside the vessel, inserts have been bonded in suitable positions for fixing experimental equipment. 6 in diameter holes fitted with cover plates are positioned at intervals in the top and bottom faces to give access for instrumentation and experimental equipment.

A flexible sealing diaphragm (section 8.9), manufactured from PVC nitrile, is secured to the inner vessel and seals the inner and header vessels. At the same time it marries to and seals the outer vessel. The flexibility of this seal accomodates small inaccuracies in manufacture of the curved vessel flanges.

8.2.7. Polythene Closing Plate

At a later date in the construction of the machine, polythene closing plates were designed to replace the header vessels for half of the octants where provision for beam extraction was not necessary. This achieved a considerable saving in cost and speeded the construction programme. The use of polythene as a structural material required special consideration of the working stress levels because of the creep characteristics of polythene. It was specially selected for good vacuum properties and adequate radiation resistance. Low density polythene was used since, at the time of manufacture, no manufacturer was prepared to attempt to make the plates in high density polythene. The polythene plate is 54 ft long $1\frac{1}{4}$ in thick and is made from pieces, each approximately 5 ft long, welded together.

The atmospheric load carried by the polythene plate is taken by a system of tie rods as shown in Fig. 8.2.7(i). Each tie rod is secured to the polythene via a bracket and four inserts. The load applied to each insert is 245 lb while the actual pull out strength is 2100 lb. In the region of the pumping ports, seal clamp rings are used around the pump header tubes to seal the hole and support the polythene. The maximum stress in the polythene due to bending is approximately 220 lb/in^2.

Special attention was needed during installation to achieve uniform load distribution. Creep of the plate which causes the inserts to be displaced is minimised by the low stress levels used in the design; nevertheless, creep at the centre of the plate (without allowing for stiffening which will take place in time due to irradiation) is about 0.07 in/year.

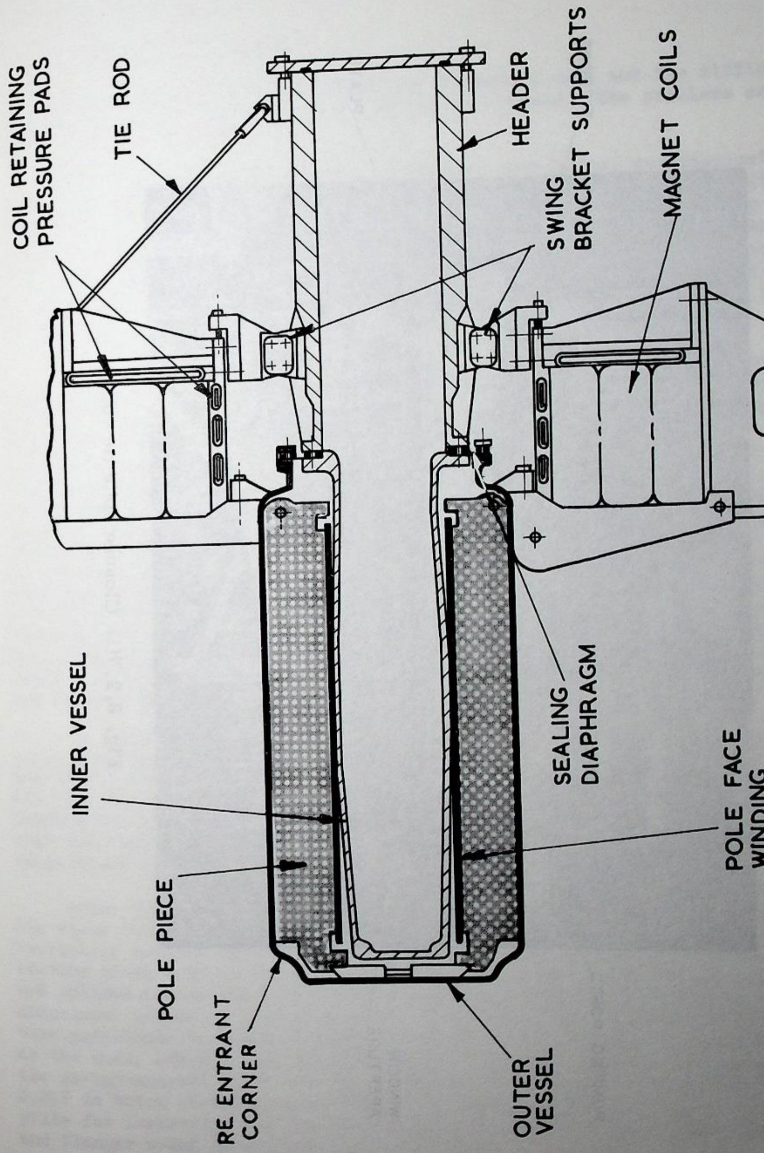


Fig. 8.2.5(i) Inner vessel crowning and header supports

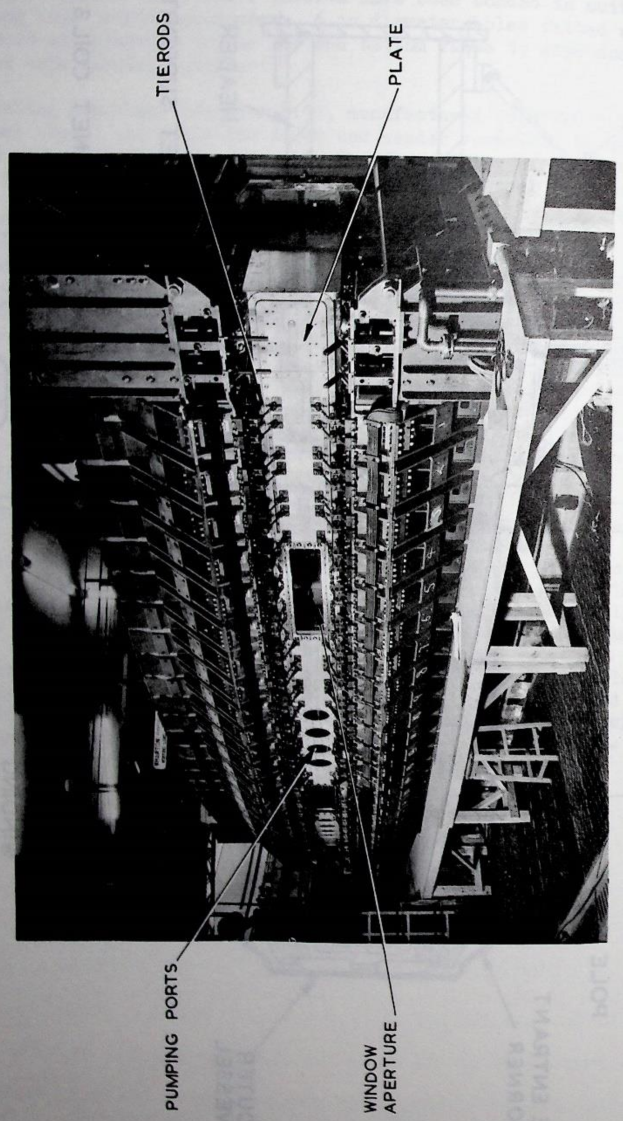


Fig. 8.2.7(i) Closure plate tie rods.

8.3. Vessel Manufacture

8.3.1. Summary of Method Used

The following paragraphs summarise the method used and the difficulties encountered in the manufacture of the vacuum vessels. The problems are more fully described in reference 12.

For reasons of convenience and economics each vessel was fabricated from a number of pieces, which were basically units of one third of the length of a vessel side (Fig. 8.3.1(i)). Each third of a side was produced by laying up glass cloth and resin on a curved die bed approximately 20 ft long and 5 ft wide. The individual dies were about 14 in wide and were fitted with control of heating and/or cooling. A limited length of the die bed could be covered by punches with similar heating and/or cooling facilities. These punches were moved in steps along the bed as manufacture of the laminate proceeded (Fig. 8.3.1(ii)).

The glass cloth was pre-impregnated with resin and allowed to soak for 24 hours. Lengths were then cut and laid along the die bed, alternate layers being placed diagonally to give more uniform strength to the finished laminate (Fig. 8.3.1(iii)). Additional resin was added during the process and, every few layers, the laminate was rolled to force out air bubbles trapped between the cloths and to consolidate the lay up. Pre-fabricated, semi-cured (or 'B' stage) packs, specially shaped to form the main vacuum flange and dorsal shoulder were positioned on the outer and inner circumferences of the die bed and retained by the boundary layers of glass cloth (Fig. 8.3.1(iv)). For an outer vessel further cloths were added to the laminate at one end of the die bed to increase the thickness to 1 in, the remainder of the area consisting of 20 layers of 0.006 in cloth. Punches were then positioned and a portion of the lay up cured by heating. To facilitate subsequent processes, whenever the edge of a laminate was to be joined to another component by splicing, that edge of the punch and die was cooled so that the resin was not cured and could in fact be washed out of the protruding cloths by solvents. This allowed the fabricated sections to be stored indefinitely.

The next third of a side was manufactured similarly but with the thickened portion at the opposite end of the die bed. A complete vessel side (Fig. 8.3.1(v)) was then formed by laying these two opposite handed sections on extensions to the die bed. The protruding cloths from the ends were re-impregnated with resin and interleaved with new cloths laid on the die bed to form the centre section of the side and this portion cured by the same step by step movement of punches and by temperature cycling as before.

After two such sides had been produced they were spliced together on a special rig where the dorsal wall and the two end flanges were formed. Each side was clamped vertically against the rig with the larger circumference nearest the floor. The protruding cloth ends at the smaller circumference were then re-impregnated with resin and spliced across the width of the rig, (Fig. 8.3.1(vi)) beginning at the centre, with additional cloths to form a laminate 30 layers or 3/16 in thick. Special tools were then positioned to press the laminate to shape and raise the temperature to cure it. At the ends, other tools, in the form of a "picture frame", were positioned so that the re-impregnated cloth ends from the two sides could be formed with additional 0.017 in thick cloths into a flange 2 in thick. The vessel was then moved to a loft plate for inspection and the many machined and drilled holes were provided in the walls and flanges using accurately positioned jigs.

Finally, all surfaces which were required to form a vacuum sealing surface, such as the vessel flanges, rough pumping ports, pole face winding and pole piece fixing bolt holes, were prepared. All of these areas had to be smooth and free from scratches or other blemishes. The surfaces were dressed by hand or by portable sanding machine, as appropriate, to smooth the surface to the correct profile, and then coated with an epoxy varnish and rubbed down by hand with 'wet and dry' Garnet paper.

Inner vessels were produced in a similar manner on a different die bed. These vessels were smaller in cross section and the walls were $\frac{1}{4}$ in thick. The covering of stainless steel foil on the high vacuum surface of the vessel was laid on top of the resin and glass cloth before the punches were lowered to press and cure the laminate.

Header vessels required a slightly different approach since they were mainly 2 in thick. To maintain the strength of the laminate while shortening the lay up time, only the outer layers on each side were wholly of 0.006 in cloth, the bulk of the laminate consisting of 0.017 in cloths, interspersed with 0.006 in cloths every seven layers to reduce resin drainage to the bottom of the laminate.

The inner flange rail on the moulding bed was fixed but the outer flange rail was sectioned and components made interchangeable to allow the contour to be varied for each third of a side. The differing thicknesses of laminate necessitated an assembly of metal shoes and plates to form the correct contour. The shoes were fixed to loading arms stretched between inner and outer flange rails.

After lay up, the whole moulding bed was moved on a wheeled trolley into a gas-fired oven for the curing schedule. The technique of splicing components to form sides and then vessels, was similar in principle for the header vessels to that for the other vessels. Selected sides were machined to provide the apertures for the pumping ports on the completed vessels.

8.3.2. Production Problems

(a) Outer vessels

(i) Release

The release of the epoxy resin laminates from the moulding tools presented the manufacturer with a difficult problem. Many types of release agent were used to coat the forming tools but without obtaining a completely successful release. Ultimately a glass cloth based on PTFE release agent 'Tygaflor' was used to cover each tool and proved highly successful.

(ii) Appearance of voids

The thermostatically controlled heating for both punches and dies caused bowing of the tools by setting up severe temperature gradients through them. This produced vacuum voids on or near the surface of the laminate. The fault was eliminated by reducing the rating of the electrical heating, so that less power was applied more often to the tools to maintain the required temperature.

(iii) Regions of undercure

It was noticed on some laminates, particularly along the edges of each die sector, that mouldings were receiving an inadequate degree of cure. By re-arranging

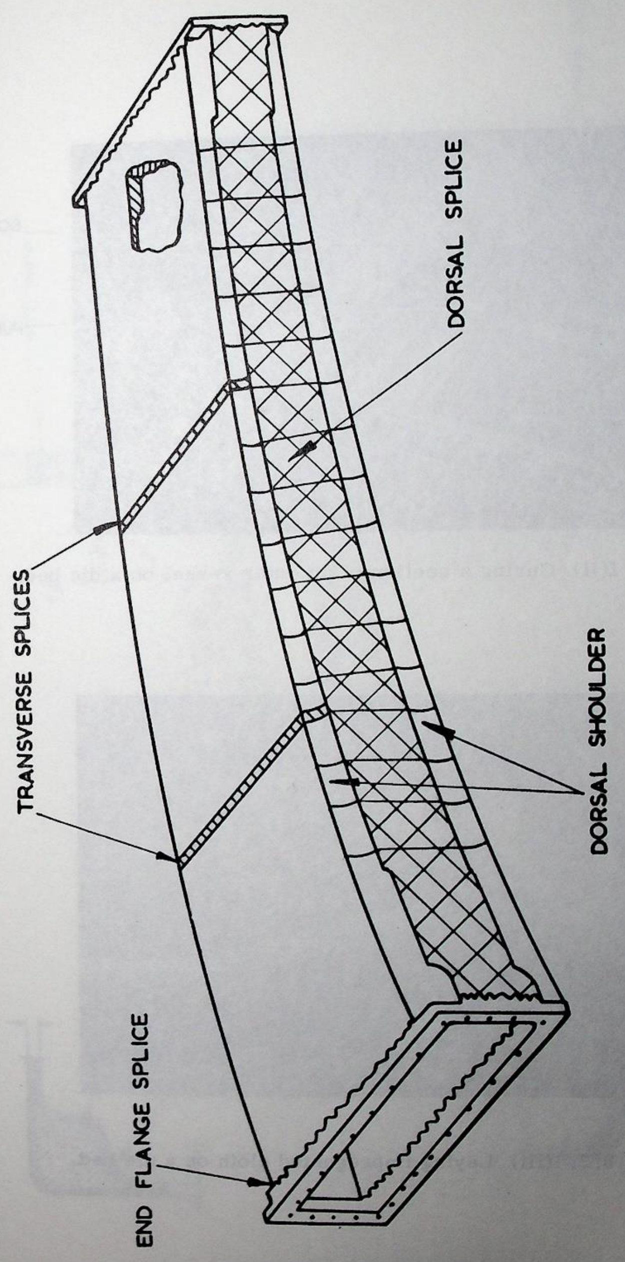


Fig. 8.3.1(i) Outer vessel splices.

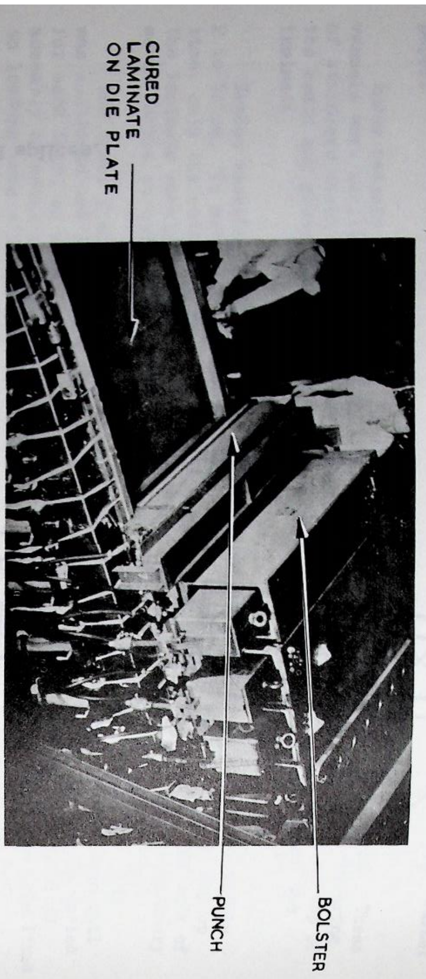


Fig. 8.3.1(ii) Curing a section of an outer vessel on a die bed.

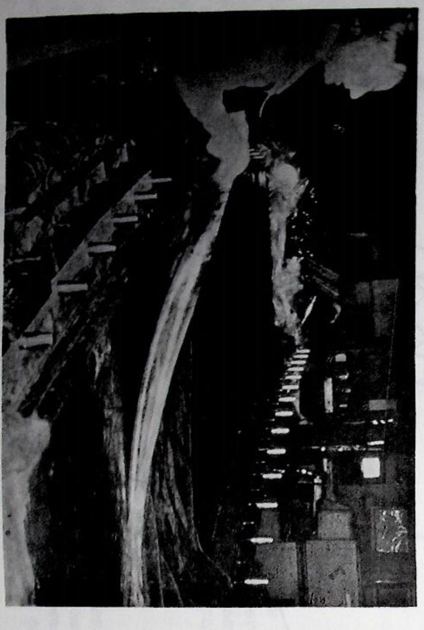


Fig. 8.3.1(iii) Laying impregnated cloth on a die bed.

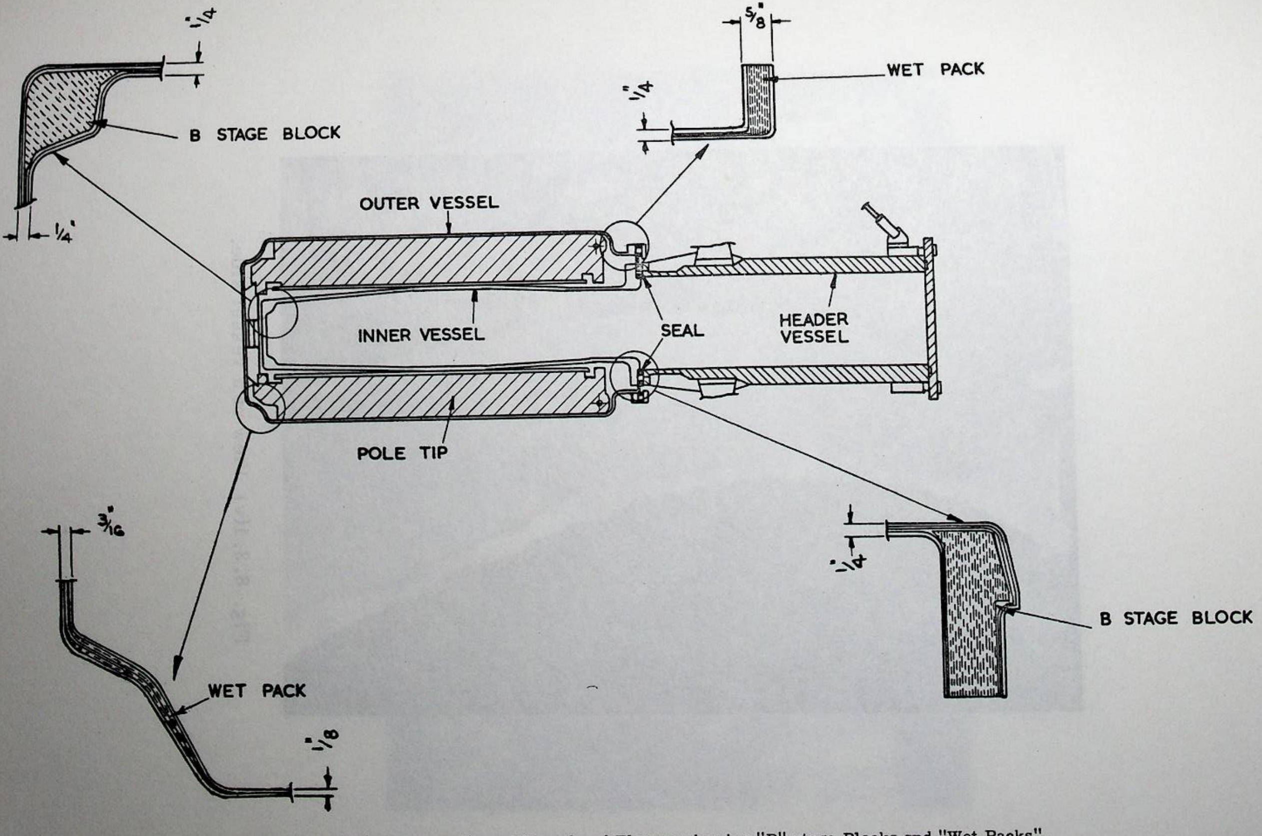


Fig. 8.3.1(iv) Cross section of Vessel and Flanges showing "B" stage Blocks and "Wet Packs".

Fig. 8.3.1(v) View of a vessel side.

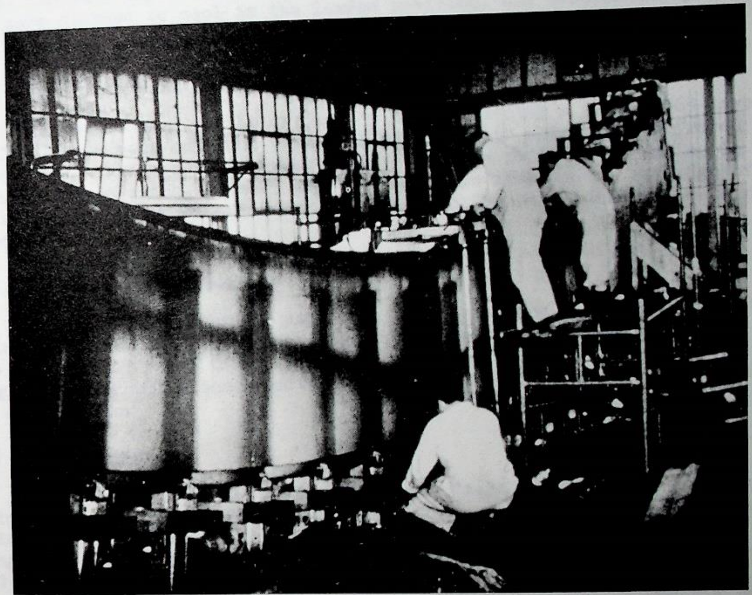


Fig. 8.3.1(vi) Dorsal splicing in progress

the heater network in the punches and dies, more heat was supplied to these areas with a satisfactory result.

(iv) Whitening in the dorsal region of tool intersection

This was caused by a relative movement of adjacent tools during the latter part of the curing cycle. This caused glass cloth and resin to be crushed and the effect was visible as a whitened strip on the laminate. To reduce the fault, shims were used on the top and bottom of all laminate inter-sector lines and, on completing the cure, the punches were lifted ⅛ in and their temperature maintained for a further two hours. In this way the shearing action on the laminate, caused when the punches and dies were allowed to cool in the loaded position, was substantially reduced and crushing of the laminate minimised.

(v) Voids and resin richness on the vacuum flanges

This was caused by the difficulty of positioning a pack of 65 layers of cloth. The layers were cut from bulk supplies of cloth which gave a frayed edge and caused resin rich areas during lay-up. The fault was rectified by using 1¼ in cloth tape with selvedges which, as well as reducing resin richness at the edge of the pack, allowed the layers of overlapping cloth from the main laminate to be cut and formed more accurately.

(vi) Dorsal pack location

Considerable difficulty was found in maintaining the position of this pack during lay up, which led to resin drainage from the bottom of the wall. It was overcome by securing tapes to the pack and tying the loose ends of the tape to the moulding bed and ensuring that positioning of overlapping cloths was carried out as quickly as possible.

(vii) End flanges

Because of the length of time taken to shape the profile of the end flange before the cure could be attempted, resin drainage gave areas of resin richness and cavitation. It was overcome in two ways - first by increasing the bulk factor of the flange and compressing it to its final size, (this consolidated the cloths and expelled air) and second, by adjusting the accelerator content of the resin mix to ensure a shorter gel-time. Care was taken to control the rate of heating such that, during the subsequent cure, the resin mix did not turn liquid before solidifying. With practice, the time scales for the formation of the end flange was reduced and, with the introduction of thixotropic resin, the accelerator content could be reduced to regain the longer pot-life of the resin mix.

(b) Inner vessels

Many problems overcome during the production of the outer vessels also applied to the inner vessels.

(i) Application of stainless steel foil

Some work was done on this problem by I.C.I. Ltd. (13)

Two faults, which had not previously been resolved, soon became apparent. First, the inadequacy of the bond between the stainless steel foil and the laminate and second, the ripple on individual strips of foil after lay-up. It was possible to increase the bond strength by ensuring that an acid primer was used on the appropriate surface of the stainless steel, before it became the inner surface layer of the third side and was subsequently cured with the side. The ripple fault was rectified by slightly tensioning the strips of stainless steel once they were located on the laminate. Lowering of the punches prior to the cure was also expected to increase the tension in the foil. Care was taken during this process to ensure that the ends of the foil strip retained their positions.

(ii) Laminate quality

The dorsal splice had many faults which, because of the pressure of the production programme, remained unsolved. However, it was found that removing three layers of cloth from the dorsal wall and replacing them by three fresh cloths, provided a leak free laminate.

(c) Header vessels

(i) Poor definition between cured and wet end material

When a third of a side was produced, the protruding cloths from the ends and outer circumference of the side were found to be either cured and quite rigid, or uncured, with a region of undercure or uncure extending into the laminate. This fault was eliminated by ensuring that the wet ends were adequately cooled during the cure cycle of the laminate.

(ii) Steps on the top surface of the laminate

This fault was caused by the floating action of the plates laid on the top of the laminate. During cure, the change in relative position between adjacent plates caused steps to form on the laminate. A modified system of loading was devised and the plates were no longer allowed to float but were clamped in position. The surface finish of the laminate was not as good but a nearly step-free laminate was produced.

(iii) Dorsal splicing and end flanges

Great difficulty was experienced in wetting the 2 in bulk of cloths before splicing occurred. The only way this problem could be resolved was to repair these areas after the laminate had been cured. Some extensive repairs were necessary and a dielectric heater was used to obtain uniform heating throughout the repair.

8.4. Inspection at the Manufacturers' Works.

8.4.1. Introduction

Inspection of the vacuum vessels was carried out by two teams - the manufacturer's own staff (who carried out the bulk of the dimensional checks and the process control during manufacture) and a resident U.K.A.E.A. team supplied by the Inspection and Progress Group, Risley.

The overall inspection task was a formidable one because of the vast number of checks which had to be carried out and the extreme stringency on dimensional accuracy and quality of material required. In addition, all the checks had to be recorded and the records kept in such a manner that analysis of the checks would show any wrong trends.

The supervisory staffs were involved in all aspects of manufacture and their assistance was used on manufacturing processes such as the resetting of the arcs of tools to counter-act cooling and arc shrinkage on the finished laminate.

8.4.2. Flexibility in Inspection

A part of a vessel was not automatically rejected because of any one error. Tolerances were specified so that, if all were held, the vessel would be acceptable dimensionally even if the errors were cumulative. Because of the large sizes involved, the tightness of the tolerances and the unique method of manufacture with relatively unconventional materials, it was necessary to train the supervisors to recognise which dimensions were interdependant. Only three factors were essential:

(a) The vessels should fit the machine and their mating parts,

(b) They should be made of the correct materials,

(c) They should have the required vacuum and strength properties.

8.4.3. Process Control

In the majority of engineering jobs, process control is left in the hands of the supervisory staff. After the initial production of several sections of laminate, which were faulty for a variety of different reasons, it became obvious that two steps should be taken. First, sporadic errors due to the measurements being taken by different people had to be eliminated by the introduction of a process control team, and second, an examination of the actual processes had to be implemented.

The method of process control was to:-

(i) Set up a group of process controllers as members of the inspection team,

(ii) Establish a chart enumerating each individual step in the process,

(iii) Stop any step being taken before the process controller had stamped the chart, that he was satisfied with the previous step. Initially, each step was also checked and stamped off by the U.K.A.E.A. inspector as well as the manufacturers process controller. This improved the quality of the laminates but slowed the production rate. Eventually, after about one quarter of the final production of each type of vessel was complete, a satisfactory balance was found between rigidity of control and rate of production.

8.4.4. Quality Control

Quality control is described more fully in reference 14.

Basically it comprised the following stages:-

(i) Inspection staff obtained samples of all batches of raw material before it was supplied by the manufacturers. The samples were sent to the Rutherford Laboratory for chemical and physical tests after being made up into laminate and cured.

(ii) All raw materials, on delivery at the factory, were held in a special store and the date of delivery was noted. Only materials drawn from this store were used in making vessels.

(iii) Each mix was checked by inspection staff and before it was released a gel-time test was performed. A sample of the mix was sent to the Rutherford Laboratory for an independent cross check.

(iv) As lay-up and cure proceeded, a sample laminate was laid up and cured from the main laminate mix. The resulting sample was sent to the Rutherford Laboratory for physical tests.

8.4.5. Production Tool Inspection

This inspection involved three separate stages:-

(i) Initial inspection for faults, flaws, and dimensional accuracy. (Sufficient inaccuracy was found to justify this inspection).

(ii) Erection inspection for correctness of assembly and dimensional accuracy of setting up.

(iii) Subsequent checks during production.

The inner and outer vessel side moulding beds were stout steel structures built about 3 ft high and approximately 20 ft by 5 ft in plan view. The top surface of the structure was a flat ground plate suitably drilled for clamping bolts and locating dowels; it was levelled to within about 0.020 in by screw jacks. The laying up bed comprised 21 separate dies each approximately 3 in thick, 50 in long and 14 in wide. These dies were set up under the supervision of the inspection survey team. The method used was to set up the main datum points accurately (Fig. 8.4.5(i)). These points were the octant centre (an optical target securely fixed into the shop floor) and the main datum dowels. The datum radii and datum chord length were fixed by using accurate invar tapes. The chord length was checked by a theodolite set up on the octant centre. Intermediate dies were set up radially, relative to an accurate curved template located from the datum dies.

The horizontal plane of the dies was adjusted by the use of shims, fixed for level by spirit levels and fixed for height by the theodolite. Intermediate dies were set for height and level by checking the vertical step at the edges of adjacent tools. This step produced a step on the laminate and the maximum permitted step was

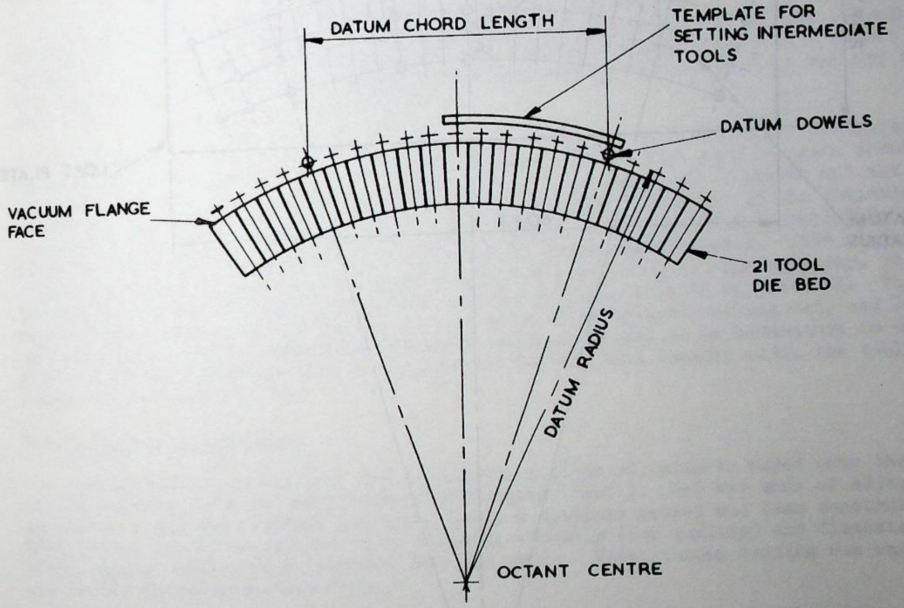


Fig. 8.4.5(i) Diagram of the Side Moulding Bed.

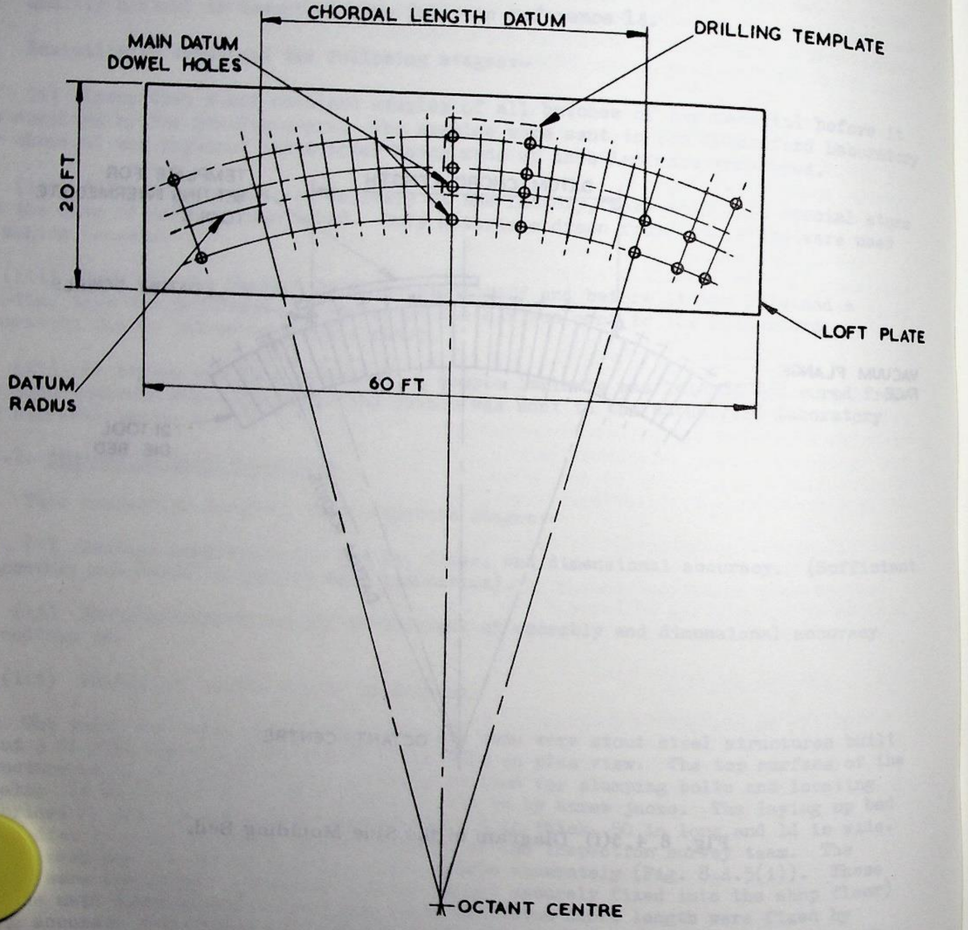


Fig. 8.4.7(i) Diagrammatic arrangement of the Loft Plate.

0.007 in. As the laminate step was found to be within 0.002 in of the die step, the maximum limit for the die step was set at 0.005 in.

Setting of the die bed then became the responsibility of the inspection department. The manufacturer's inspection staff were responsible for checking and for compiling suitable records. The U.K.A.E.A. team checked the records and did spot checks on the tools. The flatness of the die bed was checked after each heat cycle and the main datum points were checked periodically. All principal moulding beds were treated in the same manner.

8.4.6. Checking of Lay-Up

The majority of checks during lay-up were the responsibility of the process control team. They ensured, for example, that the correct numbers of pre-impregnated cloths were laid up, that the cloths did not overlap and were laid with the weft and the warp in the correct direction, and that the heating was switched on and off in the right sequence and at the right time.

One particularly important aspect at this stage is 'bulk factor' - the surplus resin which is forced out on closing the matched tools. This surplus resin ensures that the dies are completely filled and when it is pressed out it sweeps out the remaining air in the laminate. Too little excess bulk leaves air in the laminate; too much causes the cloths to move. A bulk factor of 10% was finally selected, which means 0.012 in excess thickness on the 0.125 in outer vessel panels. Thin plate aluminium templates were cut to simulate the top tool but with excessive gap, to allow the space between the laminate surface and the template edge to be measured. The melinex skin, which is laid on the wet laminate to facilitate rolling out, was left in place during this dimensional check and enabled the gap to be determined to within about 0.002 in. Pressure was not applied to the top tool (punch) until the tools were closed to within 0.010 in.

8.4.7. Laminate Inspection

The method of manufacture was to produce a piece of laminate cured over the bulk of its surface, with selected edges left uncured ('wet'). The wet ends of adjacent pieces were spliced together and cured until a complete vessel had been constructed. Each piece, therefore, needed to be checked, visually (for quality) and dimensionally after curing, before being married into the whole. Final vacuum testing was carried out at the Rutherford Laboratory.

The final arbiters on whether a piece of laminate should be rejected were a member of the Laboratory scientific staff for the vacuum properties and a member of the Laboratory Engineering Design staff for the mechanical and dimensional aspects. In general, however, the visual inspection was carried out by the senior member of the U.K.A.E.A. resident inspection team, who, by consultation and discussion with the Laboratory staff and by visiting the vacuum testing laboratory, had learned with a high degree of surety what was required.

All dimensional checking, whether of piece parts or of the whole, was carried out on the 'loft plate', (See Fig. 8.4.7(i)). The 'loft plate' was the centrepiece of the inspection equipment, and was highly successful in use. It served two principle functions:-

(i) As an accurate surface table for mounting inspection equipment to check dimensions.

(ii) As a drilled frame to hold drill jigs for the accurate drilling of all flange bolt holes.

The loft plate was constructed by setting up a steel structure mainly consisting of 15 in by 6 in steel joists each 20 ft long on which were mounted 4 ft by 2 ft plates (each 0.5 in thick) which were ground flat on one side to form a table top about 16 in above floor level. This table top measured 60 ft by 20 ft and the individual plates were levelled to lie in a flat plane to within 0.010 in. The level was checked from time to time and was so stable that by the completion date it was still within 0.020 in. The loft plate was in such demand that it became necessary to erect a second full size one and a third one measuring 20 ft by 20 ft.

The surface was drilled to accommodate dowelled drilling jigs and dial gauge checking jigs, the holes being located within 0.008 in. The octant centre was sited on the shop floor at approximately its final position and from this the location of the datum dowel holes were fixed and drilled from the jig-bored drilling template. The octant centre was then located accurately from these two holes and the fiduciary bolt locked firmly. The pitch of the dowel holes was a constant over the bulk of the length of the vessel which meant successive use of the drilling template around the arc. The extreme holes in the template were fitted with optical targets and checked relative to the octant centre with theodolite and invar tape before drilling commenced. The datum dowel holes in the template were fitted with eccentrics for any correction of the template position. Only three different templates were required for the drilling of about 250 holes in the loft plate.

Hollow cast iron cubes (9 ± 0.001 in) were used to support the bottom panel of the vessel. Aluminium plates $\frac{1}{4}$ in thick were cut accurately to the internal profile of the vessel and used to support the top panel and flange face at the correct aperture for dimension checking. The flange bolt hole drilling jig was fitted with accurately positioned locating faces and clamps to hold the flange square and firm during drilling.

8.4.8. Dimensional Accuracy

Some values are given here to illustrate the accuracies achieved:-

(i) Outer vessel top and bottom panels

The thickness tolerance specified was 0.125 ± 0.010 in. On ten vessels approximately 12000 readings were taken and in 98% of cases the specification was met. The other 2% were between + 0.010 in and + 0.016 in and occurred consistently on the same part of the panel. No action was taken to correct this because of its position.

Steps on the laminate caused by using press tools of approximately 14 in width along the 54 ft length of the vessel were specified as not to exceed 0.007 in. A total of about 5,000 readings were taken of which only 12 were outside tolerance and the maximum value was 0.009 in. A pair of thickness checks, one each side of a step, were made wherever a step check was performed. This permitted a direct check on the accuracy of the readings because one thickness plus step should equal second thickness plus second step. Four readings were involved and, if a discrepancy of more than 0.002 in occurred, the four readings were re-taken and checked.

(ii) Outer vessel front clamp bolt holes

To carry the atmospheric load on the outer vessel the magnet pole pieces are clamped back to the magnet by jacks, at the back of the throat, and by bolts, which run from the polepieces through the vacuum vessel out to the magnet coil bracket, at the front. There are two bolts at the top and at the bottom for each magnet sector. 168 bolt holes per vessel were drilled on the loft plate. The distance between extreme holes was 50 ft, the tolerance on each hole was 0.030 in and only two holes out of 1344 needed to be opened out on assembly, and these by only 0.010 in.

(iii) Chordal height on all vessels

The chordal height of the 54 ft arc length of the main vacuum flanges was approximately 5 ft 6 in. These chordal heights were used for checking the effective radius. The tolerances specified were + 0.125 in, - 0.0625 in for the outer vessel; + 0.187 in, - 0.060 in for the inner vessel and ± 0.030 in for the header vessel.

The outer vessel was subject to thermal stresses on final cooling of the back wall. The effect of this was difficult to predict with accuracy and the re-setting of tools to correct it would have been very expensive and time consuming. The tolerances were relaxed when it was found that the outer vessel could be strained by 0.25 in without danger and four of the ten vessels required this concession.

All inner vessels as measured on the loft plate were within tolerance.

It was found to be impractical to produce header vessel flanges by moulding methods to the extremely tight tolerances specified. Templates were bolted to the header vessel on the loft plate and located by reference to the dowel holes. The flange faces were then cut back to the template face, using a hand router. In this way the specification was met. Inner and header vessels proved to be individually interchangeable in every case examined.

8.4.9. Dimension Analysis

A further duty performed by the inspection staff, was the analysis of dimension trends in order to correct tools before tolerances were exceeded.

An example of this occurred during the manufacture of the prototype outer vessel. The steps on the flat panels caused by adjacent tools were found to be steadily increasing. A graph was drawn of all the steps on the tools, after each successive heat cycle, for three different positions across the tools. It showed that certain tools were climbing above their neighbours at an average rate of 0.002 in/cycle and that the middle of the tool was climbing more rapidly than the ends. The tools were re-layed with certain modifications to the assembly with the result stated in 8.4.8(i)

8.4.10. Repairs and Records

Scientific and engineering staff from the Rutherford Laboratory, together with the manufacturer's technical staff, developed a series of repair techniques which varied according to the repair position on the vessel and the thickness of the laminate. Before any repair was carried out a diagram of the proposed repair was presented to the U.K.A.E.A. inspection team for agreement.

The inspection team prepared a log book for each vessel delivered. They contain a full set of all the dimensional records taken during the manufacture of the vessel, a review of faults in the laminate and a full statement of the nature and location of all repairs.

8.5. Handling, Test Equipment and Installation

8.5.1. Transporting the Vessels

A special low level transporter was constructed to carry the vessels from the manufacturer's to the Rutherford Laboratory, a journey of 100 miles. To avoid wide load conditions the vessel was arranged to travel turned through 90° with the centre of the curved shape low in the centre of the transporter and the ends of vessel projecting vertically front and back of the transporter (Fig. 8.5.1(i)). The dimensions of the vehicle when loaded were 83 ft long, including traction unit, and 12 ft high. This meant special routing and police escort in 'built-up' areas. Even though some journeys were made in severe winter conditions all the vessels were delivered without mishap.

The vessel was supported during handling operations by a frame made as a welded structure from rolled mild steel sections, formed to follow the curvature of the vessel with cross bracing to produce a platform for the vessel to rest on. Felt pads were fitted to all frame members which would otherwise contact vessel surface. Collapsible wooden stiffening frames, tailored to the cross section of the vessel and upholstered to prevent damage, were inserted at approximately 2 ft intervals along the length of the vessel, with wooden spacers to hold the whole structure rigid. Cover plates were fitted to the open front face and end flanges.

Brackets were fitted to the front and back surfaces of the metal support frame. The front brackets aligned with bolts projecting from the centre of the front stiffening frame member so that when the vessel and support frame were turned through 90° the weight was suspended from the back wall of the vessel and supported by the frame. The brackets also acted as anchor points for a canvas strap which passed over the vessel, clamping it tight to the metal frame. The support frame had detachable structures which fitted to the outside curvature to act as feet when the whole assembly was turned through 90° so that the vessel and the frame could be arranged as a free standing assembly. All vacuum surfaces were protected by packing and the vessel was further protected by a clack valve to allow for barometric changes during the journey and a silica gel container to restrict water absorbtion by the vessel material. The whole assembly was then wrapped with PVC sheeting.

8.5.2. Test Equipment

On arrival at the Rutherford Laboratory the vessels were unloaded in the test bay. Four rigs were constructed, two for outer vessels (Fig. 8.5.2(i)) and two which could take either inner vessels separately or inner vessels combined with header vessels. The test area was a 'clean' area and special clothing was worn by all personnel. Cotton gloves, hats and overshoes were used when entering the vessels at any time.

The first vessels to arrive were outer vessels. All surfaces were inspected to identify areas in need of actual or possible repair. An oblique light was used to show up flaws and scores on vacuum joint surfaces. The transport frame formed part of the test rig and the vessel and frame were lifted on to the rig support members. When on its rig the vessel was 6 ft above floor level to enable the underside to be carefully probed with leak hunting gas and repairs to be carried out easily.

All transport equipment was removed with the exception of the internal stiffening frames which were later removed systematically, beginning from centre of vessel, and replaced by sets of aluminium frames to support the vessel walls against atmospheric

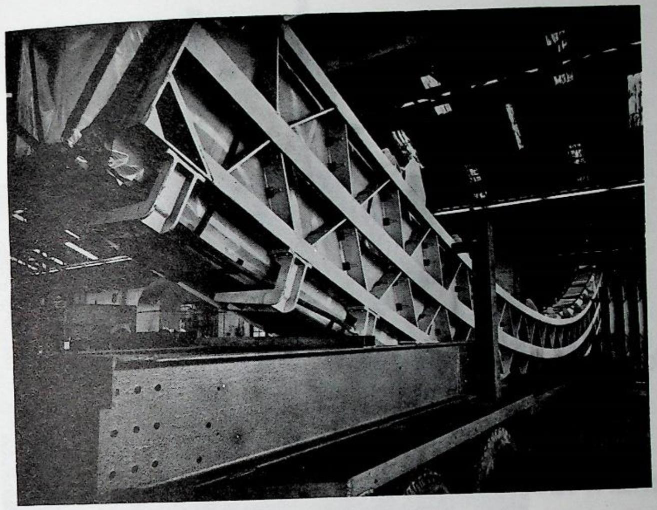


Fig. 8.5.1(i) View of a transporter carrying a vessel.

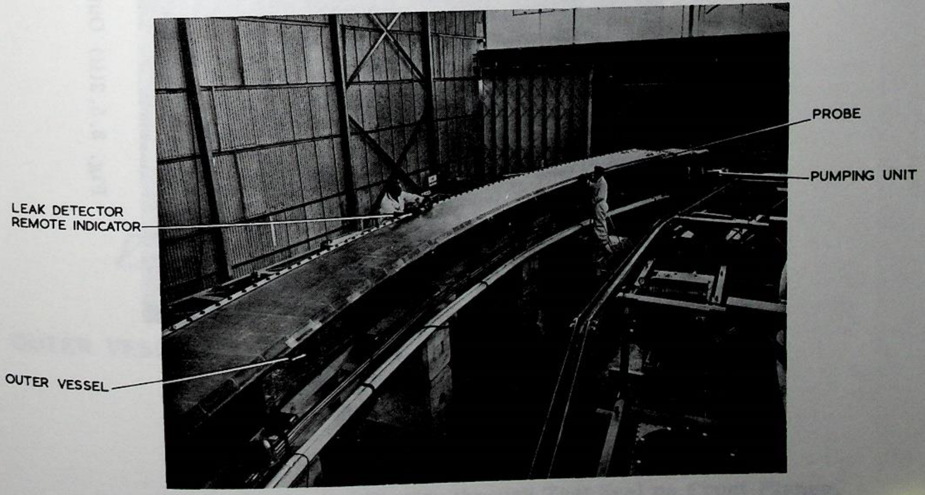


Fig. 8.5.2(i) Vessel test rig.

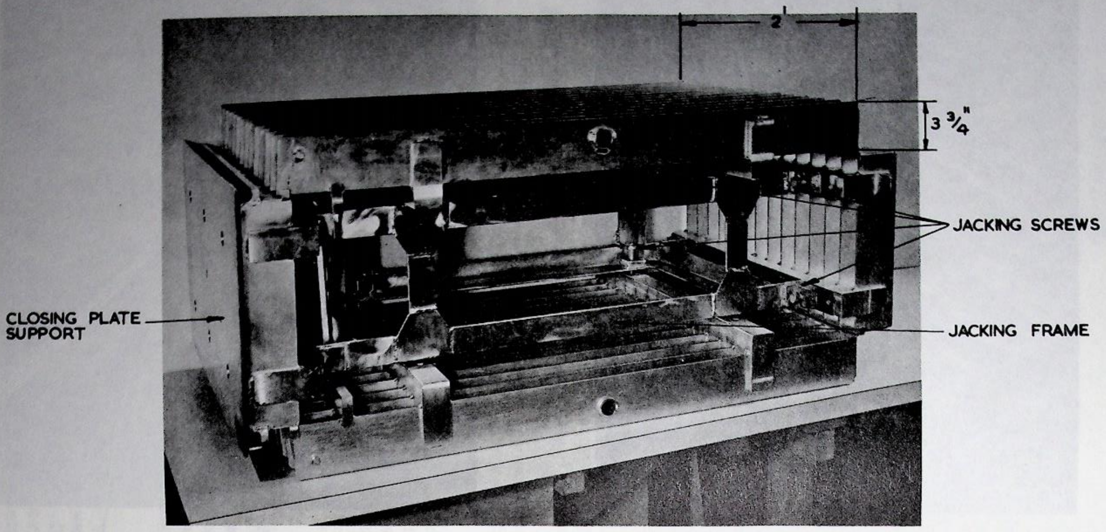


Fig. 8.5.2(ii) Outer vessel stiffening frame.

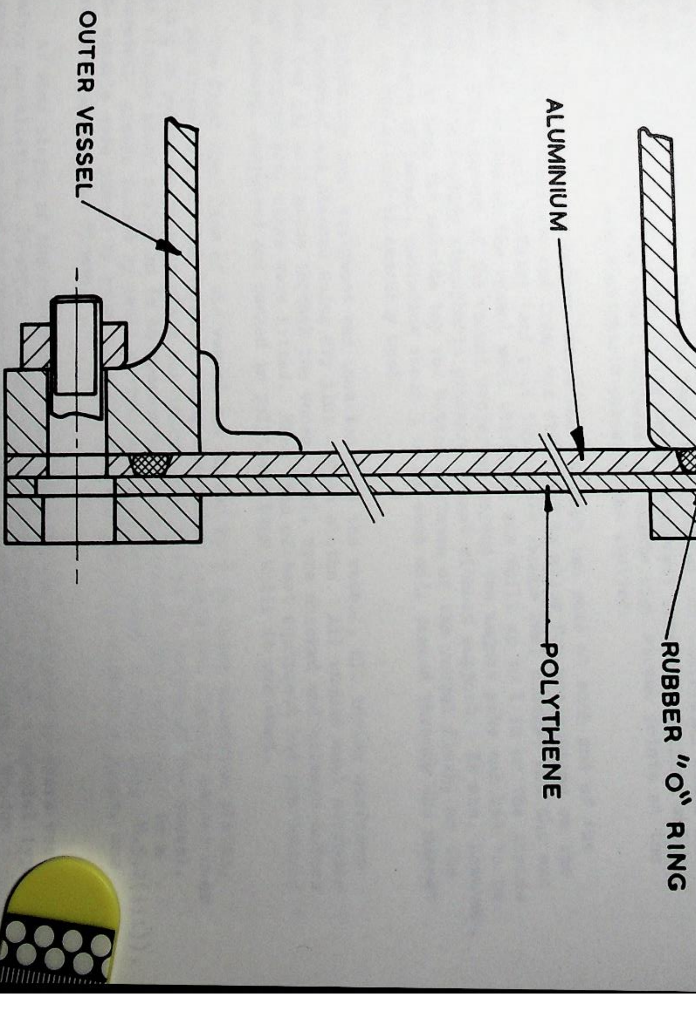


Fig. 8.5.2(iii) Typical Section through Test Seal on Front Flange.

pressure under 'pumped down' conditions.

The thickness of the vessel material, $\frac{1}{8}$ in, required a maximum unsupported span of $2\frac{1}{8}$ in if the design stress figures were not to be exceeded. During testing, support such as the machine components would have afforded would have been costly and undesirable, since most of the vessel surfaces would have been inaccessible making leak hunting impossible.

The aluminium frames (Fig. 8.5.2(ii)) were in sets, each set covering about 2 ft length of vessel and consisting of four members, supporting top, bottom and back walls of vessel with the fourth member bridging the gap between top and bottom flanges of the front open face of the vessel to support the closing plate. A jacking frame was used to jack the frames out to the profile of the vessel cross section. Each individual frame was constructed in a grille pattern with each grille member 3/16 in wide by $3\frac{3}{4}$ in deep. The 3/16 in face was in contact with the vessel surface and masked only a small section of the surface area without creating high bearing pressures which might damage the material. The span between adjacent frame members was kept to $2\frac{1}{8}$ in maximum. Care was taken when jacking out individual frame sets to use setting gauges across flange fixing holes to prevent irregular jacking which could cause steps along the vessel surfaces and create high stress points at the edges of frame sets, when atmospheric pressure was applied.

All frame sets were common except for the last two sets at each end of the vessel. The intermediate end frame was different to allow for projections on the inside of the vessel surfaces (end pole tip triple vacuum seal blocks) and the end frames were shorter as the vessel wall thickness was built up to 1 in on the inside surface. This section of the vessel projected beyond the magnet yoke and had to be capable of withstanding atmospheric pressure almost without support. It was, however, necessary to keep the outside top and bottom surfaces of the vessel flush, as the whole length of vessel, excluding about 3 in at each end, passed through the magnet throat in the method of assembly used.

Before any test equipment was inserted into the vessel, all inside surfaces were inspected and cleaned using dry lint - free cloths. All vacuum seal surfaces around the 330 bolt holes through the vessel wall, were checked and cleaned before plugs carrying seal rings were fitted. Each item of test equipment had previously been cleaned, degreased and packed in polythene bags until it was used.

The front open face of the vessel was closed by $\frac{1}{8}$ in thick aluminium plates, one per frame set, butting together along the vessel length and finally sealed over with $\frac{1}{8}$ in polythene closing plate continuous over the 54 ft length of the vessel. The closing plate sealed on to an uncemented, butt-jointed cord ring, held in a 'dovetail' groove formed by metal strips bolted to the vessel flanges (Fig. 8.5.2(iii)). The vessels were pumped by roughing pump unit and two 24 in diffusion pumps, one connected to each end flange.

At some stages of the construction programme it was necessary to store vessels before installation. In order to release the vessel support frame a special type of vessel lift was evolved to remove a vessel from its associated frame. Wooden internal stiffeners, spacers and outside cover plates were fitted and flat metal bars were inserted between the vessel and the frame in the space provided by the felt pads on the frame members. Bars were arranged to project over the back and front of the vessel. A second vessel support frame was lowered over the vessel and suspended just clear of the top surface. Bolts with spacer tubes were fitted between special brackets on back and front surfaces of top frame and metal bars under vessel

(Figs. 8.5.2(iv) and (v)). By hoisting the top frame, the vessel was removed from the bottom frame and held suspended and could be set down at any suitable position. This was called 'suspended lift'.

For manoeuvering vessels under the shield bridge or other areas not provided with crane coverage, four trollies mounted on castors were arranged in coupled pairs towards the front and back of the vessel. The span between the trollies could be varied to allow the vessel to sit on its frame on the trollies, as in the case of an outer vessel, or to allow the vessel to be suspended under a frame, as in case of inner and header vessels.

The equipment for testing inner vessels closely followed that used for the outer vessels. The height of the vessel, however, was much less than the outer and only two frame members were used per set, jacked apart to the top and bottom surfaces. The frames were of a different design and profiled to the 'crowned' shape of the vessel. After jacking out to the vessel shape, a further pad was jacked off a frame member on to the back wall of the vessel, the reaction being taken through the frame which was held by its fit into the crowned shape. These support frame members were made of mild steel coated in nylon for cleanliness and to protect the stainless steel foil lining of the vessel. During early vacuum test runs, the nylon caused considerable contamination due to out-gassing and it was removed and the frames electro-polished. To prevent damage to the vessel, the edges of the frames were covered with split polythene tube.

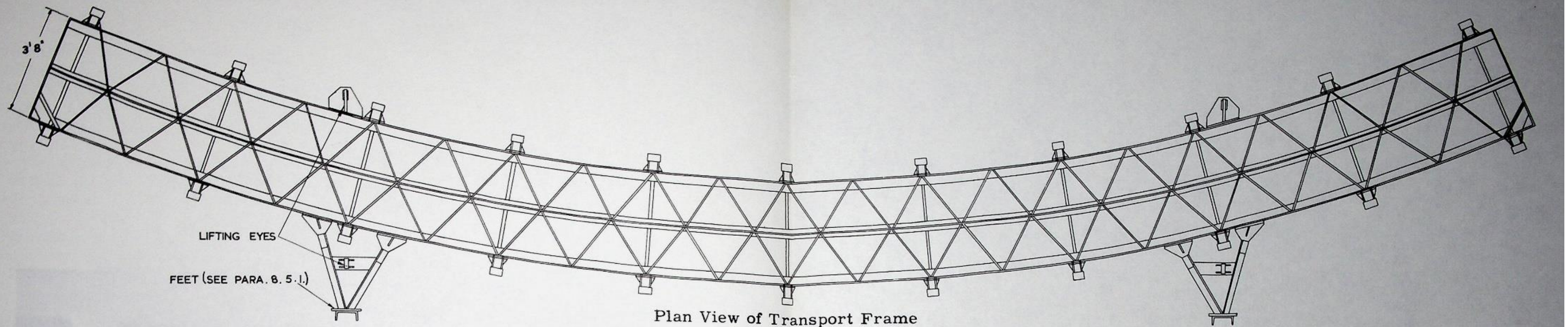
The header vessel, which was constructed to withstand atmospheric pressure between external attachment points, did not require the continuous frame support. Instead an internal jack was fitted to coincide with the position of external ties. No arrangement was made to test a header vessel separately and they were matched to a previously tested inner vessel.

During the test programme, some trouble was experienced on all vessels with leak paths around tapped metal insert positions and around metal ferrules lining holes in the flange. It was necessary in a number of cases to remove these to bond in new ones and it was desirable to do this while the vessel was pumped so that the resin would be drawn into the voids in the material. The test equipment proved very versatile during such operations, although some of these requirements were not consciously ' designed in'. Inserts on the front face of the header vessels were fixed parallel to the lay of the cloths and leaking inserts became so troublesome on the first and second header vessels that it was decided to remove all inserts on the front face and remake the surface as a vacuum seal surface only. Cover plate attachments were then arranged to fix to the top and bottom outside surfaces where inserts could be housed in the vessel material normal to the lay of the cloth.

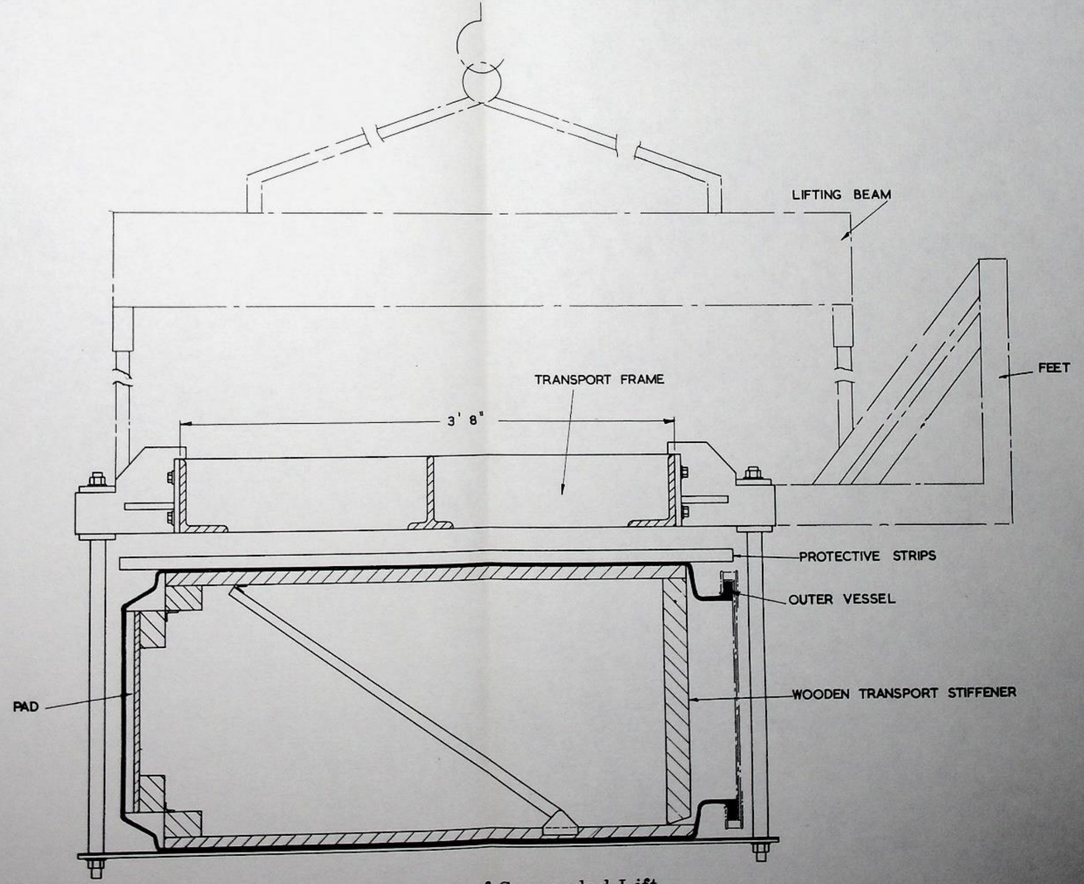
8.5.3. Vessel Installation

Before the outer vessels were installed all magnet sector throat dimensions were taken and where steps between adjacent sectors exceeded 0.012 in cloth and resin shims were fixed to the throat surfaces. This ensured that sudden steps in the vessel walls were not created when the vessel was clamped between the magnet yoke and the pole tips. In the later stages of outer vessel manufacture, steps in adjacent vessel wall panels were found to exceed 0.012 in due to tooling faults and some shimming of the outside surface of the vessel was necessary.

To install an outer vessel, the frame with the vessel on it was placed on fabricated trestles which spanned the mechanical services trench in front of the



Plan View of Transport Frame



Typical Section of Suspended Lift.

Fig. 8.5.2(iv) Top Lifting Arrangement for Outer Vacuum Vessel.

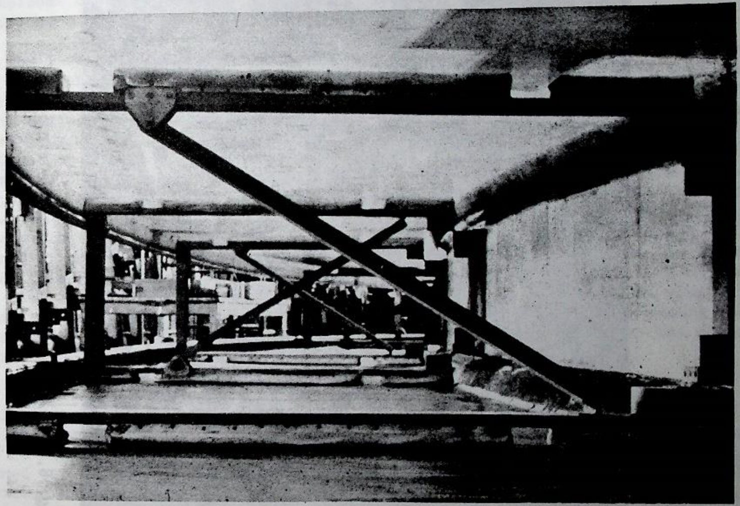


Fig. 8.5.2(v) View inside an outer vessel. (The wooden jigs are for packing purposes only).

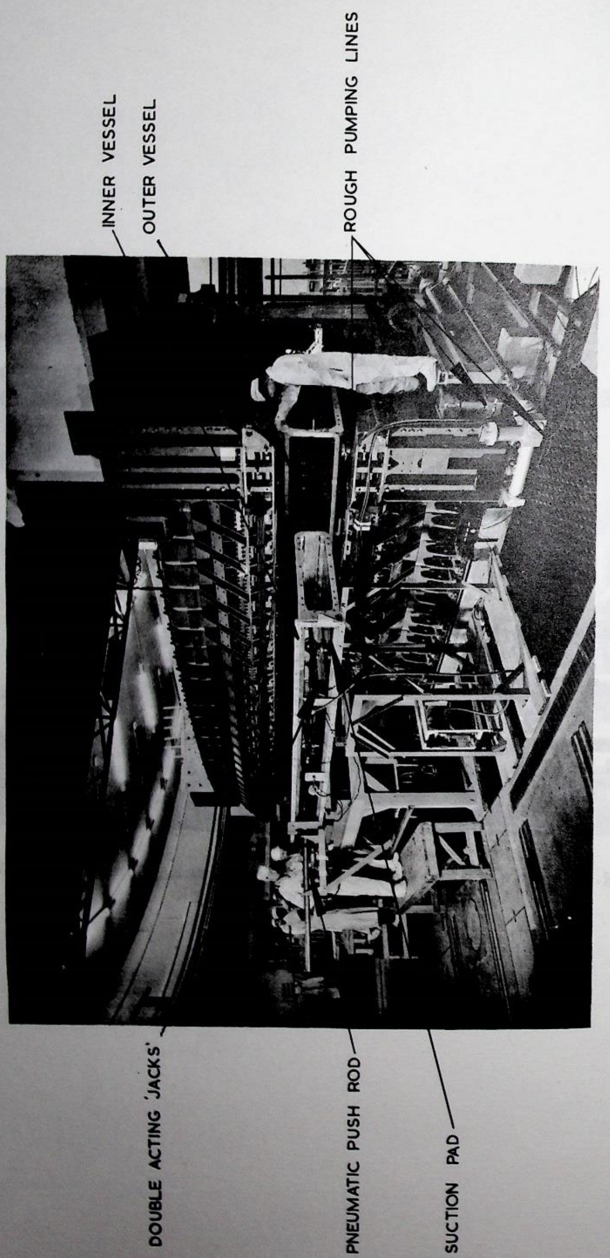


Fig. 8.5.3(i) Inner vessel assembly rig.

appropriate octant. The vessel was lifted clear of the felt pads on the frame by the insertion of 'drifts'. Initially the drifts had a PTFE top surface to allow the vessel to travel over them smoothly, but this was later removed in favour of a polished surface due to the PTFE tape 'picking up'. The vessel was adjusted to the correct height for feeding into the throat by means of jacking screws on the trestles and was pushed in, supported on the drifts, until it had entered 2/3rds of the way into the throat. The clearance between the height of the back wall of the vessel and the height of the magnet throat was increased by clamping the front flanges of the vessel closer together than their designed position. This 'bowed' the back wall slightly. It was not possible to do this near the ends of the vessel because of the stiffening effect of the end flanges and the end pole tip blocks, and careful dimensional checks and visual inspection for 'resin flash' were carried out before insertion.

The first outer vessels were pushed into the throat by man power; two men, at each of seven points equally spaced around the vessel, applied a load to a push rod which moved the vessel in, a stage each time, to a preset locking pin. The push rod was in contact with the back wall of the vessel and the load was spread on the material by means of a large pad. Although this method was successful it was later abandoned in favour of two pneumatically operated push rods which became available after the inner vessel assembly rig was designed. This gave much finer control of the process. After the vessel had been inserted to the correct depth into throat it was aligned circumferentially by equipment designed to pull the vessel sideways by attachments to the end flanges. The final position of the vessel was set as the best nominal alignment of the vertical pole piece bolt holes, gauged from the datum faces on the principle sectors (see section 4.5.2). When errors in curvature of the vessel were discovered, pairs of pole tips were assembled into the throat to clamp the vessel at the centre or the ends (depending on the direction of the error) and slight pressure was applied to the back wall of the vessel to move it on to the correct line of curvature. Further clamping pole tips were then assembled.

To install the inner vessels the same trestles were used with additional intermediate ones. No frame was involved except that used to bring the inner vessel into the magnet room in the 'suspended lift' condition. The vessel was then set down on slide rails assembled across the tops of the trestles (Fig. 8.5.3(i)). The crowned top and bottom surfaces of the vessel were designed to give a vessel height in excess of the gap between the pole tips in the throat. This was of such an order that the interference fit of these two items would give the vessel walls a thrust on to the pole tip faces, sufficient to resist the deflection of the vessel under its own weight and under the pressure due to the vacuum in the outer vessel. The crowning had, therefore, to be reduced in order to install the vessel in the throat.

When the vessel was placed on the trestles, the cover plates were removed and metal straps with a dimension slightly less than the designed span were bolted across the front flanges around the centre section. This reduced the height of the vessel over about 70% of its length. The ends, however, which are stiffened by the end flanges, remained almost at their 'free state' dimension. Three pneumatically operated, double acting jacks were inserted into the vessel at each end on the section of peak crowning. The jacks were spaced about 2 ft apart beginning 2 ft from the end flange; the end jack was larger than the other two. Rubber sucker caps, connected to a small roughing vacuum pump, were fitted at the top and bottom of each jack. The jacks were expanded pneumatically to a mechanical stop which gave sufficient pressure on to the inside surface of the vessel to effect a vacuum seal and the volume within the suckers was evacuated. The jacks were then retracted pneumatically to a mechanical stop, so pulling in the top and bottom surfaces of the vessel.

Two push rods, pneumatically operated, one positioned about 15 ft each side of the centre line of the vessel were arranged to push on the plate bolted across the front flanges of the vessel. The cylinders of both push rods were connected to a common control valve and the push rods travelled in stages to mechanical stops. This arrangement kept the push rods in phase by allowing for any lag occurring between the cylinder movements. The control valve was interlocked with the sucker caps to ensure that there was no movement into the magnet throat if the vacuum was lost on any sucker.

After insertion, the inner vessel was aligned to give the best nominal position of the front flange relative to the outer vessel front flange and an equal gap between the inner and outer flanges at the top, bottom and ends. When this had been achieved, the vacuum was released from all suckers and the vessel was allowed to expand to the pole tip faces.

The header vessel was transported to the appropriate octant by the 'suspended lift' method and was lowered on to small trollies mounted on support frames spanning the mechanical services trench. These were of a different construction to the frames used on outer and inner vessels because of the greater weight involved. There were seven trollies, two of which, placed at approximately 15 ft from the centre of the vessel, were attached to long lead screws. The vessel was gradually fed into the machine on the trollies, by means of the lead screws, until the inner and header flanges met. Flange bolts were then fitted and tightened by a torque wrench, commencing from the centre of the vessel and progressing out to the ends to gradually blend the flanges in together. Top and bottom support brackets and tie rods were fitted after careful shimming, to ensure the vessel was held in this position so that the weight of the vessel was kept off the matched flanges when the supports were removed.

8.6. Vacuum Testing

8.6.1. Introduction

10% of the total pumping speed of the high vacuum pumps was allowed to cover leakage into the system (Section 8.10.1). Based on the design specifications for the pumps, 5 pumps per octant would permit a leakage of 1.25×10^{-3} torr litres/s for each octant.

Most components in the vacuum system, other than the vacuum vessels, were likely to be of metal and individual leak rates for these items could be small. In fact for all such components, except straight section boxes, a tolerance of 10^{-7} torr litres/s was specified. The leak rate was to be established using palladium barrier gauge or mass spectrometer leak detectors in dynamic systems. In this way more than a thousand such components could be connected to each octant before any significant change in the total octant leak rate would occur. It was therefore reasonable to allow all of the permissible leak rate for the combination of inner and header vessel alone. In practice each inner vessel was individually tested and allowed 6×10^{-4} torr litres/s leakage and header vessels were tested with a previously proved inner vessel. Outer vessels had to meet a less stringent test but, since they were the first to be delivered, the opportunity was taken to try to achieve the lowest possible leak rates. Experience proved that leak rates of 5×10^{-3} torr litres/s could readily be attained.

Vessel leak rates were measured by pressure rise methods but were not continued long enough to eliminate the component due to outgassing. It was not practical to hood an entire vessel so that leak rates could be measured on the mass spectrometer by comparison with a reference leak.

Cleanliness was considered to be of prime importance in view of the tight leak rate tolerances. Since palladium barrier methods could be used for many of the tests, the use of solvents containing halogens was banned. If the use of such a solvent became necessary because of heavy contamination with oil or grease, a final rinse was always given using an approved solvent such as acetone or iso-propyl alcohol. In the case of the resin/glass laminates methylated spirits was the only approved cleaning solvent.

From the beginning of the testing programme, a final proof test took place at the Rutherford Laboratory before the component was installed, no matter what component testing had been carried out previously at the manufacturer's works. This protected against damage in transit and deterioration in storage. Strict control was maintained over tested items so that the test was not invalidated by subsequent modifications, etc.

Leak test facilities were required to be adaptable for large and small components. On large components particularly, the method of connecting the leak detector to the item for test could greatly affect the final sensitivity. For a system of volume V_1, leak rate L, pressure p_1 and pumping speed S_1 using a particular test gas,

$$V_1 \, dp_1 = S_1 p_1 dt$$

Whence $$p_1 = \frac{L}{S_1} \left[1 - \exp(-S_1 t/V_1) \right]$$

In the backing space of volume V_2 of this system, with the test gas partial pressure p_2 and pumping speed S_2,

$$V_2\, dp_2 = S_1\, p_1\, dt - S_2\, p_2\, dt$$

Whence

$$p_2 = \frac{L}{S_2}\left[1 - \frac{1}{S_1/V_1 - S_2/V_2}\left\{\frac{S_1}{V_1}\exp(-S_2t/V_2) - \frac{S_2}{V_2}\exp(-S_1t/V_1)\right\}\right]$$

Fig. 8.6.1(i) shows two curves plotted for a typical system and indicates the marked advantage of placing the leak detector in the backing space of the pumping system. All the pumping units were therefore provided with facilities for connecting a leak detector in the backing space and also with a throttle valve on the backing pump so that maximum advantage could be gained from the method.

For smaller components, static leak detection equipment consisted of a 9 in oil diffusion pump backed by a 2 in oil diffusion pump and rotary pump with a Palladium Barrier detector fitted in the interspace between the two diffusion pumps. Other versions of this equipment, but without the 9 in diffusion pump, were available for use with the 24 in pumping units on the synchrotron for vessel and octant testing. Mass spectrometer leak detectors could be used with any of the units.

8.6.2. Vacuum Vessels

(i) Outer vessel proof tests

A prototype vessel was the first to be tested. The vessel was known to be unfit for use in the machine because it was outside tolerance on several dimensions. It was also known to have many areas of laminate of inferior quality but it was considered very worthwhile to carry out the full test procedure in order to establish techniques and to attempt to specify the quality of laminate necessary to achieve the required leak rate.

This prototype vessel was estimated to have a leak rate in excess of 30 torr litres/s when it was first tested. Several large leaks existed and were fairly easily detected. There followed a long and tedious process of finding a large number of leaks, each of which was small in comparison with total throughput and often had a long time constant. Also, only the roughing pump was in use at this stage and the leaks were only just detectable, even with a mass spectrometer leak detector, due to the limitation of the sampling.

It was found, during vessel testing, that leaks in excess of 10^{-1} torr litres/s were readily detected on a Pirani gauge using hydrogen as the probe gas. Areas of the vessel were covered with anti-static rubber sheet (Fig. 8.6.2(i)), taped in position and the space between vessel and sheet filled with hydrogen. The sheet size was then reduced until the leaking area was localised. Further checks were then carried out using a hyperdermic needle attached to the probe with substantially reduced hydrogen pressure in order to determine the leak boundary of the porous area. The leaking area was them temporarily sealed using "twin pack" Araldite. The vessel pressure was noted before and after this operation. The process was repeated in successive passes over the vessel surfaces, successively smaller leaks being detected as the larger leaks were sealed.

This procedure was tedious and time consuming on the prototype vessels

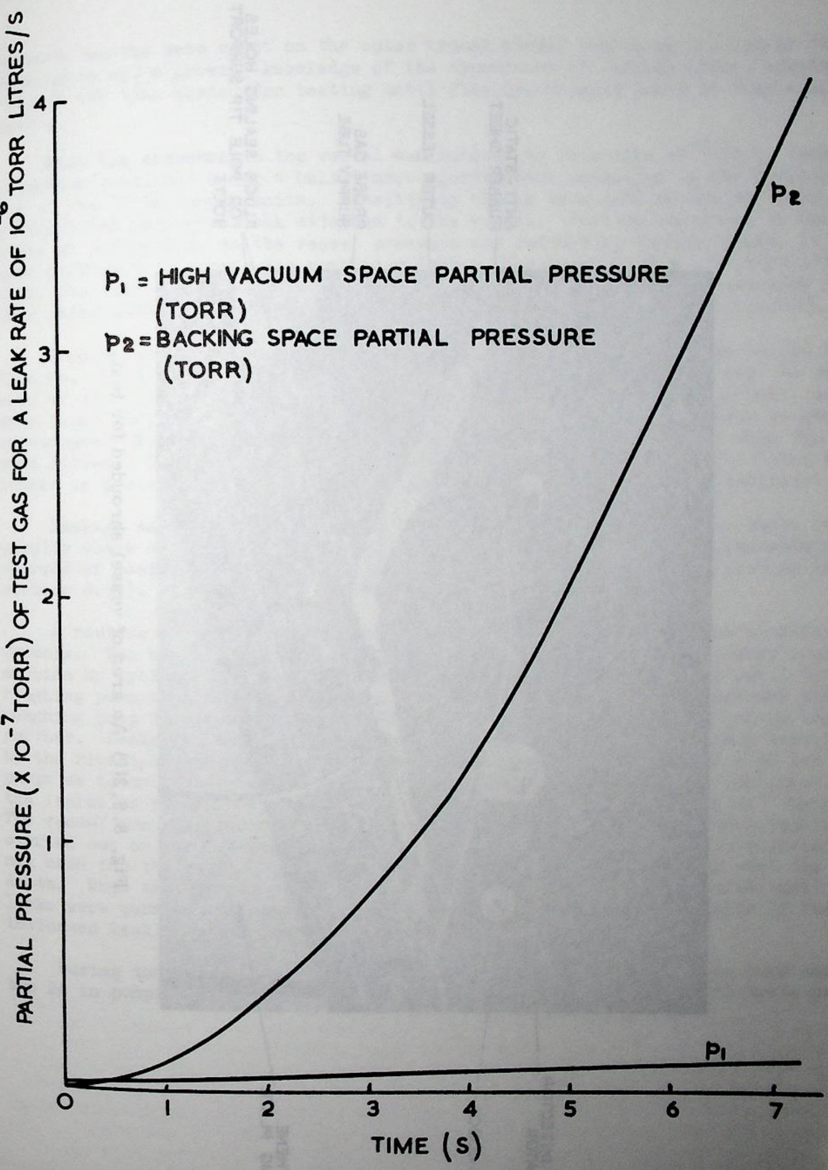


Fig. 8.6.1(i) Leak detection sensitivity

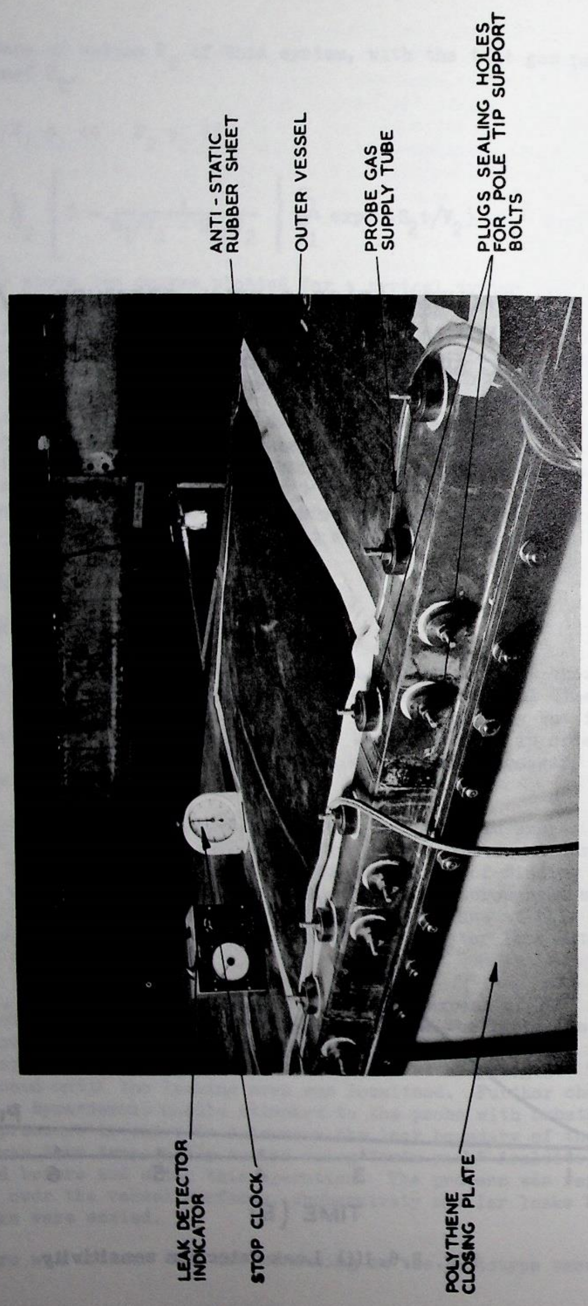


Fig. 8.6.2(i) An area of vessel shrouded for test.

(several months were spent on the outer vessel alone, including the repair time). Experience and a growing knowledge of the appearance of leaking areas, substantially reduced the time needed for testing until finally, vessels could be completed in two weeks.

When the pressure in the vessel was reduced to less than 10^{-4} torr, leak detection continued using a helium mass spectrometer connected to the backing line of one of the 24 in vacuum units. Sensitivity checks were made periodically by probing a calibrated reference leak attached to the vessel. Probing continued by shrouding areas as before and, as the vessel pressure was reduced by sealing leaks, it became more difficult to locate the remaining leaks. For leaks of 5×10^{-3} torr litres/s or less, the time constants were liable to increase as small porous areas with long leak paths were located. The test results are summarised in Table 8.6.2(I).

A major source of leakage was the large number of drilled holes in the vessel flanges. These had been coated with a thin film of resin in an attempt to seal the ends of any hollow glass fibres cut by the drill. Despite this treatment, many leaks were found and, even if the process of sealing was repeated, there was no guarantee of success. Subsequently it was discovered that damage could occur when the bolts were fitted. The resin coating was therefore replaced by thin walled brass ferrules bonded in position. This has eliminated this type of fault almost entirely.

Leakage was also troublesome in the region of whitened areas or white lines, usually where sections of the vessel had been spliced or where the laminate was starved of resin. A repair technique was evolved to overcome this problem (see section 8.7.).

A routine examination technique soon became established for the production vessels. The vessel was flexed to simulate the probable operating conditions in the machine by cycling the absolute pressures several times between 760 and 1 torr. The roughing pump then pumped the vessel down to 10^{-2} torr, at which pressure the roughing pump was isolated and the 24 in vacuum units were used to reduce the pressure further. Leaks in the range of pressures covered by the roughing pump were located by the Pirani/hydrogen technique and the mass spectrometer was used with the 24 in pumps as described above. The drill of locating and sealing leaks continued until the isolation pressure rise indicated a leak rate of less than 2×10^{-2} torr litres/s. The vessel was then isolated from the pumping system and the permanent repairs were carried out on the leaking areas with the vessel under vacuum. This allowed the resin mix used for the repair, to flow along the leak path and adequately seal the leak at depth. When the repairs were complete, the test sequence was repeated until all known leaks were permanently repaired. The vessel was considered acceptable if the indicated leak rate was less than 5×10^{-3} torr litres/s.

During the last phase of assembly on the test rig, the roughing pump and the two 24 in pumping units were checked for operational sequence and ultimate pressure.

TABLE 8.6.2(I)

Outer Vessel Proof Tests

Vessel Number	Number of Leaks	Final Leak Rate (10^{-3} torr litre/s)	Installed in Octant Number
1	3	4.1	5
2	5	1.8	4
3	10	2.6	1
4	10	1.6	8
5	7	2.2	2
6	6	2.8	3
7	3	1.9	6
8	14	2.0	7
9	5	3.8	Spare
10	2	1.1	Spare

(ii) Outer vessel installation test

During the installation of the outer vessels in the machine, the standards of cleanliness were maintained and all the vacuum faces and joint rings were inspected before assembly. On a number of occasions, damage occurred which necessitated a 'through' repair on the vessel as described in 8.7. These repairs were vacuum tested locally using a 'top hat' (Fig. 8.6.2(ii))on the inside face of the vessel. The leak rate through the repair was ascertained by the isolation pressure rise method, with a tolerance of 10^{-5} torr litres /s/ft^2 surface area.

When the installation of the pole tips, pole face windings, roughing pumps and associated pipework was complete, the main polythene blank was again fitted and the system was pumped down using the permanent roughing pumps. Leak detection was carried out using the Pirani/hydrogen method until the leak rate of the system was less than 2. 10^{-1} torr litre/s. Before this leakage rate could be considered acceptable the pole face winding tubes were pressurised to 80 lb/in^2 before and during the measurement of the final pressure rise. If no additional leakage occurred the outer vessel was acceptable. Some 500 seals are introduced by the installation of the pole tips and pole face windings in each octant and these, together with the greatly increased surface area, account for the higher leak rates compared with the vessel proof tests.

(iii) Inner vessel proof tests

The inner vessels were treated in the same way as the outer vessels when they were received. It was found that the threaded inserts in the main and end vacuum flanges were susceptible to leakage at some stage of installation and after the first vessel was tested, it seemed advisable to pre-test these inserts before the overall proof test of the inner vessel began. Small 'top hats' (Fig. 8.6.2(iii)) were used with a threaded central projection which screwed into the insert. The circular ring in the base of the top hat was compressed against the vacuum face of the vessel flange and the top hat was evacuated using a small rotary pump. A leak rate of 1 x 10^{-5} torr litres/s. was acceptable. The biggest part of this indicated leakage was found, in practice, to be outgassing and it in no way influenced the ultimate leak

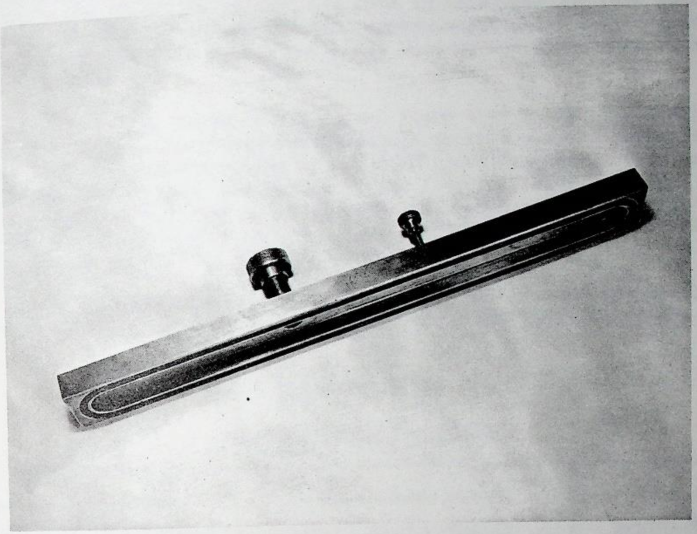


Fig. 8.6.2(ii) "Top hat" for local testing of a repaired area.

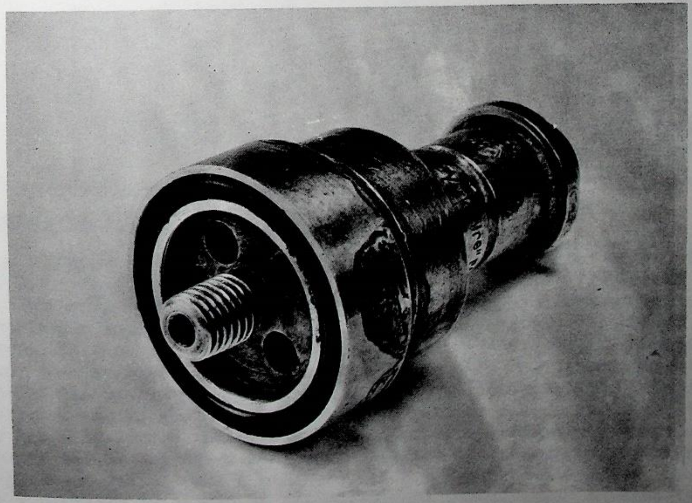


Fig. 8.6.2(iii) "Top hat" for vacuum testing inserts.

rate of the vessel. If an insert with an indicated leak rate in excess of 1 x 10^{-5} torr litres/s was found, an attempt was made to determine the leak path but if it could not be located it was assumed that excessive outgassing was occurring. This generally implied that the insert was badly located and steps were taken to remove and replace the insert.

On the first inner vessel tests it was found that the $\frac{1}{8}$ in thick polythene blank used to seal off the main flange was permeable to both air and helium causing an additional leakage into the system of 1.5 x 10^{-3} torr litres/s. This permeability caused difficulty for some time before it was finally traced. Probing around the vessel flanges gave reactions after some 20 min, reaching a peak after one hour, and considerable effort went into ensuring that the joint seals and the bolt holes were leak tight before eventually the polythene was suspected.

An aluminium blank of similar dimensions was substituted and enabled the vessels to be proof tested to a leak rate of less than 5 x 10^{-4} torr litres/s.

TABLE 8.6.2(II)

Inner Vessel Proof Tests

Vessel Number	Number of Leaks	Final Leak Rate (10^{-4} torr litre/s)	Installed in Octant Number
1	4	2.6	1
2	3	1.7	8
3	3	1.8	2
4	5	2.1	4
5	2	3.8	5
6	7	0.9	6
7	4	5.0	3
8	5	3.0	7
9	3	3.3	Spare
10	2	1.2	Spare

Header Vessel Tests

Only 4 header vessels have been provided and they are fitted to octants 3, 4, 5 and 6 to facilitate beam extraction. Great difficulty was experienced with the first vessels. Not only were there numerous leaks but they had long path lengths which made detection a tedious process. The leaks were eventually traced to tapped inserts bonded into the edge of the vessel on its larger radius. These inserts were provided for fixing the 'window' plates to the vessel and were positioned with their axes in the plane of the layers of glass cloth forming the laminate. By removing the inserts completely and making good the edge of the vessel by a wrap round repair after plugging the holes, more than 90% of the leaks were eliminated. This modification was incorporated in the third and fourth vessels by the manufacturers before delivery and on the first vessel (which was returned for rectification) but the second vessel was made acceptable by repair at the Rutherford Laboratory. Alternative means of fixing the window plates was provided by fixing aluminium clamp bars to the top and bottom of the vessels using inserts with their axes perpendicular to the plane of the cloths. This method has now been satisfactorily proved.

TABLE 8.6.2(III)

Header Vessel Proof Tests

Vessel Number	Number of Leaks	Final Leak Rate * (10^{-3} torr litre/s)	Installed in Octant Number
1	96	30 (approx)	Returned for Rectification.
2	97	3.5 **	3
3	2	1.1	6
4	4	1.1	4
1	5	0.66	5

* Leak rate includes associated inner vessel leakage.
** Further repairs were carried out after installation in octant 3.

8.6.3. Straight Section Box Proof Tests

All straight section boxes were retested when they were received although they had been tested at the manufacturers. Of the seven boxes tested, all had leaks varying from 6 to 160 times tolerance. Vacuum testing was carried out using a 12 in pumping unit fitted to one vertical face of the box, with a separate roughing pump and connecting pipe. The prefabrication of the box conformed to normal vacuum practice with external welds intermittent, and internal welds continuous, but for magnetic reasons, each wall consisted of two mild steel plates separated by fibre glass insulation. With the box evacuated, leak detection was carried out by probing the gaps between the intermittent external welds. Having determined the leaking area approximately, the box was returned to atmospheric pressure. The inner weld leak was pinpointed by pumping the gap between the intermittent external weld and probing the inner continuous weld. All leak rates were indicated by isolation pressure rise and the acceptable leak rate was 1 x 10^{-4} torr litres/s.

TABLE 8.6.3(I)

Straight Section Box Proof Tests

Box Number	Number of Leaks	Final Leak Rate (10^{-5} torr litre/s)
1	2	15
2	2	42 *
3	2	6.2
4	4	5.1
5	8	13
6	1	8
7	1	6.7
8	-	18 **

* included some internal structures
** included epoxy resin insulators

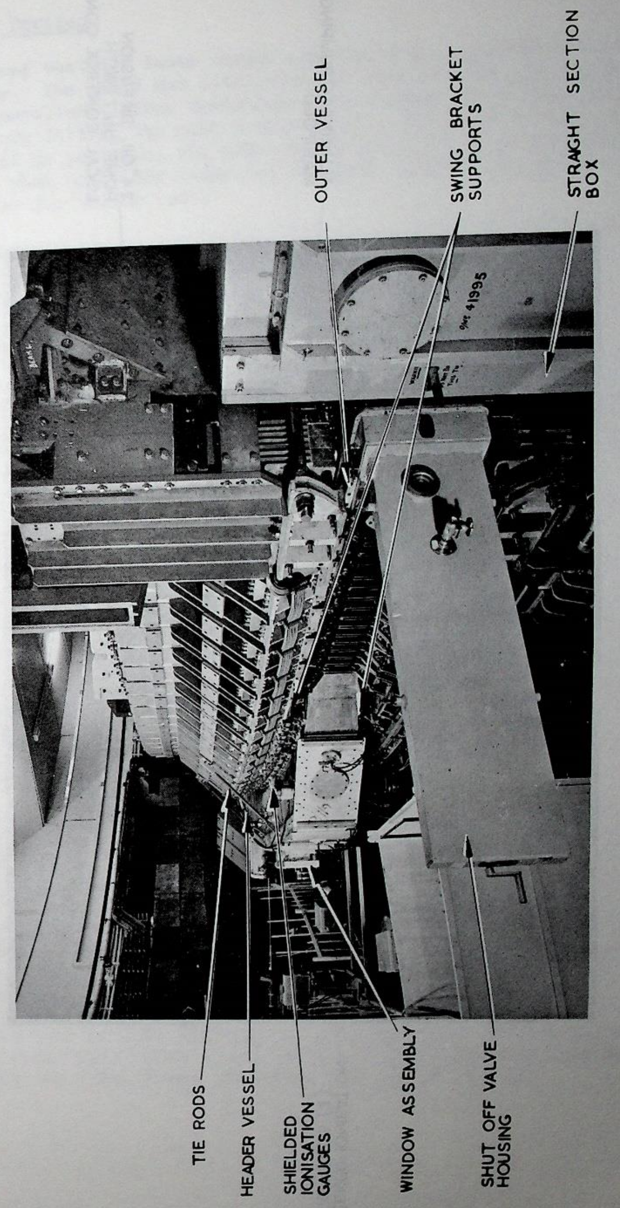


Fig. 8.6.4(i) An installed header vessel (octant 6).

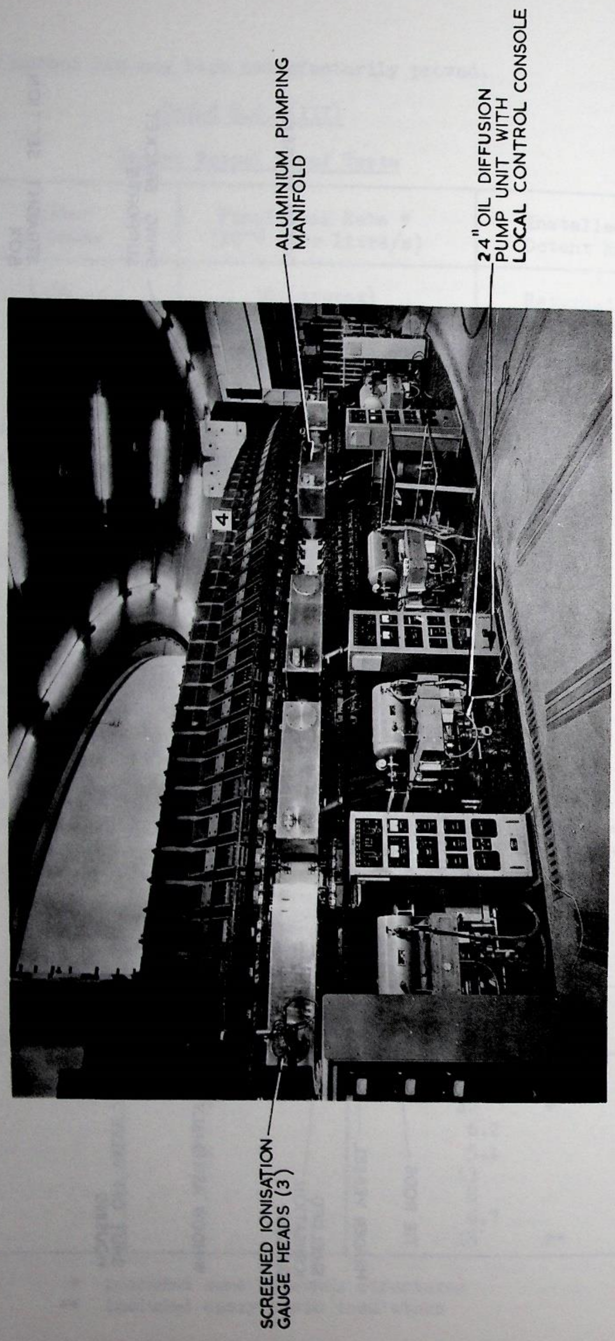


Fig. 8.6.4(ii) An installed closure plate (octant 4).

8.6.4. Octant Testing

After proof testing, inner vessel was then moved adjacent to its final position in the machine. The inner and outer surfaces were cleaned and the vessel was immediately installed. After installation all vacuum faces were inspected and faults rectified before fitting the main vacuum seals. The closure plate or header vessel was then fitted in position, the main vacuum units and pump manifolds were permanently attached and, when ancillary items and roughing pipework was installed, the octant was handed over for vacuum test.

The octant was pumped down using the permanent pumping system and leak detection was carried out using a mass spectrometer connected to the backing line of one of the main units.

Inner vessels have been fitted to all octants, with four header vessels (Fig. 8.6.4(i)) and four polythene closing plates (Fig. 8.6.4(ii)). To date, one octant fitted with a closing plate has had a full vacuum test and a leak rate of about 10^{-3} torr litre/s was measured. The required machine operating pressure of 10^{-6} torr was achieved in 15 hours and after 60 hours the pressure was 4×10^{-7} torr (Fig. 8.6.4(iii)). Three other octants, which are not yet fully tested and have repairs still to be carried out, have indicated leak rates of less than 5×10^{-3} torr litres/s. A group of four octants recently coupled together by their associated straight section boxes was estimated to have a total leak rate of about 10^{-2} torr litre/s. The tests were carried out before diagnostic equipment was fitted to any of the octants.

The policy of pre-testing each component before installation paid handsome dividends. The vacuum system was so complicated, had so many seals and in some cases was so inaccessible after installation that tests would have been long drawn out, if in fact they were possible. This was particularly true of the outer and inner vessels the main surfaces of which are almost completely enclosed and the work entailed in removing an outer vessel for a major repair could have added three months to the Nimrod programme.

8.6.5. Leak Detectors

The programme of testing was frequently held up because of failure of the mass spectrometer leak detectors. Three types were in use, two of each type being available. Of these, one was never successfully used except in a permanent position where smaller components were brought for testing.

The second type could be moved around to a certain extent but this involved a loss of sensitivity by a factor of at least 10. These instruments were also subject to excessive background noise on their most sensitive ranges when connected to the larger systems, so that small leaks could not be detected.

The third type of mass spectrometer gave excellent service in comparison. It retained its sensitivity after being moved and was, therefore, the only instrument to be used for the final stages of vessel and octant testing.

8.7. Vessel Repairs

Techniques had to be developed to allow repairs to be carried out on the vacuum vessels either after initial fabrication to repair obvious mechanical defects, or during vacuum test, to cure leaks. The materials used for repair had to have the same properties as the vessel material (see section 8.1.) except in respect of manufacturing feasibility. Resin systems which complied with the requirements for gas evolution rate and mechanical properties had also to:

(i) cure satisfactorily at a temperature below the heat distortion temperature of the parent material,

(ii) have a minimum contraction on curing, to avoid introducing areas of high stress around the repair, and

(iii) be compatible with the resin system of the parent material.

Other factors influencing the choice were the ease of 'wetting out' the fabric, the pot life at room temperature and the drainage which occurred when repairs were done on vertical surfaces.

Studies on available materials showed that a modified bisphenol A type resin system cured with a liquid aromatic hardener was the most satisfactory. This system required curing for 24 hours at room temperature (20°C) followed by 16 hours at 60°C (10°C below the heat distortion temperature of the parent material).

Suitable surfacing mediums for vacuum sealing faces were also investigated. At one time it was thought that the desired quality of finish could be obtained direct from the moulding tools. This proved impracticable for a number of reasons; for example, bad release, creases in release films, such as PTFE tape and damage caused in handling and transporting the vessels. The surfacing material must have similar properties to the parent laminate; in particular, it must cold cure and have a thermal coefficient of expansion close to that of the parent material, to prevent crazing of the sealing surface during operation.

Both solvent containing and solvent free formulations were considered. The most satisfactory was a solvent free proprietory material X83/44. It was whitened so that seal surfaces were readily identified. Later a formulation known as TSW 120 was developed at the Rutherford Laboratory, which contained silica flour and also bentone (which makes the material thixotropic). This formulation was very successful and its flow characteristics eased the problem of application considerably. In all cases vacuum sealing surfaces were dressed and polished to the required finish using 'wet and dry' Garnet paper.

Faults on the vacuum vessels may be classified into the following types:-

(i) Crushed or insufficiently wetted fabric.

These areas were easily defined by a whitened appearance (Fig. 8.7(i)) and Fig. 8.7(ii)) and the complete removal of the faulty area was necessary. The faulty fabrics were removed singly using a sharp knife, or a wood chisel and a spatula. A half inch step was introduced every two layers of fabric (Fig. 8.7(iii) and Fig. 8.7(iv)) to achieve the required mechanical strength in the finished repair.

When the desired profile had been achieved, fabric was pre-wetted with the

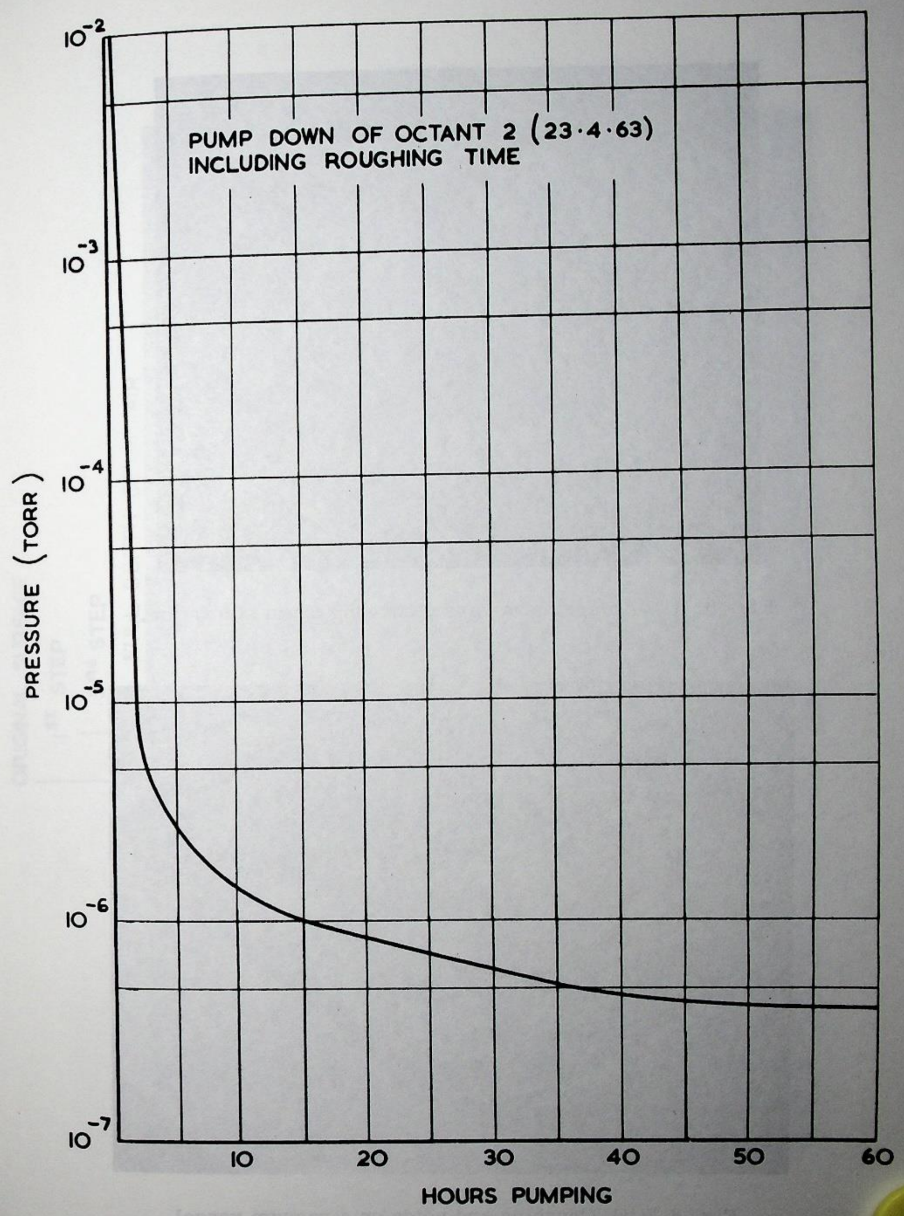


Fig. 8.6.4(iii) Pump down of octant 2.

Fig. 8.7(i) An area of a vessel showing resin starvation.

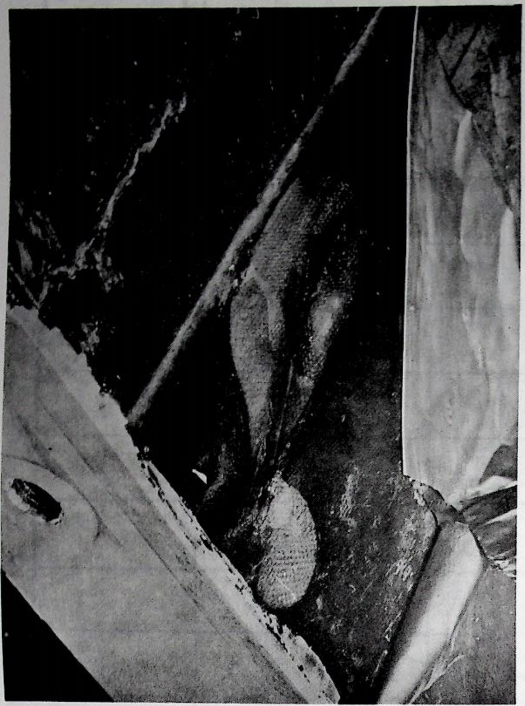


Fig. 8.7(ii) Crushing and voids on a vacuum vessel.

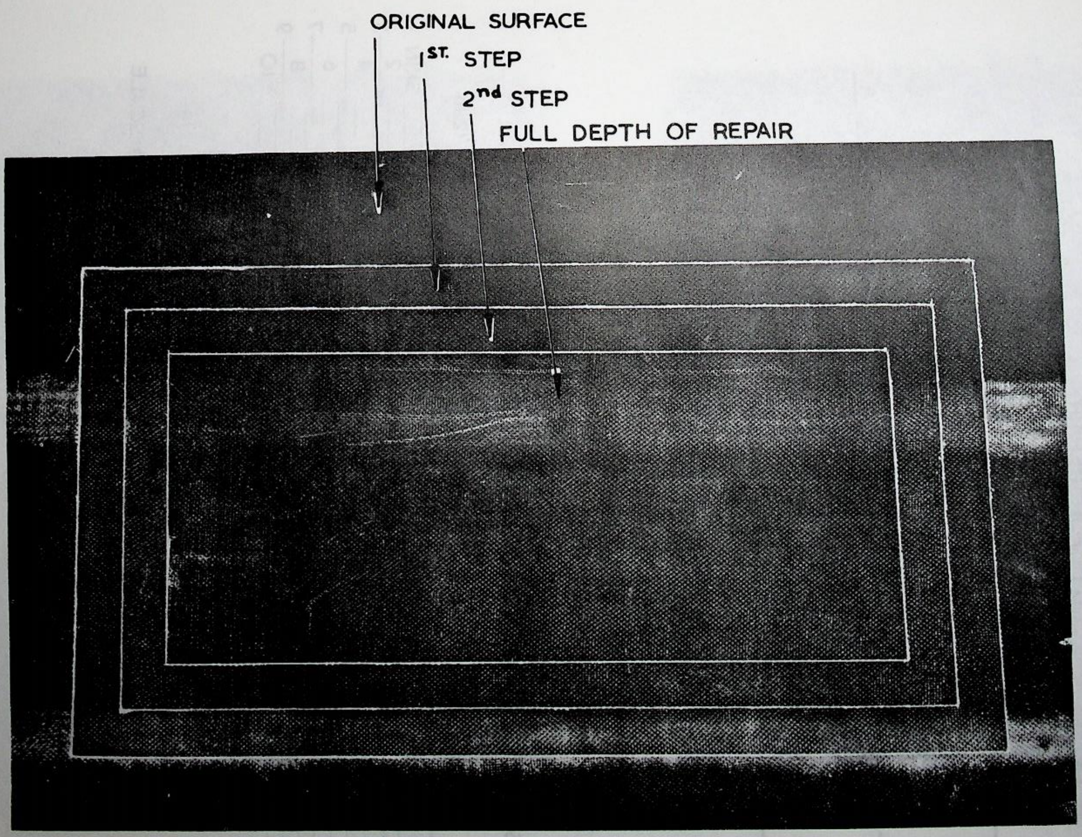
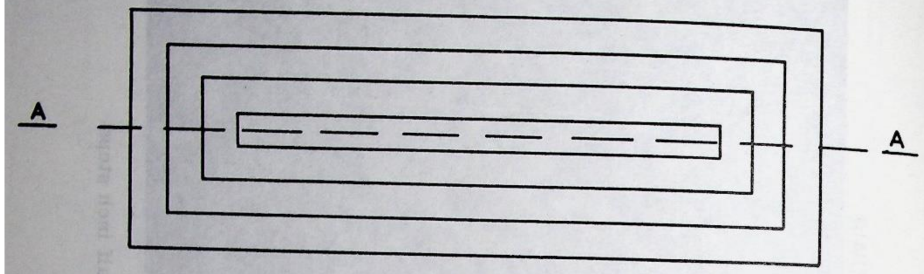
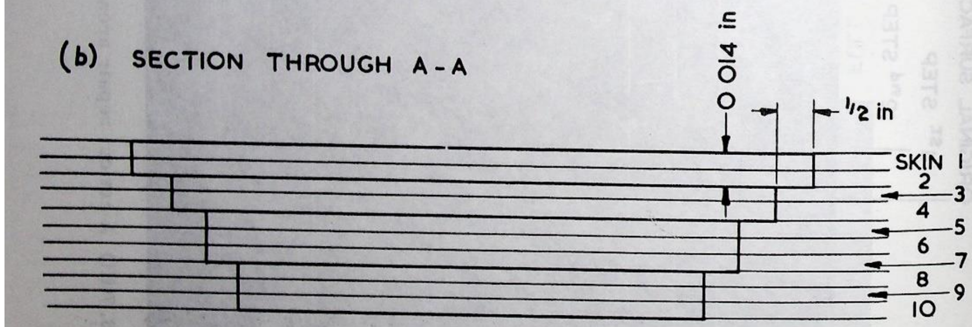


Fig. 8.7(iii) A cut out repair area showing the half inch steps

(a) PLAN VIEW OF PORTION OF VESSEL CUT FOR REPAIR



(b) SECTION THROUGH A-A



NOT TO SCALE

Fig. 8.7(iv) Typical repair profile

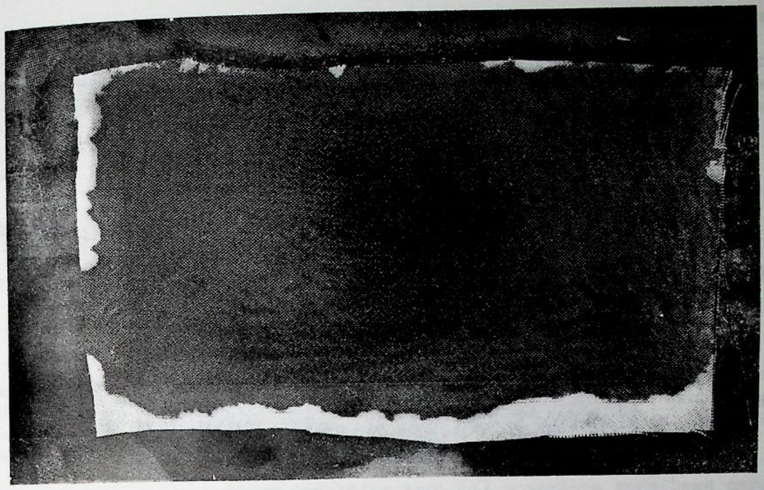


Fig. 8.7(v) Final stage of repair.

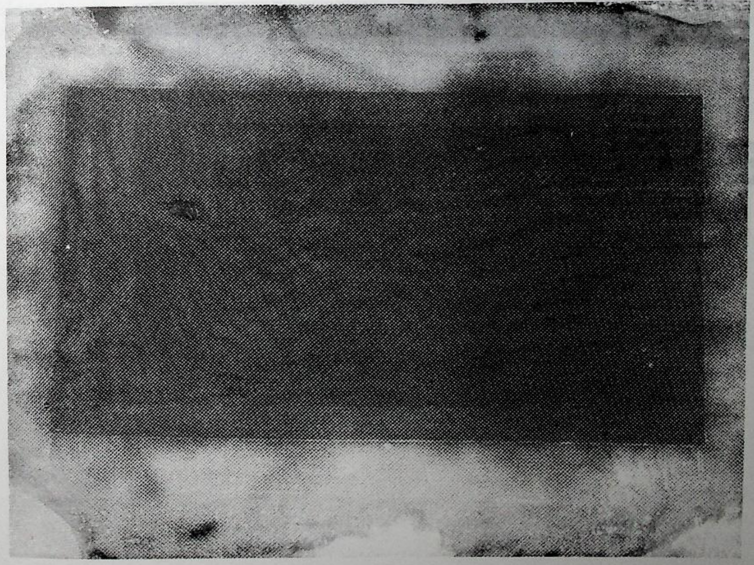


Fig. 8.7.(vi) A completed repair.

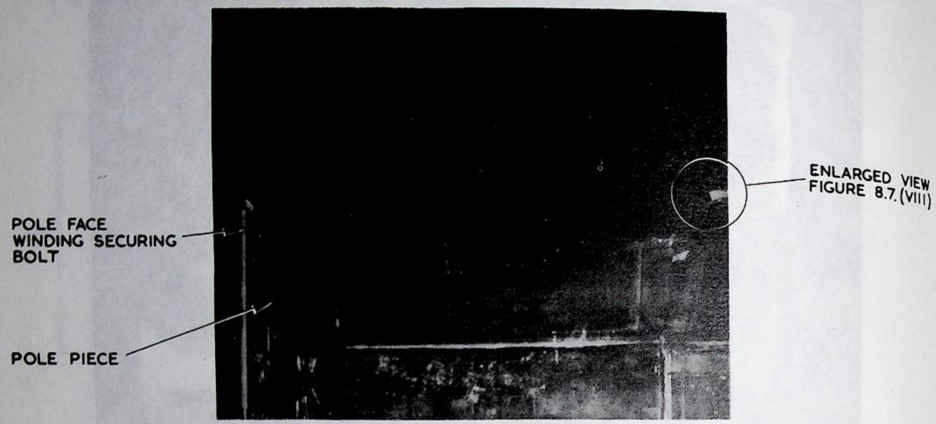


Fig. 8.7(vii) Accidental damage to an outer vessel.

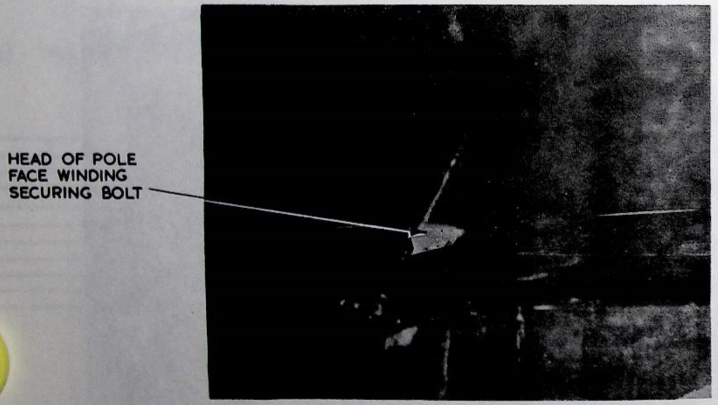


Fig. 8.7(viii) An enlarged view of the damage.

repair resin, fitted into the cut back area and tailored to size. Each layer was rolled to consolidate the repair and remove excess resin. This procedure was repeated until the area was built up to the level of the surrounding laminate. An additional skin larger than the repair was then added (Fig.8.7(v)) and was removed after curing (Fig.8.7(vi)). This gave an even finish and prevented drainage during the curing procedure. Temperature controlled electric blankets were used in curing the repairs.

(ii) Voids in laminate.

When no other fault was evident, voids were filled with the approved resin using a hypodermic needle or a grease gun.

(iii) Leakage round drilled holes due to hollow fibres.

Apart from flange bolt holes, where leaks were eliminated by fitting brass sleeves (see section 8.6.2), there were many larger diameter drilled or machined holes in the laminate where sleeves could not be used. Many of these holes were associated with vacuum seal surfaces and by using the surface coating material, thinned with 10% solvent, the leaks were dealt with satisfactorily.

To date about 130 repairs involving type (i) procedure have been carried out. Details are being published (15). A typical example of accidental damage is illustrated in Fig.8.7(vii) and Fig.8.7(viii). A pole face winding securing bolt was incorrectly placed between two pole tips (removed from the photograph for clarity). The rectangular head, with its long side at right angles, instead of parallel, to the pole tips was driven through the outer vessel laminate in the narrow gap between adjacent magnet sectors. It proved possible to slide a thin backing plate between the vessel and the sectors and a satisfactory repair was made without removing the vessel. This was extremely useful since the installation of pole tips in this octant was almost completed and to remove and replace the vessel with its 350 seals and 84 pole tips, positioned to an accuracy of a few thousandths of an inch would have lost a great deal of time.

8.8. Radiation Damage

A programme of high level radiation dosimetry has been instituted, to determine the rate of degradation of the vacuum vessels under radiation. Commercially available glass dosimeters do not register sufficiently high doses for our requirements and methods involving the change in the modulus of rubber and the change in optical behaviour of polystyrene, are being studied.

Samples of vacuum vessel material, suitable for mechanical testing, have been placed in the cavity between the inner and outer vessels during assembly and further samples, with stainless steel foil and aluminium foil on opposite surfaces, are being placed on the floor of the inner vessel.

Groups of rubber samples and strips of polystyrene are being placed at intervals on the floor of the inner vessel. They will be used to measure radiation doses up to at least 100 Mrad and will indicate when the properties of the vessel material dosimeters should be examined.

The mechanical properties of the vessel material samples will be determined at approximately 250 Mrad intervals, except for those placed within the pole piece cavity which will be examined as the opportunity arises. The outer vessel is substantially shielded by the pole pieces so that monitoring will be needed less frequently. To ensure maximum life from each vessel, targets and/or vessels may be rearranged if the dosimeter investigations show this to be necessary.

8.9. Main Vacuum Seals

8.9.1. Choice of Materials

The principal considerations in choosing the materials for the main vacuum seals were outgassing rate and irradiation stability. Outgassing rate was of greater importance than is usual for vacuum seals since the vacuum vessels are allowed wider engineering tolerances than metal fabrications and larger areas of the seals may be exposed to the vacuum.

Due to the complex nature of rubber formulations, an indication of their relative outgasing rates could only be obtained by examining the raw polymer forms. Outgassing measurements were therefore carried out on sheets of uncured polymer 3 mm thick. The following polymers were studied - isocyanate, butyl, neoprene, butadiene acranitrile, butadiene styrene, silicone, ethylene propylene and natural rubber. The results are shown in Fig.8.9.1(i). The silicone polymers were eliminated because of their high gaseous permeability and isocyanate polymer appeared to be the most satisfactory. The stability of this material under irradiation was determined and the results are shown in Fig.8.9.1(ii). The material still has adequate properties at integrated doses of 10^8 rad. However, it subsequently proved to be impracticable to manufacture the seals from this material, since the only method of fabrication was a casting technique. Difficulties were also experienced in producing satisfactory joints between the cast sections. Polyurethane materials, which can be moulded by standard rubber processing techniques, were therefore examined but did not have the required properties.

The material finally chosen was a polymer mixture known as PVC nitrile, which had the desired vacuum properties combined with satisfactory stability under irradiation (Fig.8.9.1(iii)) and could be processed by normal rubber moulding techniques.

8.9.2. Manufacturing Processes

The first manufacturing procedure considered was to extrude the profile and subsequently mould the ends, making four joints on each seal. Experiments with extrusion techniques indicated however, that the polymer would not have a satisfactory surface finish when produced by this method. It was necessary therefore, to mould the vacuum seal in 4 ft lengths and join these to produce the 50 ft sections. Preliminary mouldings suffered from severe mould corrosion due to the liberation of hydrochloric acid in the moulding process which gave a poor surface finish. All the tools used in the operation were chromium plated to reduce this effect. Changes were made in the plasticiser content and type and a better surface quality was produced. These changes did not materially affect the outgassing characteristics or the stability of the polymer under irradiation.

Experiments were carried out to determine the most satisfactory method of jointing. Various techniques were tried and a butt joint proved to have properties most near those of an unjoined seal. A joint strength 60% that of the parent material was regarded as acceptable (tensile strength of the parent material was 1900 lb/in^2). Experiments with scarf joints experienced difficulty in the moulding process. The moulded sections were forced out of the mould, resulting in a low pressure area with entrained air at the joint, which was also outside dimensional tolerances.

The following technique was finally evolved and produced satisfactory joints in nearly all cases. The ends of the moulded sections were carefully cut at 90° and coated with a solution of uncured polymer in 50-50 acetone/tetrahydrafuran. They were left for 15 min to permit the solvent to evaporate before being placed in the mould at 150°C and pressed at 1,000 lb/in^2 for 8 min. The joint was then dressed down using 400 grade 'wet and dry' emery paper and water to give a satisfactory vacuum sealing surface. Experiments showed that the double cure in the area of the joint did not materially affect the properties of the finished product.

8.9.3. Properties of the Final Material

The material had a tensile strength of 1900 lb/in^2, an elongation at break of 450%, a hardness of 60° Shore and a compression set of 17%. Table 8.9.3(I) illustrates how the properties change with irradiation dose.

TABLE 8.9.3(I)

Dose (rad)	Hardness (°Shore)	Tensile strength (lb/in^2)	Elongation (%)
0	60	1900	456
5. 10^7	85	1900	107
10^8	100	3240	30
5. 10^8	100	7856	75

Table 8.9.3(II) shows the effect on compression set of various cure times since, as indicated in 8.9.2, the seal will have a cure time of 16 min at 150°C in some cases.

TABLE 8.9.3(II)

Cure Time at 150°C (min)	Recovery after 25% compression for 24 hours at 80°C (%)
8	90
16	89.2
24	87.0

The recovery is significantly affected by irradiation as can be seen from Table 8.9.3(III)

TABLE 8.9.3(III)

Dose (rad)	Recovery after 25% compression (%)
0	90
5. 10^7	81
10^8	74
5. 10^8	70

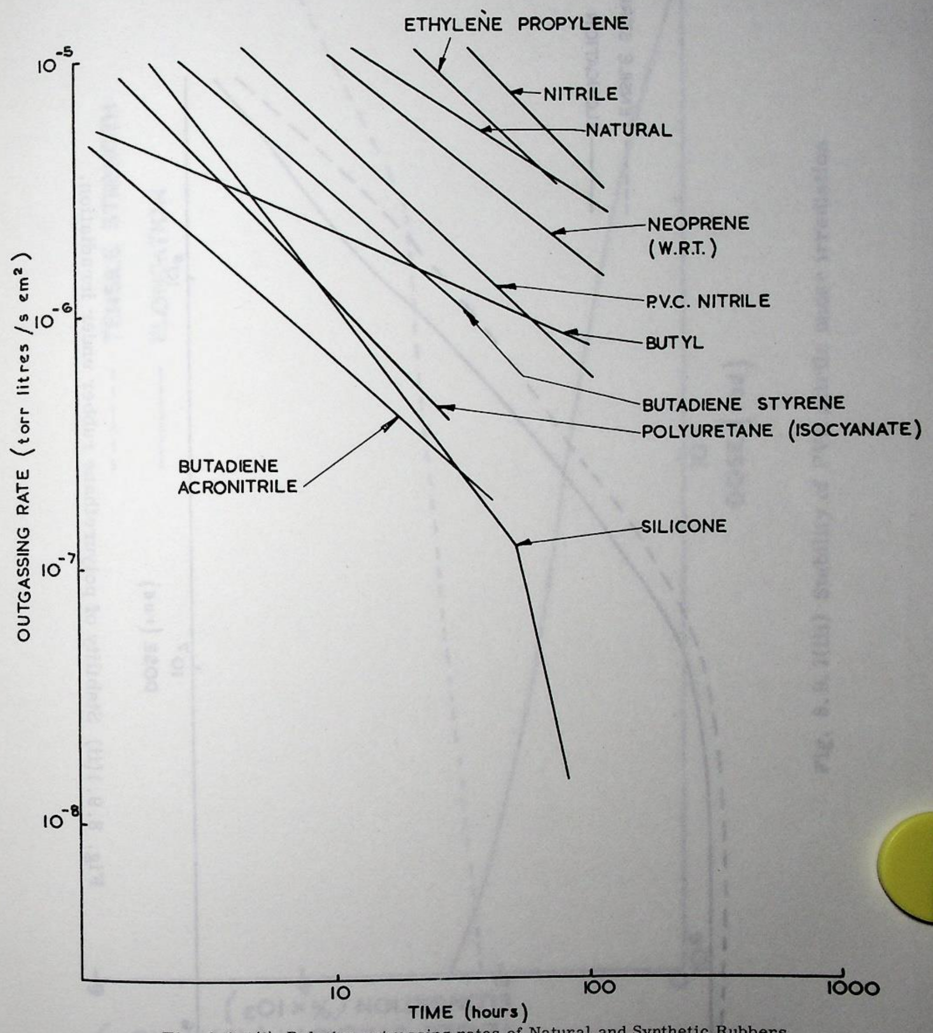


Fig. 8.9.1(i) Relative outgassing rates of Natural and Synthetic Rubbers.

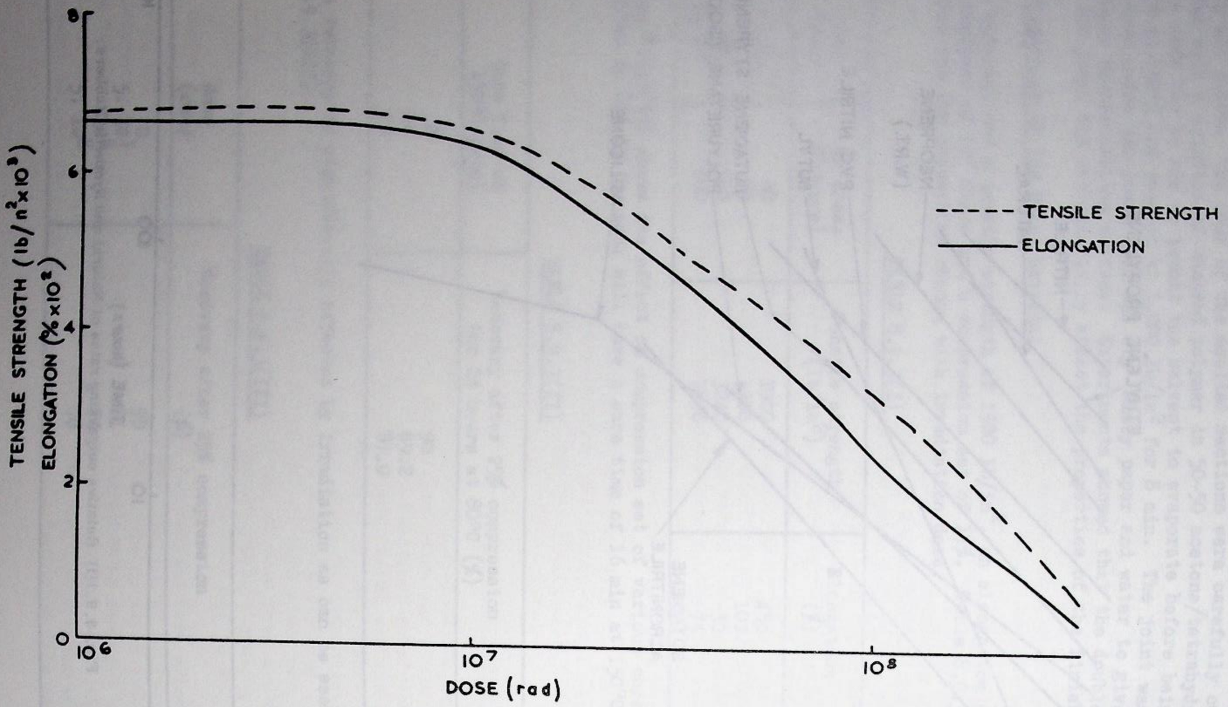


Fig. 8.9.1(ii) Stability of polyurethane rubber under irradiation.

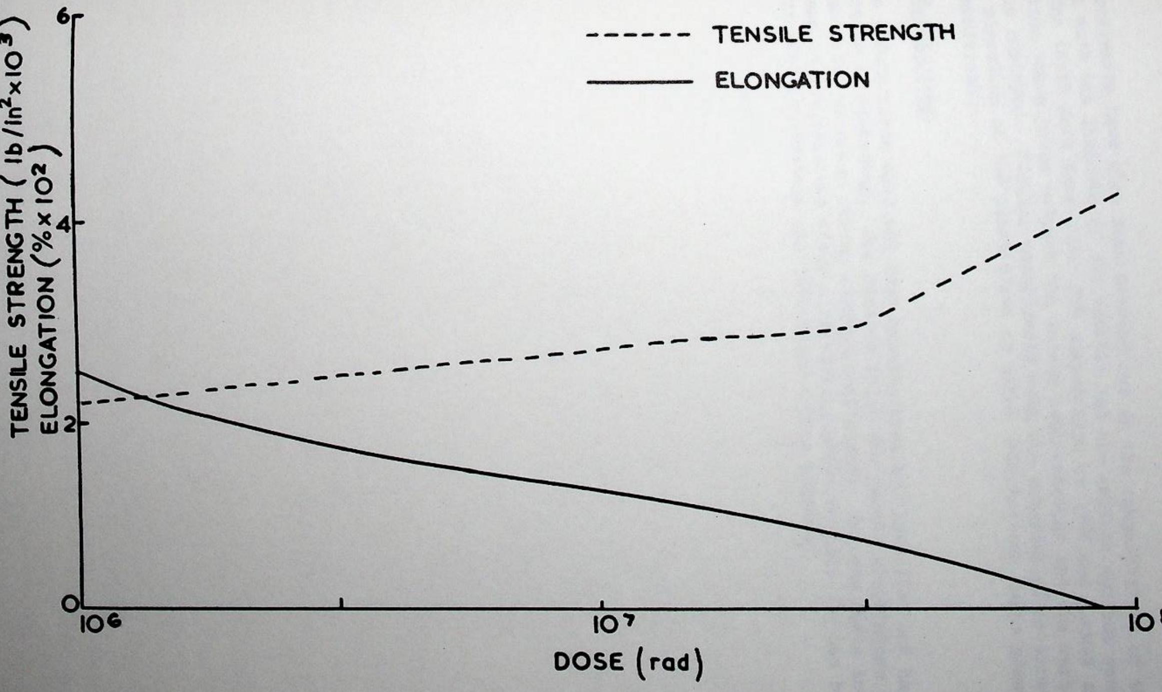


Fig. 8.9.1(iii) Stability of PVC nitrile under irradiation

Experiments have also been carried out on the compatibility of the vacuum seal material with the laminate of the vessels and the various surface coating materials used. The tests were done under 25% compression at 35°C and showed that no interaction takes place between the vacuum seal material and the various coating materials employed. Similar experiments with the material after irradiation showed that no migration of the plasticiser or other interactions takes place, even under these conditions.

8.9.4. Conclusions

The vacuum seals have now been manufactured and installed and have proved satisfactory in operation. One feature which has proved troublesome is the tendency of the material to creep during storage, sufficiently for the seals to be outside the dimensional tolerances after a relatively short period. It has been necessary to ensure that no stresses are introduced during storage.

8.10. Pumping System

8.10.1. Introduction

The theoretical considerations leading to the final choice of the main pumping units for the vacuum vessels have been discussed in reference 4.

Each of the 40 pumping units (Fig.8.10.1(i)) was specified to have a speed of at least 5000 litres/s for most of its pressure range, giving a total speed of 200,000 litres/s. However, at the machine operating pressure, 10^{-6} torr, the minimum overall speed of the system is only 100,000 litres/s which is equivalent to a throughput of 0.1 torr litre/s. The vacuum torus has a volume of about 100,000 litres and a general rule calling for 1 litre/s pumping speed for each litre of volume is therefore satisfied at the operating pressure.

Only 1% of the internal surface area of the inner and header vessels is epoxy resin laminate, not coated by stainless steel. Early work indicated that after 24 hours pumping most epoxy laminates had outgassing rates of the order of 10^{-6} torr litres/s cm^2 compared with 10^{-9} torr litres/s cm^2 for stainless steel. Calculations assuming that eight header vessels would be used gave the following results:

TABLE 8.10.1(I)

Material	Total Surface Area (cm^2)	24 Hour Outgassing Rate (torr litres/s cm^2)	Total Outgassing (torr litre/s)
Stainless Steel	6.4×10^6	10^{-9}	6.4×10^{-3}
Epoxy resin	6.4×10^4	10^{-6}	6.4×10^{-2}
			Total 7.0×10^{-2}

This total outgassing figure represents 70% of the available throughput at 10^{-6} torr. An allowance of 10% was arbitrarily made for leaks, leaving a 20% excess for future degradation. The final choice of epoxy resin showed a much better initial outgassing rate (almost 4×10^{-7} torr litres/s cm^2 after 24 hours) but a slightly higher rate (2×10^{-6} torr litres/s cm^2) after an irradiation dose of 10^9 rad. After this dose the mechanical properties of the laminate also became suspect so that the increase in pump down time would be a secondary consideration.

8.10.2. High Vacuum Pumps

Each pumping unit (16) consists of a 24 in bore sliding gate valve, a refrigerated chevron baffle, and a 24 in bore fractionating oil diffusion pump backed by a vapour booster pump and a rotary pump of 150 litres/min capacity. The gate valve is rigidly fixed to the header vessel by a two part header Fig.8.10.2(i), the part nearest the magnet being made of stainless steel and the lower part made of mild steel. Because of this rigid fixing, the pumping unit must be supported so that it is free to move with the header vessel under temperature variations. This is achieved by suspending the gate valve on four short wire ropes from cantilevers fixed to the magnet sectors and by supporting the frame of the pumping unit on four steel balls. The load on the steel balls can be adjusted to be a minimum by means of jacks which react with the outer part of a frame which is carried by four wheels. This carriage moves on rails fitted to the edges of the services trench encircling the magnet.

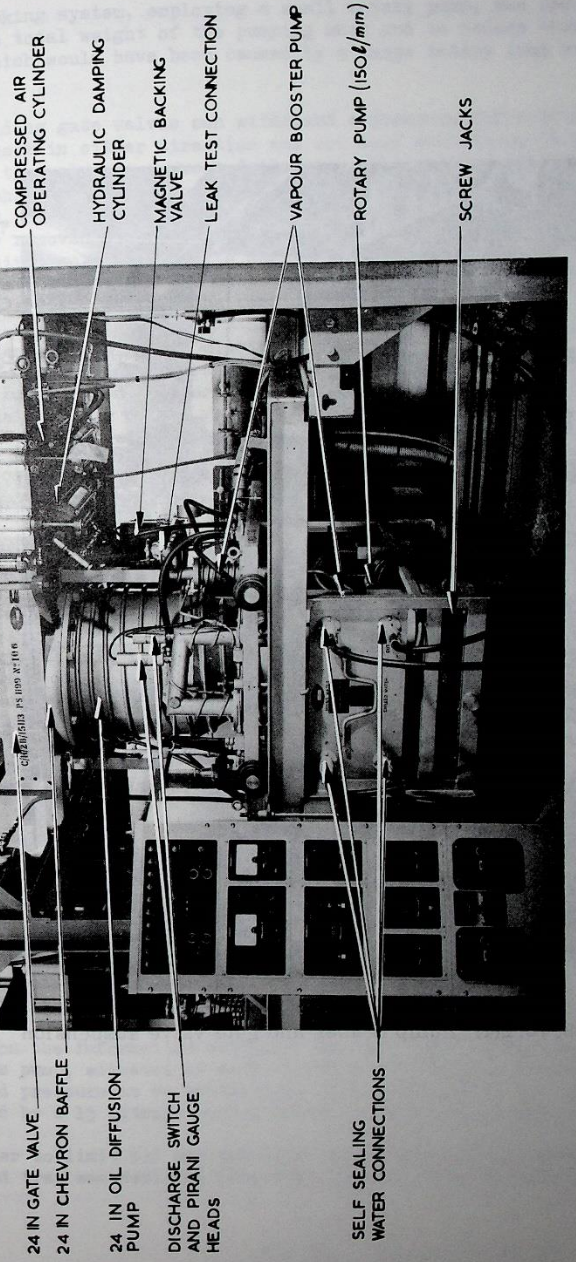


Fig. 8. 10. 1(i) 24 in oil diffusion pumping unit

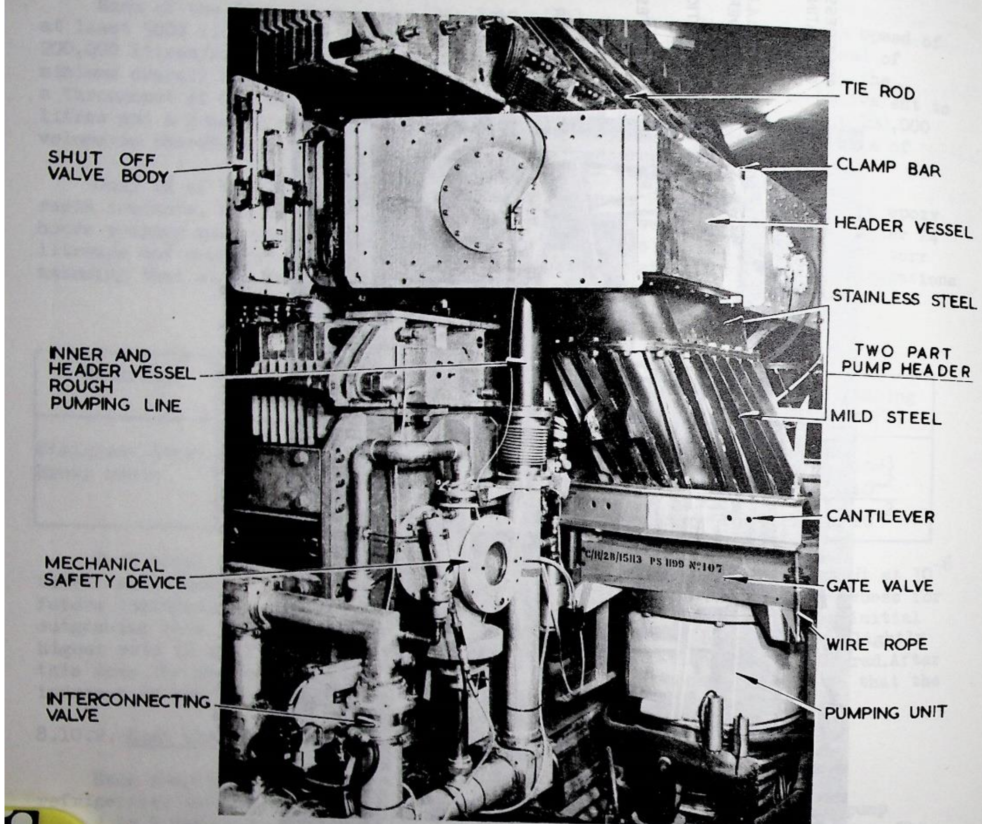


Fig. 8.10.2(i) Pump header and gate valve suspension

The backing system, employing a small rotary pump, was specially chosen to minimise the total weight of the pumping unit and to reduce substantially the vibration which would have been caused by a large rotary pump with no vapour booster pump.

The sliding gate valves can withstand a pressure differential of one atmosphere across the seat in either direction and are self sustaining in the closed position. This allows the valve to serve a dual role. The pumping unit may be isolated from the vacuum chamber and remain operating while the chamber is let up to atmospheric pressure and, alternatively, a faulty unit may be isolated from the system and subsequently removed and replaced. Services to the unit, such as water and compressed air, are provided with self sealing couplings and the jacks and wheeled carriages are used to free the unit from the gate valve and to move it to one side, where it can be hoisted from the services trench by crane.

The rates of opening and closing of the gate valve can be separately adjusted at the hydraulic damping cylinder so that fast closing (less than 10 s) and slow opening can be achieved. In order to limit the gas load on the pumping units during initial pumping of the vacuum chamber from the roughing pressure of 10^{-2} torr, the rate of opening of the valve was set such that the conductance of the aperture did not exceed 500 litres/s in the first minute, the valve taking about 30 min to open fully. In this way it was estimated that the maximum throughput of each unit (about 5 torr litres/s) would never be exceeded.

The four stage oil diffusion pump has an integral guard ring which gives a low backstreaming rate of about 5 μ g/min cm^2. This is further reduced by the chevron baffle which is cooled to -25°C. No measurement of the overall backstreaming rate has been attempted so far.

Each pumping unit is provided with a separate control console which houses the local operating controls and the power units for all the subsidiary items of pressure measurement and switching. The unit must be able to be controlled either locally or from the control room. The control system is therefore automatic and is arranged to follow a predetermined sequence of operations to avoid mal-operation. It is designed to 'fail-safe' wherever possible. A fuller description of the control system is given in section 9.2 and reference 16.

8.10.3. Roughing Pumps

Early thoughts on the rough pumping system centred on a scheme for a single walled vacuum vessel and employed only a single set of pumps. The pressure was required to be about 10^{-2} torr so that a small rotary pump could be used to meet the mechanical requirements of small vibration and weight in the high vacuum units when suspended from the header vessels. To achieve this pressure the use of mechanical booster pumps was necessary. These pumps were to be sited in the concrete monolith cavities and would therefore have pumping lines longer than 25 ft.

Based on the information available at that time, it was estimated that one 100 litres/s pump, situated at each straight section, would be sufficient to enable the required pressure to be maintained. The final choice fell on a Rootes type pump, backed by a 15 litre/s rotary piston pump (Fig.8.10.3(i)).

In order to limit oil contamination from the roughing pumps, a special refrigerated trap was designed (Fig.8.10.3(ii)). This operates at -50°C and serves as a backstreaming baffle and stops the film of oil creeping along the surface of the roughing line.

When the design of the vessels and pole tips was finalised, a re-assessment of the rough pumping requirements was made. The pole tip laminations had many perforations exposing a larger area of the epoxy resin used for bonding the laminations. The pumping aperture circumferentially round an outer vessel was limited and pumping could only be allowed from the ends of each octant. Bearing in mind the early difficulties in testing the prototype outer vessel, it was thought that a reasonable pump down time could not be expected if the outer and inner vessels were pumped together to a pressure of 10^{-2} torr.

It was therefore decided to provide additional pumping units which would continually evacuate the outer vessels. No advantage could be seen in achieving a pressure lower than 1 torr since this was adequate for the mechanical protection of the inner vessel and inter-vessel leaks would not be substantially reduced by a lower outer vessel pressure. A rotating vane type pump (60 litres/s) was provided at each end of each outer vessel. These pumps were fitted with refrigerated traps similar to those on the inner vessel roughing pumps.

Fig.8.10.3(iii) shows the rough pumping pipe line layout indicating the valves and pressure switches provided. All roughing and equalising valves are solenoid controlled, pneumatically operated, 4 in nominal bore, quarter swing valves and the air admittance valve is 1 in, magnetic. Provision has been made for connecting the air admittance valves to a dry air supply (-40°C dew point) fed from a ring main.

Each pump has associated with it a capsule pressure switch, set at a relatively high pressure (15 torr) which simply ensures that the pump is working before the roughing valve can be opened. This pressure switch is then bypassed electrically. Each pump can be started locally from its own control panel but valves are only operated from a central marshalling kiosk in the magnet room.

8.10.4. Interlocks and Safety Devices

When the vessels are being pumped down, it is imperative that the separate pumping arrangements for outer and inner vessels are interconnected so that no pressure difference sufficient to cause damage to the inner vessel arises between the vessels. A specially developed thermistor type pressure switch (17) (Fig. 8.10.4(i)) has been fitted and interlocked so that the equalising valves remain open so long as any switch indicates a pressure greater than 1 torr. When this pressure is achieved the equalising valve closes automatically and the inner vessel can be pumped to 10^{-2} torr by its mechanical booster pumps.

Further pressure switches of the thermistor type then operate to complete an interlock circuit which allows the high vacuum valves on the main pumping units to be opened, provided that the inner roughing valves have closed. This sequence is assured by the use of a rotary switch to select 'Off', 'Rough Vacuum' or 'High Vacuum', all octants being controlled simultaneously from a marshalling kiosk in the Magnet room.

The thermistor switches were duplicated by providing switches performing the same function at each end of an octant and these, and other interlocks were connected in series chains so that every octant required to be in the same pressure state before the next stage of pump down could begin. It was thought advisable to arrange for all octants to operate together to safeguard the vacuum vessel,

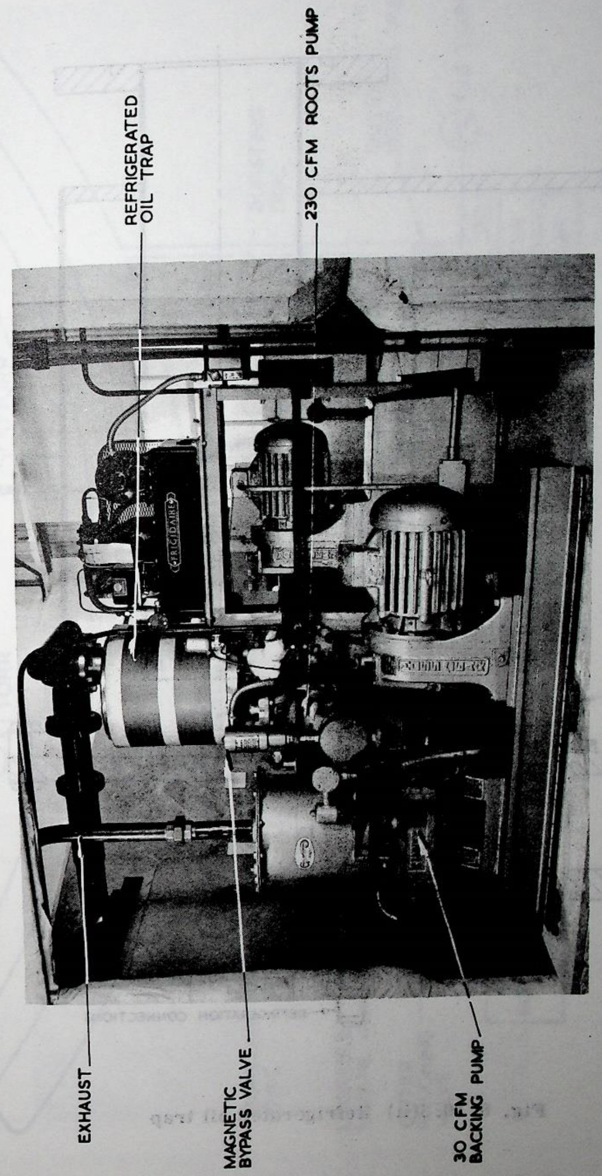


Fig. 8.10.3(i) Inner vessel roughing pump.

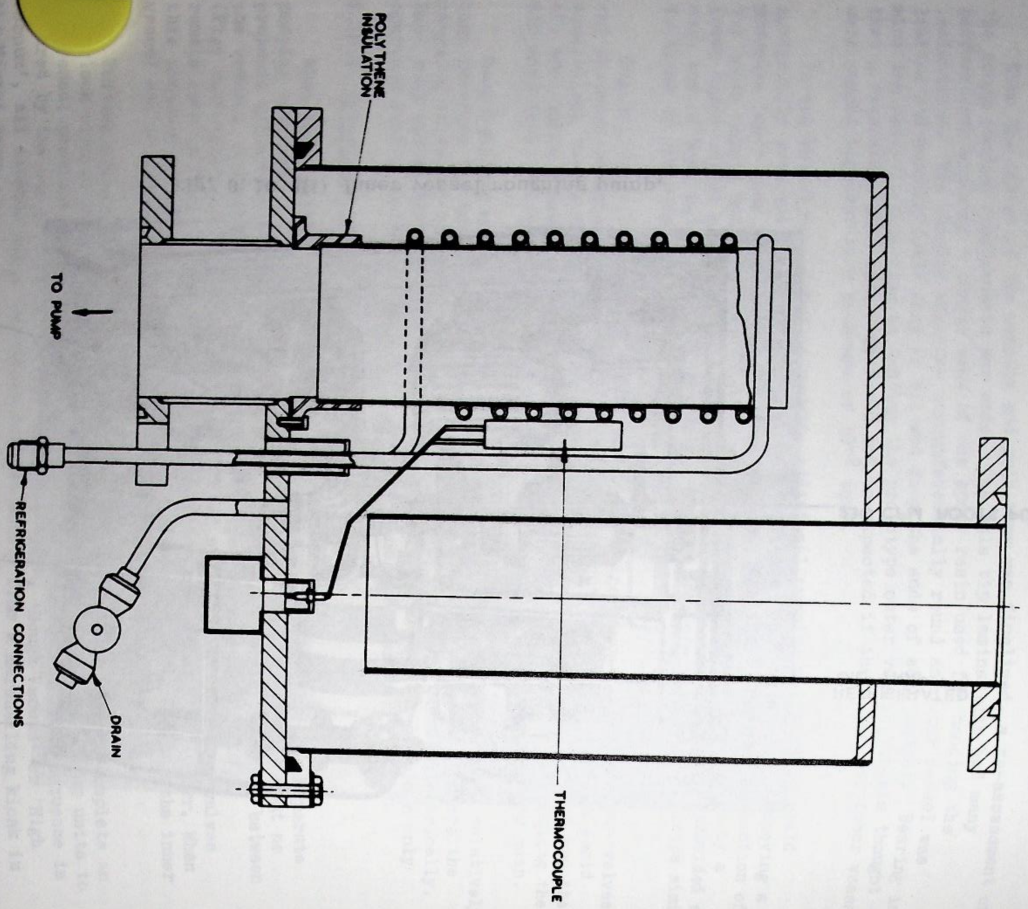


Fig. 8.10.3(ii) Refrigerated oil trap

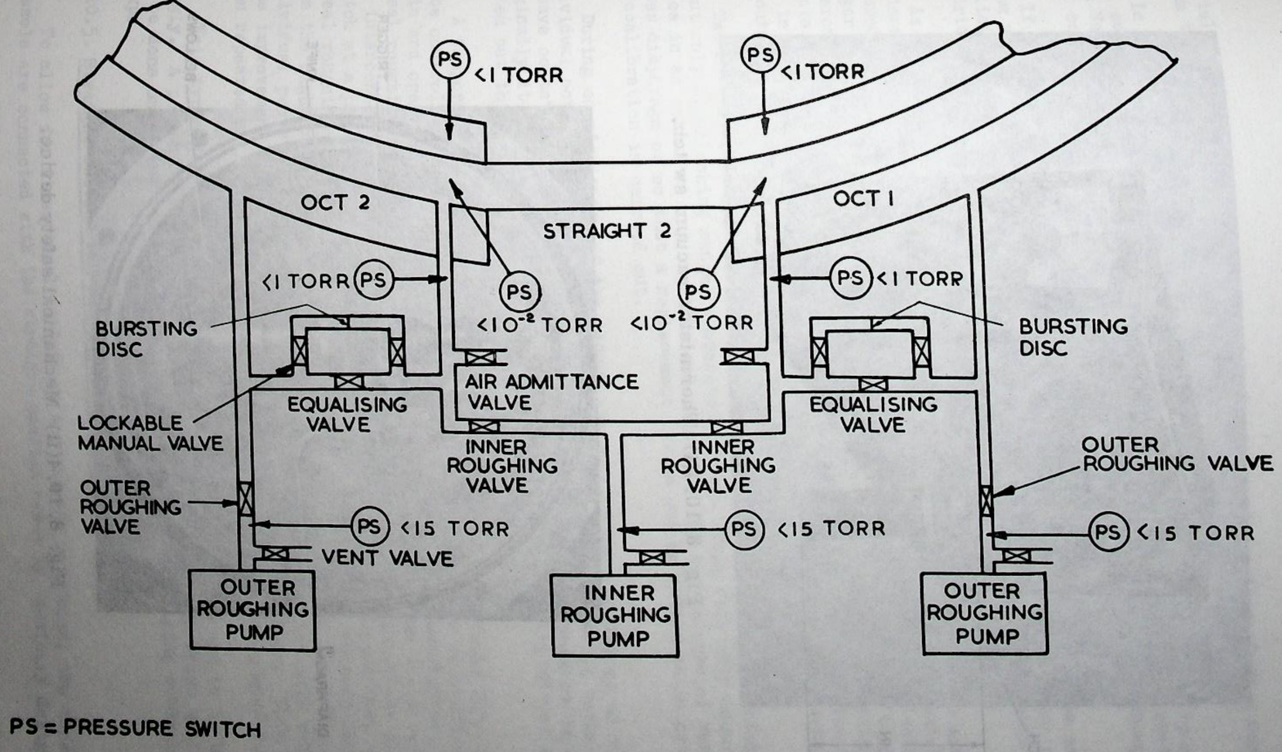


Fig. 8.10.3(iii) Layout of roughing system

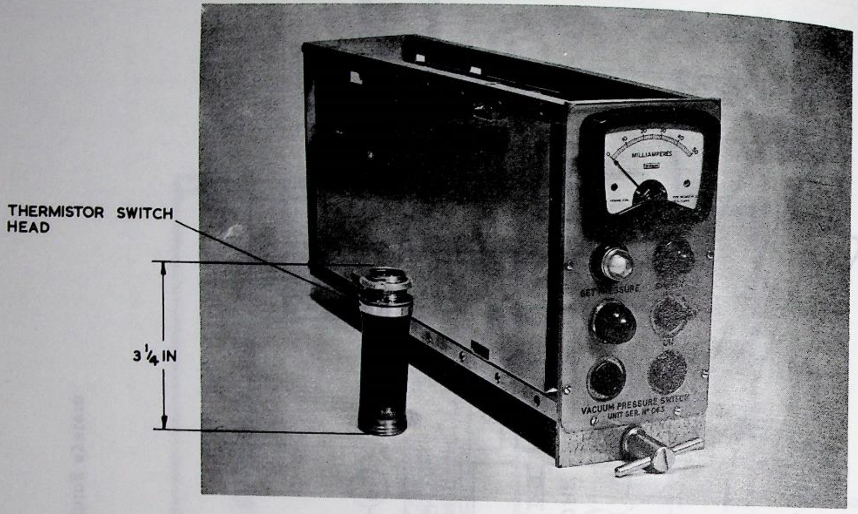


Fig. 8.10.4(i) Thermistor vacuum switch.

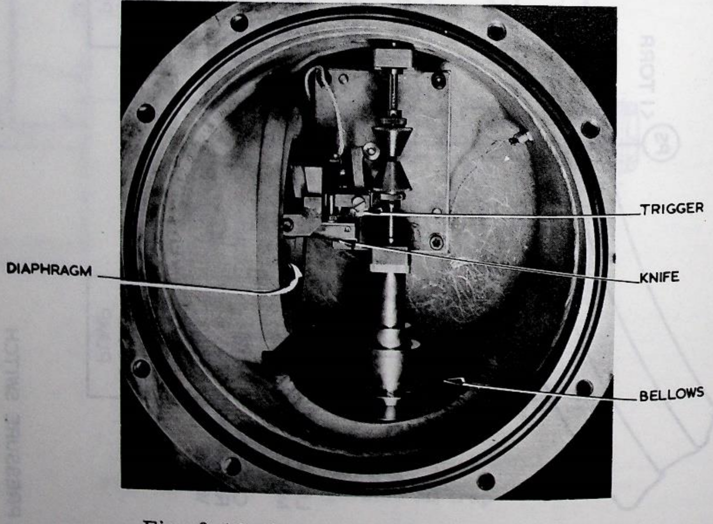


Fig. 8.10.4(ii) Mechanical safety device.

especially since the inner vessel, with the straight sections, form a continuous vacuum torus.

In the 'Off' position, air admittance valves are not automatically opened, final energising of the solenoids being controlled by a key operated switch. In the 'High Vacuum' position, each high vacuum valve is opened from the pumping unit, local control console.

If failure of the electricity supply occurs, all equipment 'fails safe' - high vacuum valves, roughing valves and air admittance valves close (or stay closed) and equalising valves open. Each roughing pump has a vent valve which opens after an electrical delay, to allow time for the roughing valves to close.

As a further safeguard for the inner vacuum vessel, a mechanical safety device was developed.(18) This consists essentially of a copper diaphragm which can be ruptured by a spring loaded knife (Fig.8.10.4(ii)). The knife is released by a trigger which is actuated by movement of a bellows when subjected to high pressure difference between the inner and outer vessels. The device is calibrated to operate when the pressure in the outer vessel exceeds that in the inner by 6 torr and, in the reverse sense, when the pressure in the inner vessel exceeds that in the outer by 30 torr.

Two such devices are provided on each octant. They can be isolated from the octant only by unlocking manually operated valves. This will only occur on one device in an octant at any one time and then only for the purpose of replacing the copper diaphragm or so that a replacement device can be fitted while maintainance or recalibration is carried out.

During commissioning of the vacuum system it became necessary to evacuate individual octants to carry out the vacuum tests on the installed vessels and also to have octants 8, 1 and the inflector system evacuated for machine experiments. Originally it was thought that incomplete octants could be shorted out of the control system but this did not allow sufficient flexibility.

A temporary control panel was therefore set up which allowed Octants 8 and 1 to be controlled separately. The appropriate interlocks were detached from the main chain and operation of the vacuum valves was controlled by push button. The inner vessel roughing pumps were not used so that the control system could be kept simple. The interconnecting valves were kept open by isolating an appropriate pressure switch at a pressure above 1 torr and the inner vessel was pumped down by the outer vessel roughing pumps. Pressures of about 0.06 torr can be achieved in this way. When the high vacuum pumps are connected, the throughput soon becomes too high for individual pumps and the protective pressure switches close the gate valves, though some improvement in the vessel pressure occurs before they close. This process is then repeated until the valves remain open and the octants are pumped down.

This type of control has now been extended to allow any octant to be operated singly. A permanent system of control is under consideration which will allow work to be done on a single octant as well as providing the full ring control using all pumps.

8.10.5. Straight Section Box Pumping Arrangements

To allow for dimensional variations and thermal expansion, the inner and outer vessels are connected with the straight section boxes by specially designed stainless steel bellows assemblies. These are essentially of two types (See Fig.8.10.5(i)). One type has a U section convolution joining the inner and outer vessels and the other with a double omega section convolution connecting the inner vessel to the straight section box. In the longer straight sections, shut off valves are interposed between the two bellows assemblies. In the shorter straight sections the two bellows types are integrated in one assembly.

The shut off valves consist of a body and a valve housing. The bodies are permanently fitted in the ring, two in each long straight making eight in all. The housing, which contains a valve plate and winding mechanism, can be attached to the body so that when the valve is closed it will withstand atmospheric pressure across its seat from one direction which can be chosen. The valve may be introduced into a body when it is under vacuum by using a vacuum lock principle, a flap on the body being controllable by a lever on the housing (Fig.8.10.5(ii)).

A reassessment of pumping requirements was made when the amount of experimental and diagnostic equipment to be fitted in the straight section boxes was known more accurately.

Electrodes with a large surface area, supported on insulators, are to be installed in several straights. On average, the total surface area (mainly of mild steel and aluminium) involved in one straight is about 5 x 10^5 gm^2 and a typical outgassing rate for these materials, even after 48 hours, is 10^{-8} torr litres/s cm^2. A straight section box could therefore contribute 5 x 10^{-3} torr litre/s to the gas load on the adjacent octant pumps. This represents 40% of the total pumping capacity of one octant at 10^{-6} torr and is a greater fraction of the capacity than could reasonably be allocated for this purpose, especially since the calculation is based on 48 hours pumping, which is at least twice as long as is desirable.

It was decided to obtain additional pumps to be mounted on the straight section boxes. The largest pumps which could be fitted without conflict with plunging mechanisms, beam outlet windows, etc., are of 12 in nominal bore. Two pumping units of this size have been obtained for each of six straights. Straight 8, which has the r.f. accelerating cavity, cannot be fitted with extra pumping but it has a relatively small vacuum chamber. Straight 1 had already been supplied with one 16 in pumping unit (2.250 litres/s at 10^{-6}) to replace a 24 in pumping unit which was displaced from octant 1 by a diagnostic probe assembly. All those units have similar control systems.

During proof tests of the 24 in units fitted on the octants, the pumping speeds were generally found to be higher by 20% than the specified minimum at 10^{-6} torr. This gives a useful margin and together with the additional pumps in the straight sections should allow the operating pressure to be achieved within 24 hours of the start of pumping.

Some pumping units have already been in almost continuous operation for 4 years and have performed remarkably well. A number of faults have occurred, mainly in the control equipment. The most important have been the unreliability of the cold cathode ion gauges and the hot wire switches used for pressure control. The ion gauges have been improved by modification and the switches require frequent re-calibration. Both devices may be replaced.

8.10.6. Arrangements for Diagnostic Equipment and Targets

Diagnostic probes and targets are introduced into the vacuum system through a

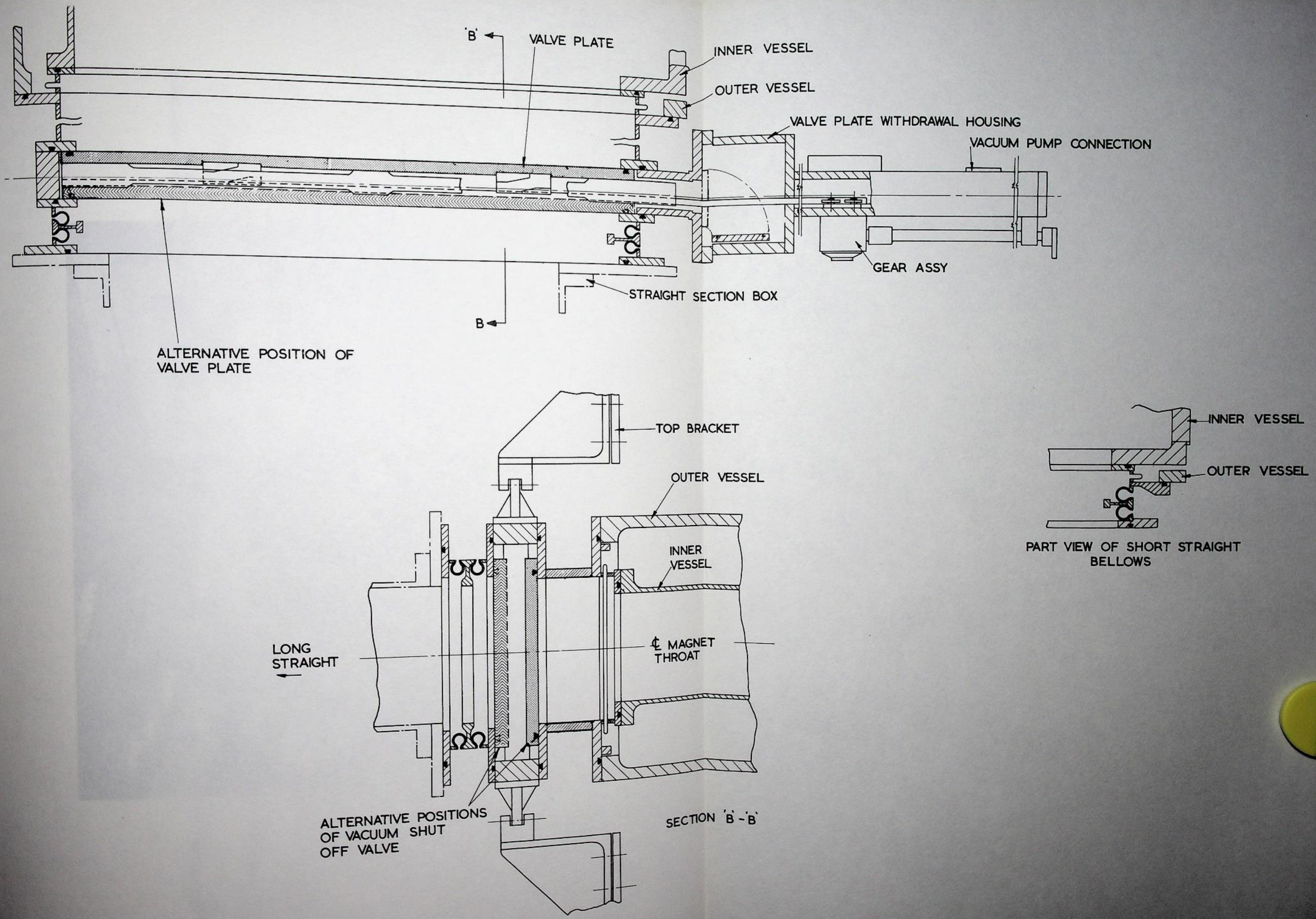


Fig. 8.10.5(i) Assembly of bellows, adaptors & vacuum shut-off valve to vacuum vessel in a long straight section.

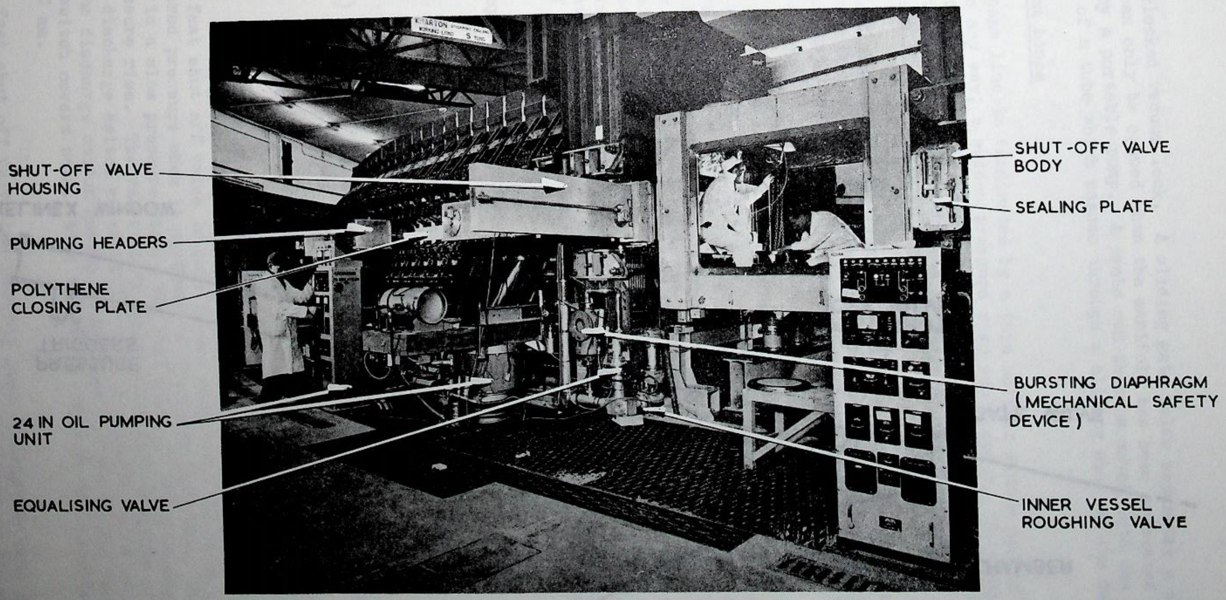


Fig. 8.10.5(ii) Shut off valve housing and body sealing plate.

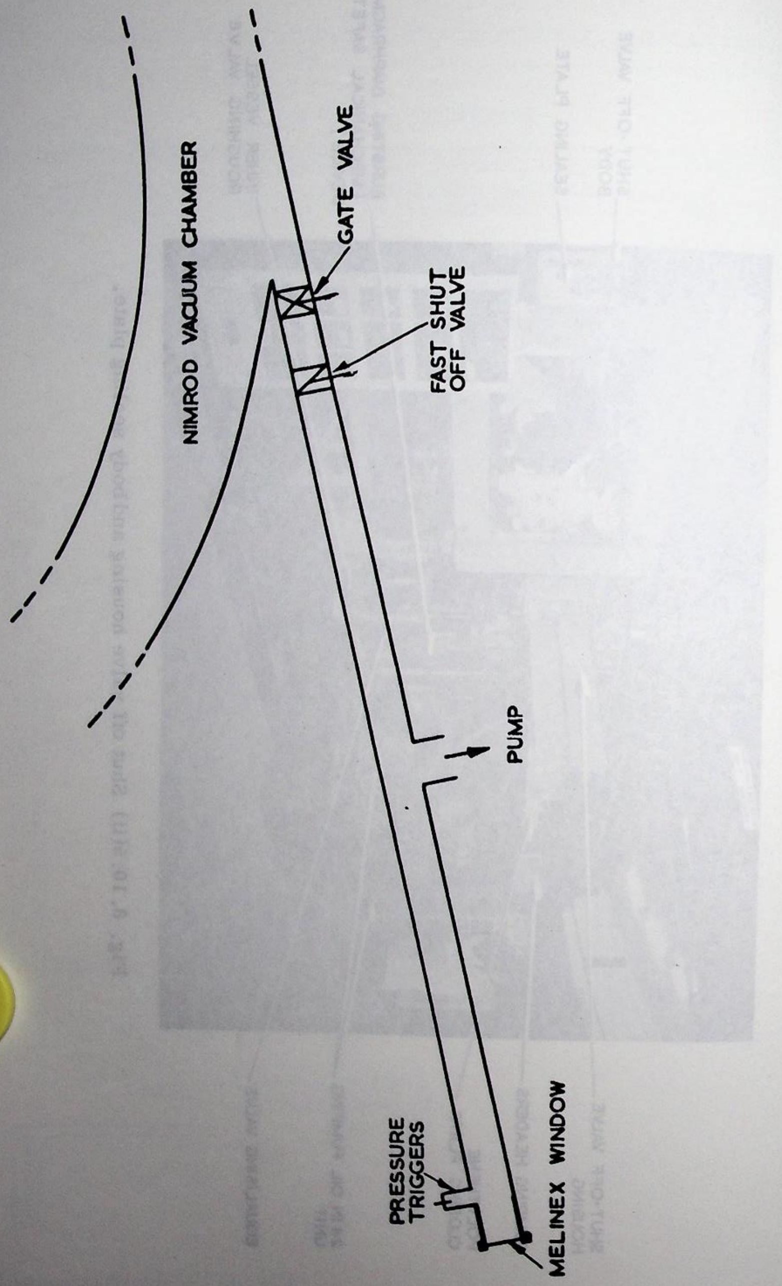


Fig. 8.10.7(i) Schematic layout of a typical beam line vacuum system

fully interlocked vacuum lock. A sliding gate valve separates a manifold from the torus and can only be opened when the manifold has been evacuated to a pressure of 10^{-1} torr by a portable pump. A probe can then be moved into the magnet aperture on the end of a tube which passes through a sliding seal on the manifold.

8.10.7. Beam Lines

Each beam line is terminated by a thin melinex window and if this is punctured or fails in any way, a sudden pressure rise would occur. To protect the vacuum vessels a fast shut off valve has been fitted on each beam line close to the machine and close to a normal isolation gate valve. The vacuum layout of a typical 8 in diameter beam line is shown in Fig.8.10.7(i).

The fast shut off valves (Fig.8.10.7(ii)) are designed to close before the "plug" of air from a burst melinex window reaches the valve. They take about 12 ms to close so that the total time from a window burst to the final closure of a valve is about 15 ms.

To give closure times of this order, the total weight of all moving parts is only 4 lb and the plate is driven by a piston which is propelled by nitrogen gas at a pressure of 1,000 lb/in^2. It is stopped at the end of its travel by an oil damper built into and around the piston rod. The valve is kept open by a system of rollers and levers which holds the plate by a 20 lb pull exerted by a solenoid. When the solenoid current is switched off the valve closes. The fast shut off valve, gate valve and pressure triggers operate on an integrated control system which is designed to fail safe under all circumstances; for example, trickle charged batteries are used to guard against mains failure. The pressure triggers consist of a Penning gauge head, a vacuum discharge switch head and a capsule switch.

The system is interlocked so that the machine gate valve can only be opened when

(i) The beam pipe is pumped down to the required pressure.

(ii) All electrical connections are made.

(iii) The piston pressures of the fast shut off valve and the gate valve are at the operating value.

(iv) The power is switched on.

(v) The fast shut off valve is open.

The fast shut off valve is kept locked open until the beam pipe is pumped to the required pressure when it switches to the ready position. The gate valve closes if there is a slow pressure rise; the fast shut off valve closes if there is a fast pressure rise. The valve is triggered by a Penning gauge at about 10^{-4} torr, a vacuum discharge switch at about 0.2 torr, a capsule switch at about 5 - 10 torr. The vacuum discharge switch guards against any failure of the Penning gauge and the capsule switch covers both. With the capsule switch, the closure time goes up to around 40 ms.

The fast shut off valve has recently been modified so that it can be used on very short pipes; extra guide rails were needed to prevent the plate slicing its way through the valve seat, since the plug of air would hit the fast moving plate before it is completely seated.

8.10.8. Pressure Measurement

The pressure in the torus is measured by double filament Bayard - Alpert type ionisation gauges using local control units with facility for remote switching and choice of filament. On the local units, several linear ranges and a logarithmic range cover pressures from 10^{-3} to 10^{-8} torr. The logarithmic indication is repeated in the control room on strip chart recorders.

Initially, ion gauge calibration proceeded along conventional lines using a manifold connected via liquid nitrogen traps to a commercial McLeod gauge and a pumping system. The gauges were calibrated with pure nitrogen. The calibrations obtained on the same gauge were inconsistent, showing a variation from day to day of, typically, 12%. This was investigated by taking a series of pressure readings on the same volume of trapped gas in the McLeod gauge, first by eye and then by reading the scale with a cathetometer. Readings were also taken with the mercury columns tapped mechanically and by hand. From these experiments the experimental error in the gauge calibration was estimated at ± 6% when the reading were taken by eye and ± 2% when the scale was read with the cathetometer. The 12% day to day variations in the calibration of a particular gauge could not therefore be due to experimental errors when using the cathetometer. The error must lie in the McLeod gauge or the ion gauges themselves and the latter were temporarily suspected.

A report(19) was published pointing out a serious error, due to the "vapour stream" effect, in the McLeod gauge when used in conjunction with a liquid nitrogen trap. The report tabulates the magnitude of the error to be expected for a particular system and several experiments were carried out to confirm this. The results agreed substantially with the predictions of the report. A more consistent way of calibrating ion gauges was therefore required and the methods of several American workers who used standard orifice techniques were followed. The pumping speed of a circular aperture in a diaphragm across a circular tube can be worked out theoretically. By knowing how much gas has been introduced into a system, and the speed at which it is being removed, the (absolute) pressure can be calculated. The results on the orifice system look promising. Two gauges calibrated at an interval of three weeks gave results which varied by only 3%, which is the order of the experimental accuracy. Batches of six gauges will be calibrated when a "bell jar" has been suitably modified.

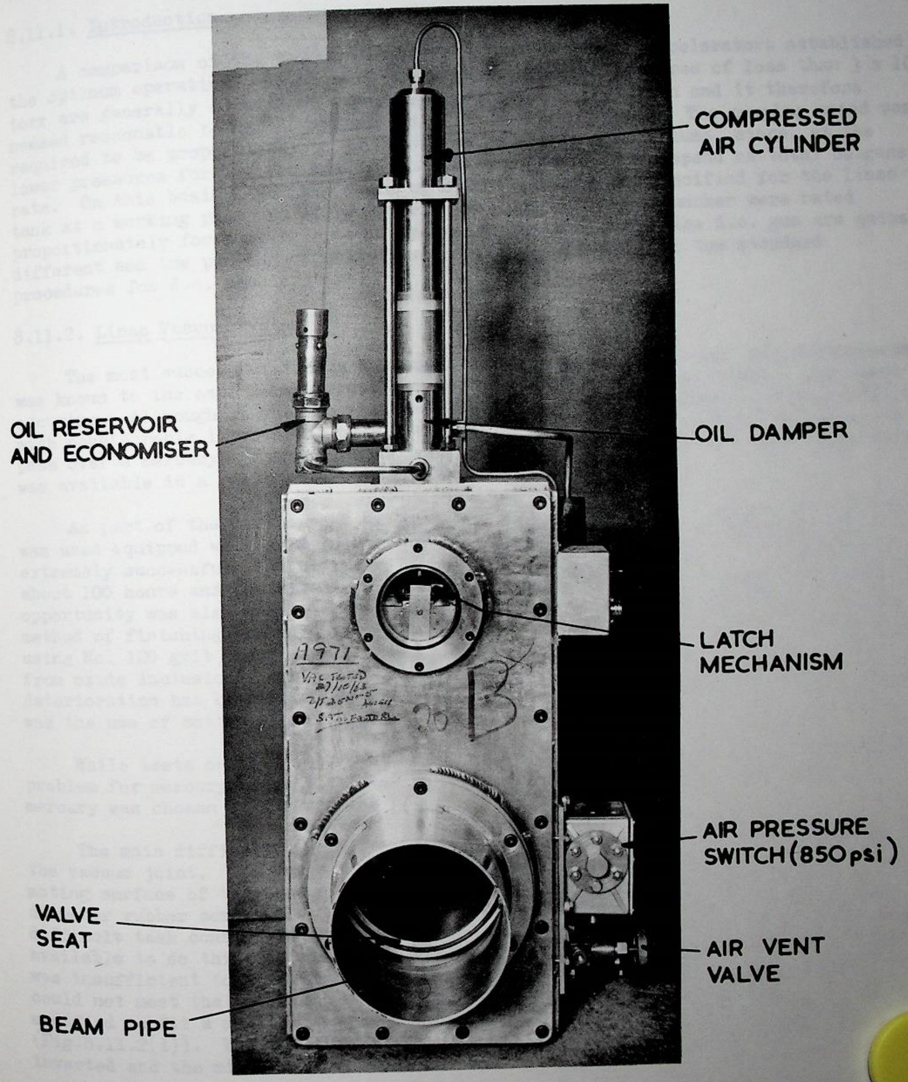


Fig. 8.10.7(ii) 8 in fast shut off valve.

8.11. Injector Vacuum System

8.11.1. Introduction

A comparison of the vacuum parameters of other linear accelerators established the optimum operating conditions for the injector (20) Pressures of less than 3×10^{-6} torr are generally considered necessary for reliable operation and it therefore seemed reasonable to aim at a pressure of 1 or 2×10^{-6} torr. The pumping speed was required to be proportional to surface area rather than to volume, since, at the lower pressures for a given speed, time for pump down would depend on total outgassing rate. On this basis a pumping speed of 8,000 litres/s was specified for the linac tank at a working pressure of 10^{-6} torr. The buncher and debuncher were rated proportionately for pumping speed. Operating conditions for the d.c. gun are quite different and the pumping capacity was determined according to the standard procedures for d.c. accelerators.

8.11.2. Linac Vacuum System

The most successful linacs have used mercury diffusion pumps. Oil contamination was known to increase X-ray production and the likelihood of multipactor phenomena occuring. Although it was thought possible that modern oil pumps could be provided with considerable improvement over previous oil systems, there seemed no reason to pass over a mercury system provided refrigeration equipment for the necessary traps was available in a reasonable time and at a reasonable cost.

As part of the development of the r.f. power system, a high-power test cavity was used equipped with a 24 in oil diffusion pump. The tests on the cavity were extremely successful. An ultimate pressure of 2×10^{-7} torr could be obtained in about 100 hours and the extent of back-streaming of the oil was very small. The opportunity was also taken in the construction of the cavity to test the proposed method of finishing the mild steel tank for the linac. The interior was scoured, using No. 120 grit emery discs, until the surface appeared uniformly marked and free from oxide inclusions. This type of surface proved very suitable and no deterioration has been noted over five years of life. The only necessary precaution was the use of cotton gloves to prevent oxidation by finger grease.

While tests on this unit were being carried out, examination of the refrigeration problem for mercury pumps suggested that there were no insuperable problems and mercury was chosen as the working fluid.

The main difficulty in the construction of the linac tank was the machining of the vacuum joint. The large flange of the D shaped cover and the face of the mating surface of the base plate had to accommodate a trapezoidal groove for a ½ in diameter rubber cord seal. A tolerance of ± 0.005 in was required and presented a difficult task considering the length and width of the base plate. The only machine available to do this job was a long bed horizontal borer. The vertical head travel was insufficient to allow any of the machining to be completed at one setting and could not meet the tolerance at the upper limit of the travel. The machine was modified to fit a milling attachment and the components were set up on edge (Fig.8.11.2(i)). When the lower half of each component had been machined it was inverted and the milling head reset.

A form cutter was used to machine the groove. At each corner of the base plate special attention was required. The groove was formed at 45° across the corner and the metal outside this groove was then removed down to the bottom of the groove already cut. A special corner piece was then manufactured and fitted to form a correct outer wall to the groove all round the corner (Fig.8.11.2(ii)) After this machining, the finish was not acceptable for vacuum seal surfaces and a certain amount of dressing (by hand and by machine) had to be performed. Tolerance was achieved over most of the length of the groove (110 ft) but was exceeded over about 20 ft near one corner. This was further aggravated by variations in diameter of the rubber cord. These difficulties were eventually overcome by using 0.01 in shims in the groove and by selecting lengths of rubber cord which met the required tolerance and accepting a greater number of butt joints, which were not cemented, in the cord seal. After installation, it was necessary to modify the base plate supports to eliminate sag and some straightening (by heating) was required before a satisfactory seal could be obtained.

The linac r.f. cavity presented a considerable vacuum problem. Large surface areas involved a high outgassing rate and practically every component in the cavity had to be water cooled, in many cases by electrically isolated cooling circuits with demountable joints. Tapped holes for screw fixings were provided with the usual pump out holes to eliminate virtual leaks. Outgassing was reduced as far as possible by maintaining strict cleanliness at all stages of manufacture, especially by eliminating all materials such as cutting oils and fluxes from surfaces before and after assembly. Slots with a total cross sectional area of 1250 in^2 (about one and a half times the area of the pumping ports to the linac tank) were provided in the cavity to ensure adequate pumping speed within the liner.

The equipment fitted inside the drift tubes is 'dirty' from a vacuum point of view and it was decided to connect these to a separate roughing system. This involved connecting each drift tube to a manifold which runs the full length of the copper liner and passes through the base plate to roughing pumps. To safeguard the drift tubes from mechanical damage in the event of failure of pumps and interlocks, a spring loaded ball valve was incorporated in the manifold. This valve opens when the pressure difference, in either direction, between the inside of the drift tubes and the main vacuum vessel exceeds a few torr. Each water circuit on the drift tubes had to be connected through a seal on the base plate to the appropriate water supply.

The water cooling pipes on the liner itself had all their brazed joints vacuum tested before the pipe was soldered to the copper cylinder. The test allowed for a pressure difference across each joint of the same order and direction as will prevail in operation. This involved the design of "outer space test sleeves" which could be clamped over a joint as shown in Fig.8.11.2(iii). The space between the sleeve and the joint under test was evacuated and connected to a leak detector. The pipe was pressurised with the probe gas. All water pipe joints throughout the system, whether permanent or demountable, were tested in this way.

Manufacture of the drift tubes (Fig.8.11.2(iv)) was arranged so that welds and brazed joints were tested before they became inaccessible in the next stage of production. In this way each drift tube was subjected to six intermediate tests before the final test was carried out. It was found after delivery that the side arm soldered joints were particularly susceptible to mechanical damage and additional tests were necessary. These were carried out after the electrical tests on each drift tube, after transportation to the injector room, and finally after installation in the liner.

266 such tests were carried out on the 50 drift tubes and 12 drift tubes with leaks in excess of tolerance were eventually accepted. Those with the larger leaks

Fig. 8.11.2(i) Machining of the linac vacuum vessel.

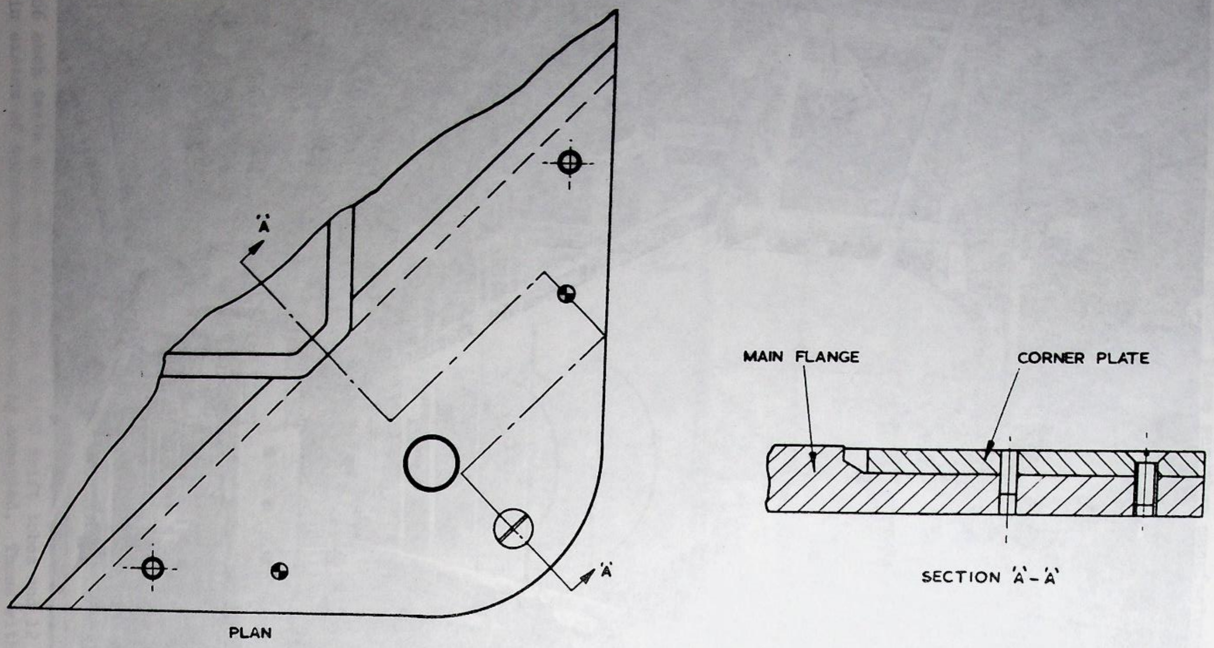


Fig. 8.11.2(ii) O-ring corner joint of the linac vacuum vessel

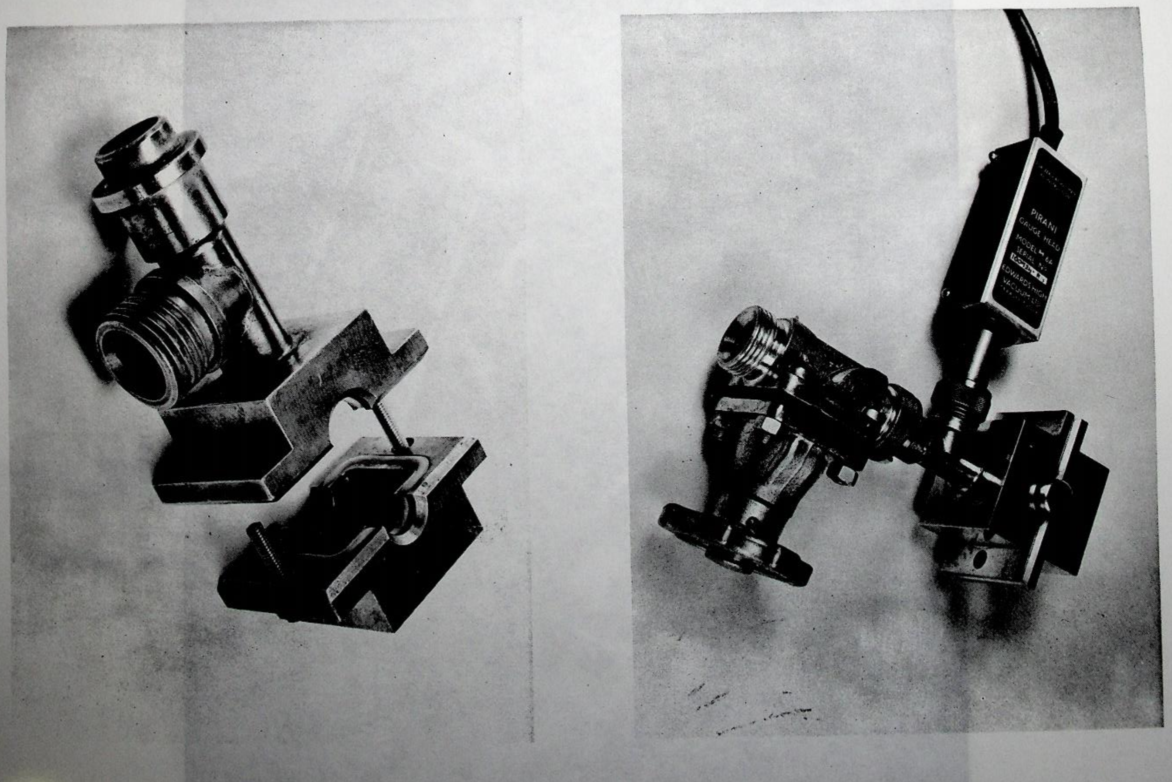


Fig. 8.11.2(iii) Outer space test sleeves.

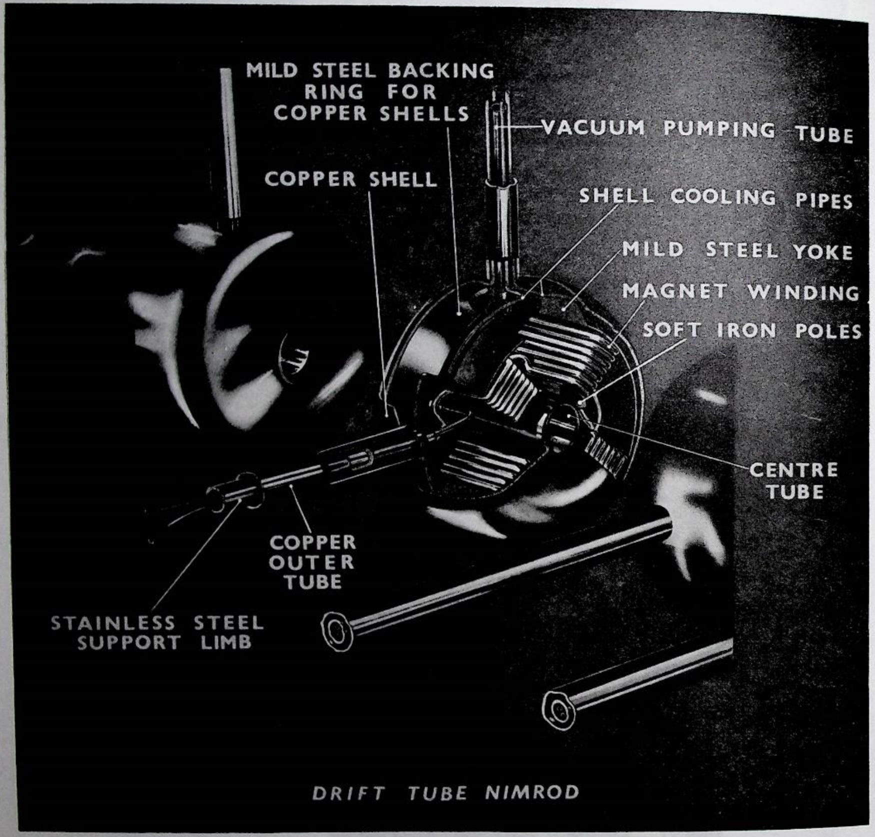


Fig. 8.11.2(iv) Linac drift tube.

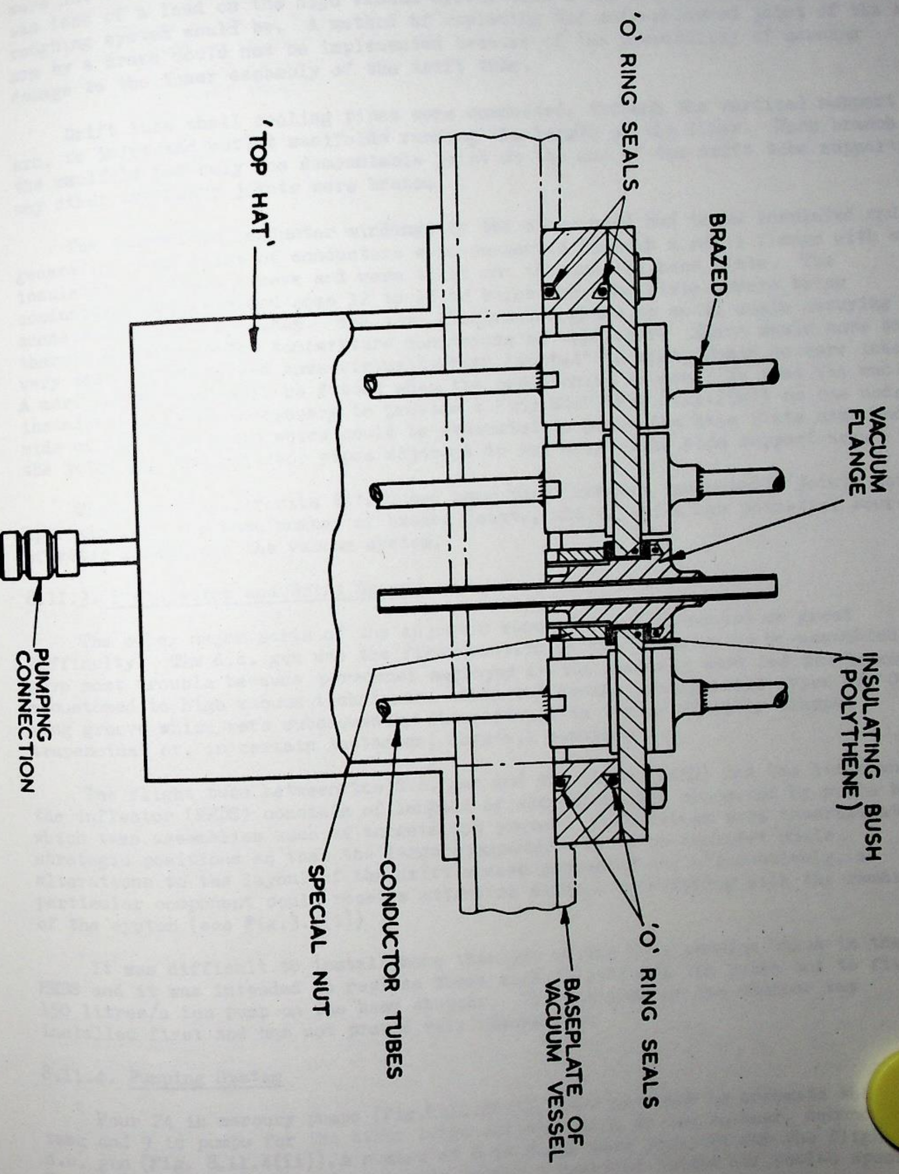


Fig. 8.11.2(v) 'Top hat' test on conductor tubes

were not connected to the roughing manifold since the outgassing of the interiors was less of a load on the high vacuum system than a continuous leak from the roughing system would be. A method of replacing the soft-soldered joint of the side arm by a braze could not be implemented because of the possibility of causing damage to the inner assembly of the drift tube.

Drift tube shell cooling pipes were connected, through the vertical support arm, to inlet and outlet manifolds running the length of the liner. Each branch of the manifold had only one demountable joint at the end of the drift tube support; any other necessary joints were brazed.

The quadrupole conductor windings on the other hand had to be insulated and, generally, four pairs of conductors were connected through a metal flange with an insulated polythene sleeve and were taken out through the base plate. The conductor pipes extended some 12 to 18 in below the base plate before being connected to flow switches. The same flanges had glass to metal seals carrying thermistor outputs for temperature monitoring of the liner. These seals have been very unsatisfactory and have virtually been 'potted' in epoxy resin to cure leaks. A more robust seal will be fitted when the opportunity arises. To test the whole installation it was necessary to provide a "top hat" (Fig.8.11.2(v)) on the under side of the base plate which could be evacuated to prove the base plate seal and the joint in the conductor pipes adjacent to the drift tube side support arm.

These cooling circuits introduced some three hundred demountable joints and approximately the same number of brazed joints, all of which are potential sources of water leaks into the vacuum system.

8.11.3. Preinjector and Drift Spaces

The other major parts of the injector vacuum system presented no great difficulty. The d.c. gun was the first section of the injector to be assembled and gave most trouble because personnel employed in the assembly work had not become accustomed to high vacuum techniques. Also the design incorporated types of 'O' ring groove which were subsequently discontinued in favour of fully trapped trapezoidal or, in certain instances, dovetail sections.

The flight tube between the d.c. gun and the linac (LEDS) and the linac and the inflector (HEDS) consists of lengths of aluminium pipe connected by probe boxes which take assemblies such as targets and probes. Gate valves were inserted at strategic positions so that the larger components could be isolated while alterations to the layout of the drift spaces proceeded or, alternatively, a particular component could receive attention without interfering with the remainder of the system (see Fig.3.1(i))

It was difficult to install more than two of the 6 in pumping units in the HEDS and it was intended to replace these with 75 litres/s ion pumps and to fit a 150 litres/s ion pump on the beam chopper. The ion pump on the chopper was installed first and has not proved very successful.

8.11.4. Pumping System

Four 24 in mercury pumps (Fig.8.11.4(i)), were provided to evacuate the linac tank and 9 in pumps for the other large cavities such as the buncher, debuncher and d.c. gun (Fig. 8.11.4(ii)). A number of 6 in pumps were provided for the flight tube. Each pumping unit consisted of a gate valve, a combined liquid air cooled spoon trap and refrigerated chevron baffle and the mercury pump backed by a mechanical rotary pump. The chevron baffle serves to reduce the rate at which mercury collects on the spoon trap. On a 24 in unit without the chevron baffle the whole mercury charge of the pump could be transferred to the trap in one day but interposing the baffle at a temperature of - 25°C, increases this time to more than 150 days.

The control system for the pumping units is essentially similar to that for the synchrotron oil pumps, the main differences being the absence of the vapour booster pump and the addition of the liquid air trap and its associated interlocks. The start up sequence required the mercury pump to be operating and the baffle chilled before liquid air was admitted to the trap otherwise it would collect unnecessary amounts of mercury vapour.

The liquid air system consists essentially of a number of direct condensation liquefying machines (Fig.8.11.4(iii)) supplying liquid air at atmospheric pressure to a depot collector which despatches batches of liquid into a reservoir which is pressurised to about 5 lb/in^2 gauge. Liquid from the reservoir is distributed to the traps via a vacuum insulated transfer line with a solenoid valve outlet to each trap. The solenoid is actuated by the pumping unit control system and by level sensing heads in the trap. A description of this system as originally conceived has been published(15). Much development work has been necessary and the system is not yet fully operational.

The rough pumping system for the injector comprises three 100 litres/s Rootes pump combinations identical to those used on the inner vessel of the main torus. The pumps are connected, via individual isolating valves, to a 10 in diameter roughing manifold from which a 9 in diameter branch is taken through a gate valve to the linac tank. The manifold is continued with reduced diameter to serve the other large cavities as well as individual sections of flight tube. In each case, electrically operated valves allow the items to be interlocked.

Individual pumping units of the injector vacuum system are started and run up to the ready condition locally and are then operated from the mimic panel in the injector hall. All the valves are operated by push buttons adjacent to the schematic position of the valve and there is indication of whether the valve is open or closed. When the appropriate pressures in the system, as determined by pressure switches, are achieved, they are indicated on the mimic panel and interlock the valves. For example: flight tube valves will not open unless the pressure on each side of the valve is less than 10^{-2} torr; roughing valves will not open unless air admittance valves in the same region are closed; high vacuum valves to pumping units will not open unless the volume to be connected to the pump is at a lower pressure than 10^{-2} torr and the appropriate roughing valve is closed; air admittance valves will not open unless a master key switch is operated and the appropriate high vacuum valves on pumping units together with flight tube valves for the particular sections are closed.

The leak rate tolerances were generally similar to those applying to the rest of the synchrotron. Exceptions included the linac tank, for which a leak rate of 2 x 10^{-3} torr litres/s was originally specified. There was considerable doubt that this standard could be achieved on a mild steel vessel of some 72,000 litres volume. Indeed the normal U.K.A.E.A. specification for vessels over one litre called for a pressure rise of less than 0.036 torr/hour (or a leak rate of 0.72 torr litres/s). However, calculation showed (Section 8.6.1), that using one 24 in oil pump for the tests, a leak rate of 10^{-4} torr litres/s would cause a partial pressure rise of

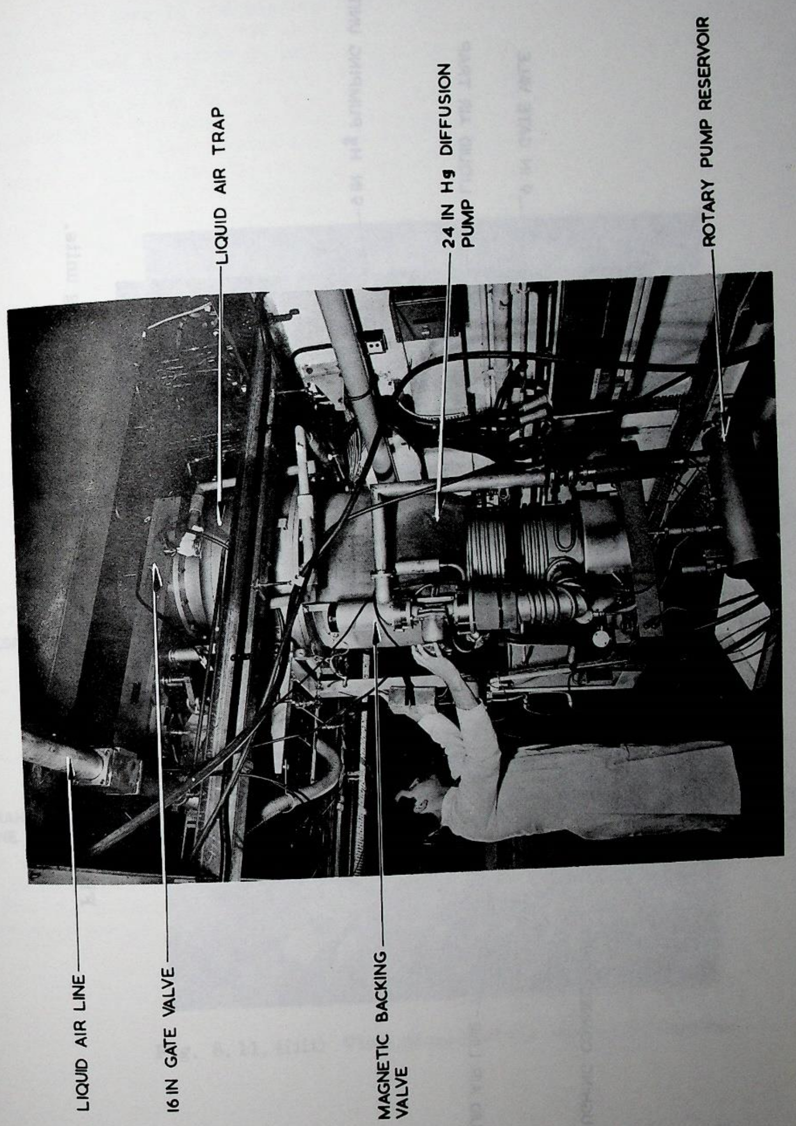


Fig. 8.11.4(i) An installed 24 in mercury pumping unit.

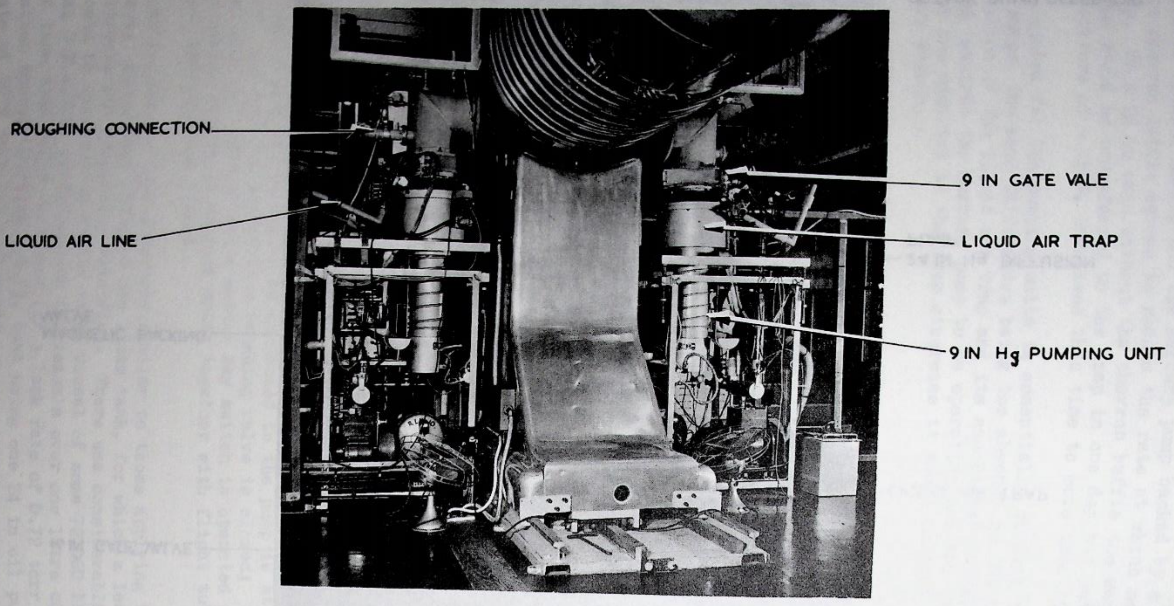


Fig. 8.11.4(ii) View of d.c. gun 9 in mercury pumping units.

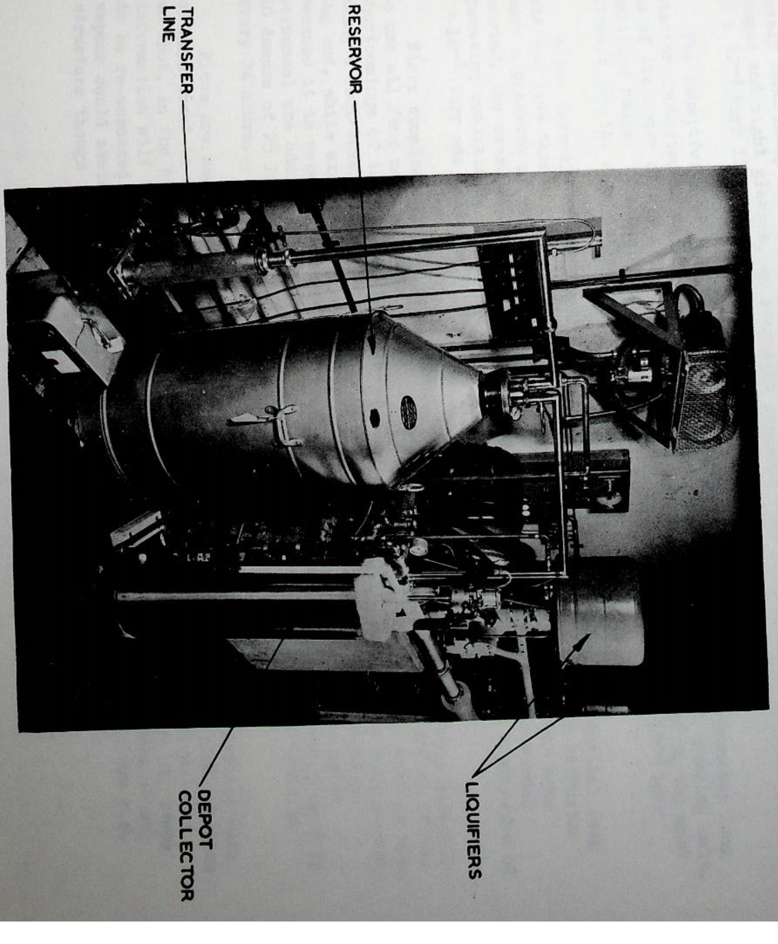


Fig. 8.11.4(iii) View of part of the liquid air system.

about 5 x 10^{-6} torr in the backing space after 5 s. This was at least four orders of magnitude greater than the minimum partial pressure detectable by a mass spectrometer leak detector in ideal conditions. Against a background due to other leaks and outgassing of the vessel walls this advantage might be reduced to one order of magnitude but it was still considered adequate for the specified leak rate to be attained. The doubt was soon dispelled for even on the first pump down before any leak detection was carried out the leak rate was 0.2 torr litres/s. No leaks were found in welded joints and after rectification of the main flange seal (as already described) and the replacement of many faulty 'O' ring seals on blank flanges and sight glasses, an overnight pressure rise equivalent to a leak rate of 2.5 x 10^{-4} torr litres/s was obtained.

The sensitivity of leak detection on the tank, using a mass spectrometer leak detector connected to the backing space of the prototype 24 in mercury pumping unit, was of the order of 2.5 x 10^{-3} torr litres/s for full scale deflection on the most sensitive range. The basic sensitivity of the mass spectrometer was 10^{-8} torr litres/s for the same deflection.

After assembly of the linac r.f. structure inside the tank, the initial leak rate was less than 2 x 10^{-3} torr litres/s. Using all the roughing and diffusion pumps a pressure of 2 x 10^{-6} torr was achieved in under 17 hours. After some pumping, the measured leak rate was 2.6 x 10^{-4} torr litres/s and under normal operating conditions, using only two of the four 24 in mercury pumps, a pressure of 2 x 10^{-6} torr was achieved in about 12 hours.

Since commissioning of the injector began, it has generally not been possible to use all four mercury pumps because of faulty spoon trap seals or because of the shortcomings of the liquid air system. Topping-up liquid air traps by hand or even using a semi-automatic system from a pressurised dewar, is tedious and time consuming and, while experimental work is in progress, is additionally troublesome because it is necessary to stop the injector operating every few hours while personnel are admitted to carry out the topping-up. It has involved carrying 6 to 10 dewars of 25 litres capacity into the injector hall at least three times in every 24 hours.

Plans are now being made to fit oil pumps on the linac tank in parallel with an experiment to determine the effect of oil pumps on the radio frequency cavities so that, in the event of continued difficulty with the liquid air system, information will be available to enable the choice between mercury and oil pumps to be re-assessed. There is some evidence to suggest that small amounts of oil vapour could assist in conditioning the surfaces of the drift tubes in the r.f. structure though it will probably result in a higher X-ray background.

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SECTION 9
CONTROL SYSTEM

The control system for the Nimrod machine is now almost completed with the installation entering its final stages. Almost all items of equipment have already operated under local control conditions and some large sections of the plant, such as the injector, have been remotely controlled from the main control room.

The control system embraces all the main items of plant such as the magnet and its power supply, the injector, the vacuum system, the radio-frequency accelerating cavity and its power supply, and the cooling plant, and integrates them into a common functioning machine, adding such interlocking and sequencing as may be required for personnel and equipment protection.

This report will take as examples for more complete description, the control aspects of the injector, vacuum system, coolant temperature and flow monitoring, personnel and safety interlocking and the main control room, these items being representative of the complete control system.

9.1. Injector.

9.1.1. Introduction.

Since the injector may be regarded as a linear accelerator which is complete in itself and is required to operate as such, especially in the early commissioning stages of Nimrod, it was necessary to design the control system so that it could either operate independently or be integrated at will into the main Nimrod control system. With this end in view, a local control room was provided and all control functions on the injector may be carried out from this position. When required the essential control functions can be extended to the main control room by the operation of changeover switches. The injector local control room can remain manned during the operation of the injector alone but when high energy beams are achieved in the synchroton, the injector will need to be remotely controlled from the main control room.

Figs. 9.1.1(i) and 9.1.1(ii) show the layout and current appearance of the injector control room, which is situated in the injector hall adjacent to the H.T. platform and d.c. gun. Fig. 9.1.1(iii) shows a simplified block schematic of the injector control system.

The injector first operated successfully under local control in August 1961.

9.1.2. E.H.T. Supply, E.H.T. Platform and D.C. Gun.

A 600 kV d.c. supply is produced by an electrostatic generator. This supply feeds the d.c. gun which accelerates protons from the pulsed ion source into the linear accelerator. Since all the equipment associated with the ion source is at +600 kV with respect to earth, all control signals must be suitably isolated and accordingly compressed air is used to convey control signals through polythene tubes to the platform. Ion source trigger signals pass via light guides and photocells, and other control adjustments are carried out by reversible geared motor units with long insulated drive shafts. Electrical power to the equipment on the H.T. platform is provided by 115 V, 2000 c/s; 110 V, 50 c/s and 24 V d.c. The generators mounted with their control equipment on the H.T. platform. The compressed air links provide control signals for sequence interlocking and