

FEATURES OF THE HIGH FIELD MAGNET LABORATORY  
AT THE AUSTRALIAN NATIONAL UNIVERSITY, CANBERRA

by

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## SUMMARY

The High Field Magnet Laboratory at Canberra is described. High-field water-cooled electromagnets produce magnetic fields of hundreds of kilogauss, consume megawatts of power and require thousands of gallons of cooling water per minute.

Engineering details are given of the pulsed water cooling system, electrical and control systems, and instrumentation.

The paper is prefaced by a description of the Canberra homopolar generator used as energy store and power source for the Magnet Laboratory, and by a discussion of the scientific uses of high magnetic fields.

## 1. Introduction

The intention of this paper is to describe in some detail the equipment and facilities at Australia's first and only High Field Magnet Laboratory. However, since the Laboratory depends entirely for its power supply upon a unique energy storage device known as a homopolar generator, and since each electromagnet, together with its cooling equipment form with the homopolar generator an integrated system for the transformation and control of energy, some space will first be devoted to a brief description of the homopolar generator and its capabilities. A fuller description will be found in references 1, 2 and 3.

The electromagnets we are speaking of consume from 5 MW d.c. upwards to an easily conceivable 100 MW. The homopolar generator can meet these power requirements and has in fact repeatedly delivered powers of 300 MW or more. Further, the techniques are well established for increasing this threefold. However, being essentially a storage device, discharge times are a function of power, the product of the two being limited to 500 MW seconds (megajoules).

### 1.1 Homopolar Generators

It was Michael Faraday, towards the middle of the last century who constructed the forerunner of the homopolar machine. He rotated a disc through which passed a magnetic field and observed an e. m. f. between the disc axis and a stationary contact rubbing on the outer edge of the disc. By taking care to preserve cylindrical symmetry in the exciting field and in the arrangement of electrical contacts and conductors, such a device can be in fact converted into a highly efficient transformer of mechanical (shaft turning) energy into electric energy. Such a device is termed a homopolar (or unipolar) generator, h.p.g. for short. On the other hand if a large degree of asymmetry in magnetic field is introduced, and rubbing contacts are dispensed with, the generated currents will flow within the disc itself forming a useful braking device often used in watt hour meters, speedometers and the like.

The symmetrical device, the h.p.g., is in fact reversible, i. e. when fed with current in the reverse direction it will motor. The Canberra h.p.g. (see Figure 1) has no mechanical connections to its shaft at all, but has large massive discs which accelerate when fed with electrical energy, thus storing it in the form of kinetic energy. The energy is reconverted into an electrical output by merely connecting the load of appropriate impedance across the discs through special brush gear. The efficiency of conversion is normally 99%.

The Canberra machine has four rotating discs each weighing twenty tons. At full storage capacity, the peripheries of the discs are moving at two thirds the speed of sound, and this is the rubbing speed for the outer brushes. The electromagnet which forms the exciting field through the disc weighs 1500 tons and stands 25 feet high. The equivalent electrical capacity of the h.p.g. is some 5,000 farads and discharge currents of up to 1.8 million amperes, lasting for a second or so have been obtained. The electrical feature most essential for its application to the generation of high magnetic fields, however, is the maximum stored energy--500 megajoules.

It is this feature which enables the powering of electromagnets requiring tens of megawatts for periods of several seconds--long enough for the majority of experimental applications and longer than is possible anywhere else in the world.

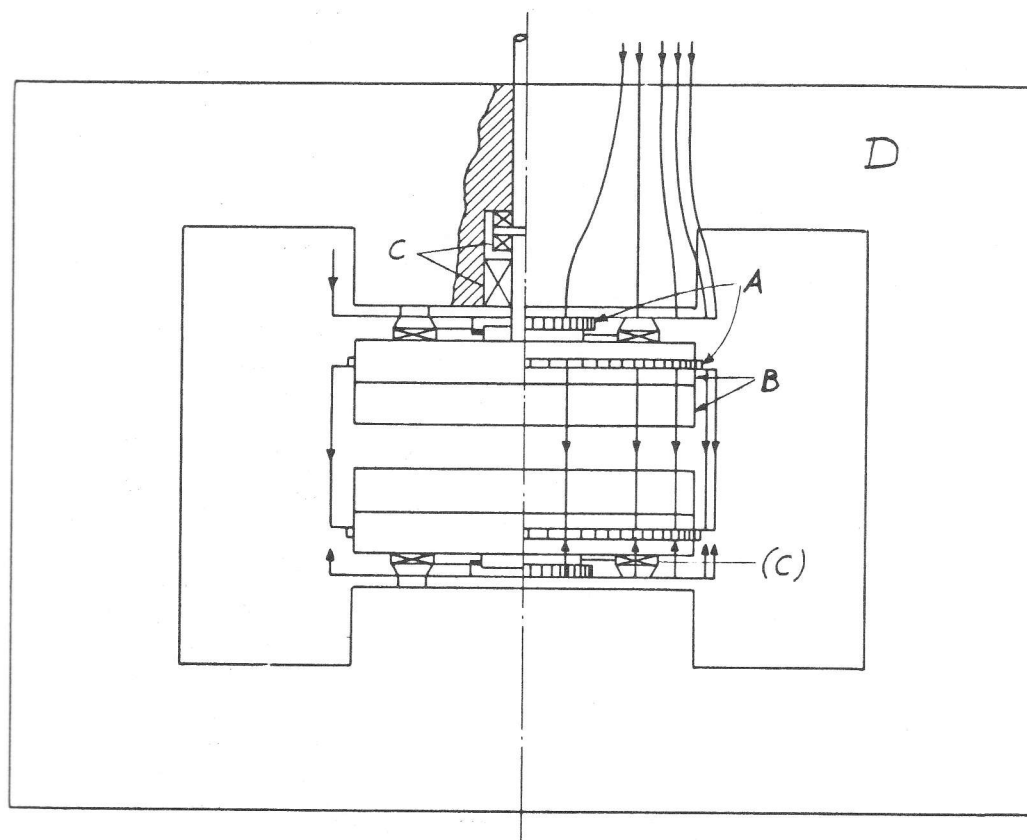


Figure 1. Diagram (half section) of the Canberra homopolar generator showing schematically the current paths (arrows), brush rings (A), rotors (B), bearings (C), and energising magnet steel yoke (D).

## 1.2 High Magnetic Fields and Solid State Physics

The chief experimental use of high magnetic fields is in the sphere of solid state physics. This branch of pure science has steadily grown in importance since World War II and received a tremendous boost with the invention of the transistor,

which grew directly from the results of research in this field. Since then, other semiconductor and magnetic devices, lasers and the like have eventuated, showing the promise of this type of research.

In many respects, the physics of the solid state is complementary to atomic physics which for so long has outshone it in prestige. For it is in the solid state, where atoms and molecules crystallise and interact in orderly fashion, that one must change from considering the properties of individual atoms to the consideration rather of one large atom with millions of permissible electron orbits and new quantum properties.

In many branches of science, a method of study is to distort the object of study and try to build up a knowledge of its properties from the relation between the properties of the distorting influence and its observed effect. Examples of this approach are to be found in nuclear physics and chemistry and this essentially is how high magnetic fields are used in the study of the solid state. Most properties of matter in the solid state are influenced to some extent by an imposed magnetic field, this being a result of the fact that the interaction between atoms is largely electro-magnetic in nature. It is not surprising therefore that high field electromagnets have proved an invaluable tool, comparable to some degree to the accelerators of atomic physics.

### 1.3 Electromagnets

High magnetic fields of the magnitude and duration we are considering here are generated exclusively by water-cooled "air-cored" electromagnets. Iron cored electromagnets are limited by the magnetic saturation property of ferrous materials to about 40 kilogauss. Super-conducting electromagnets, devices which make use of the fact that certain exotic materials at very low temperatures have zero electrical resistance, are limited to just over 100 kilogauss. Above this figure the most economical means of generation appears to be with copper or copper alloy conducting material formed into a solenoid configuration. For other than very short duration fields, water cooling is essential. Electric current densities of up to 40 k amps/cm<sup>2</sup> and power densities of up to 3 kw/cm<sup>3</sup> are common. Field intensities, dimensions and powers of the largest available electromagnets are shown in Table I.

A particularly successful design of magnet has been developed by an American, Francis Bitter. The Bitter design is essentially of a single layer solenoid. In its simplest form, each turn consists of a set of thin copper discs, each with a central hole and a radial slit. The discs are interleaved with each other and with similar discs of insulation to form a continuous helix as illustrated in Figure 2, the overlap between adjacent discs being up to 90°. Specially shaped end plates are used to make contact with the end discs, thus enabling connection to the power source and to provide a means of axially clamping the stack of discs together. On energising such a stack, an accessible magnetic field occurs in the central hole, largely in the axial direction.

TABLE I

| Country                        | Number of high field magnet laboratories | Highest available field k. g. | Highest available power M. W. |                                       |
|--------------------------------|------------------------------------------|-------------------------------|-------------------------------|---------------------------------------|
|                                |                                          |                               | continuous                    | pulsed                                |
| Australia                      | 1                                        | 165                           |                               | 300 MW for 1 sec.,<br>5 MW for 1 min. |
| Europe (excluding U. S. S. R.) | 2                                        | 90                            | 4                             |                                       |
| Japan                          | 1                                        | 120                           | 4                             |                                       |
| U. K.                          | 3                                        | 130                           | 3.5                           |                                       |
| U. S. A.                       | 7                                        | 205                           | 8                             | 32 for 4 sec.                         |
| U. S. S. R.                    | ?                                        | ?                             | ?                             | ?                                     |

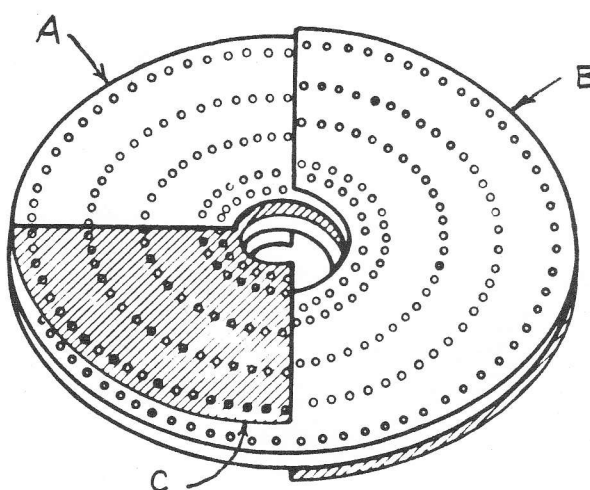


Figure 2. One turn of a typical Bitter disc comprising two copper discs A and B and one insulating disc C, all split and interleaved. Holes are for water cooling.

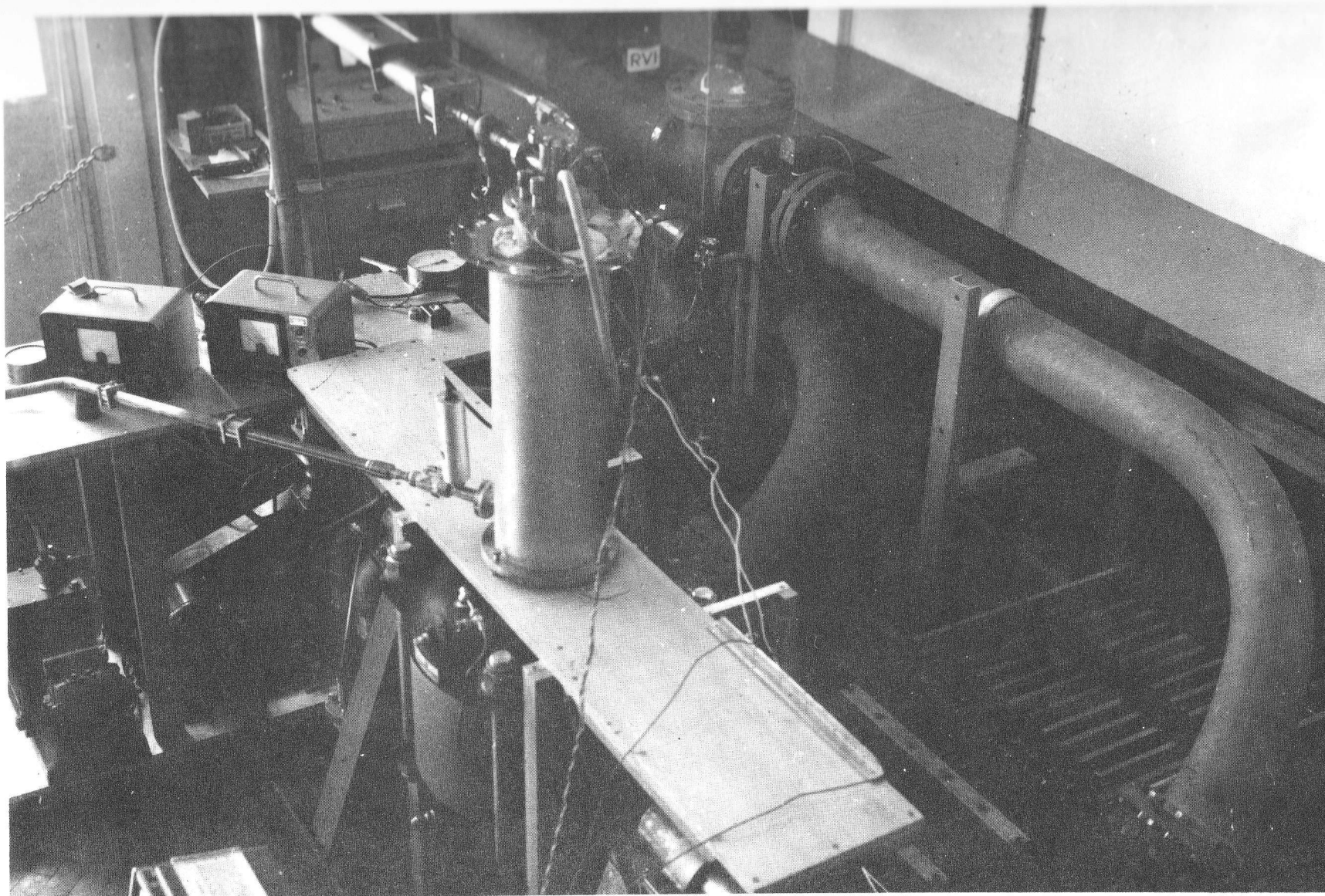


Figure 3. View of Magnet with cryostat above. Busbar and cables joining magnet and isolator can be seen, and also the cooling water pipes. 57

The interaction of the current with the magnetic field produces tremendous bursting forces and in fact the design of these magnets is in many respects similar to the design of thick-walled cylindrical pressure vessels. A magnetic field of 150 k.gauss is somewhat similar to a pressure acting in the central access hole of 13,000 p.s.i. The relationship is a square law, which points immediately to the limitation of unreinforced copper of about 52,000 p.s.i. for 300 k.gauss.

The situation is worsened by the fact that the copper discs have to be perforated with numerous cooling water holes (aligned in the axial direction) and are in any case operating at an appreciable temperature.

## 2. The A. N. U. Facilities

The Australian National University Magnet Laboratory has at present one Bitter electromagnet producing up to 165 kilogauss and requiring 5 MW, 25,000 amperes and 1000 g.p.m. of cooling water (see Figure 3). A 300 kilogauss magnet is being designed; this will require 200,000 amperes and require 3,000 g.p.m. of cooling water to remove the 30 MW of heat generated. These magnets compare favourably with what is available now in other parts of the world as can be seen from Table I.

At the A. N. U., current is carried from the h.p.g. in aluminium busbars through an electrolytic variable resistor and a hydraulically operated isolator to the magnet. The electrical circuit is shown in Figure 4.

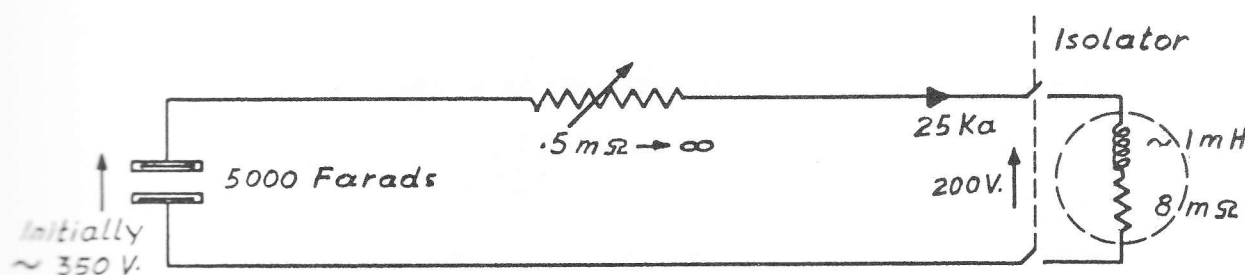


Figure 4. Equivalent electrical circuit diagram of homopolar generator (capacitor  $\approx 5,000$  farads), electrolytic variable resistor (and busbar resistance)  $\infty$  to  $\approx .5 \text{ m}\Omega$ , isolator and magnet inductance and resistance (approx.  $1 \text{ mH}$  and  $8 \text{ m}\Omega$ ). The variable resistor acts as current controller and circuit breaker.

## 2.1 Current Control and Circuit Breaker

The primary purpose of the electrolytic variable resistor is to act as a circuit breaker but it also provides current control to within a few percent of any desired law. It was built in the first place to provide a test load for the h.p.g. (see Blamey et al, reference 1). Essentially a 7,000 lb. tank of caustic soda is raised by a hydraulic servo system to submerge to varying degree a set of steel electrode plates.<sup>5</sup> The servo input is by means of easily-cut wooden cams, except that there is a secondary servo input operative only at the extreme limits of travel of the tank to bring it to rest, and a latch mechanism to disengage the primary servo system. The variable resistor acts as a circuit breaker whenever the latch is operated, the effect being to drop the tank away from the electrodes in a fraction of a second. Figure 5 shows a view of the variable resistor and Figure 6 shows an actual recording of tank height vs. time during a trial circuit break. The device is known to break currents of over a million amperes effectively and is expected to operate satisfactorily with the currents and magnet inductances anticipated.

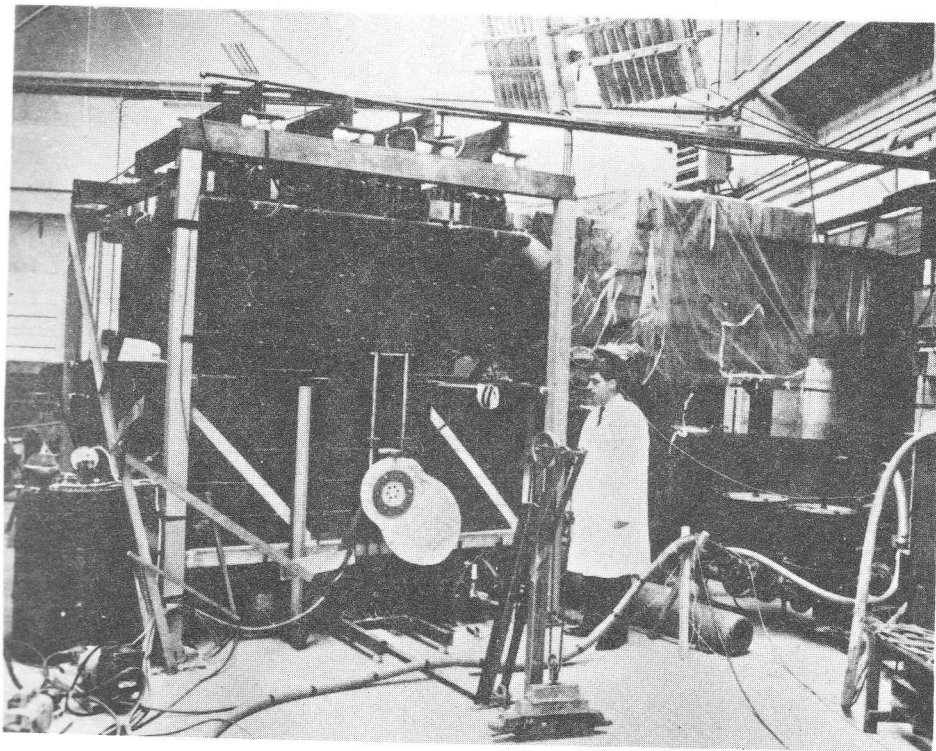


Figure 5. Photo of electrolytic variable resistor circuit breaker in open circuit position, i.e. tank lowered. The wooden cam which provides input information to the height-controlling hydraulic servo-mechanism can be seen clearly. The overhead busbar system is designed to take the full 1.6 million amperes capable of being delivered by the homopolar generator.

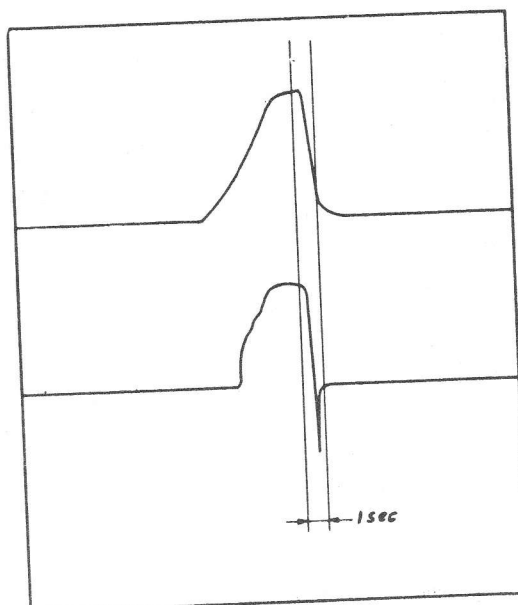


Figure 6. Upper curve shows an actual recording of electrolytic resistor tank height vs. time during a trial circuit break, together with the corresponding record of high field magnet voltage showing acceptable reverse voltage at break.

## 2.2 Electrical Isolator

An isolator capable of carrying 200,000 amperes has been included in the circuit for reasons of safety and to facilitate circuit checking. It is, of course, an essential item when more than one magnet is available for connection to the h. p. g.

The A. N. U. design is intended to be compact to match the geometry of the busbar system. The principle of operation is shown in Figure 7. A single row of copper bars of alternate polarity enter the isolator horizontally, turn right angles and rise vertically to a "switching line". A similar set of separate bars drop vertically from the switching line to the level of the incoming bars, turn at right angles and continue horizontally out of the isolator. The two sets of vertical bars are interleaved and firmly clamped at their lower ends. The upper ends may be slightly sprung apart and are in fact interleaved yet again with a set of copper bridging bars at the switching line. When a hydraulic clamp acting along the switching line is pressurised, the circuit through both poles of the isolator is complete. On the other hand, when this clamp is relaxed and the bridging set moved horizontally, bakelite insulating sections are drawn between the contacts thus effecting electrical isolation.

The bridging set is moved by hydraulic means and the whole switching sequence is controlled by an electronic logic circuit which derives information from limit switches and pressure switches on the isolator. Figure 8 is a logic diagram showing the connection between operations involved in opening and closing the isolator.

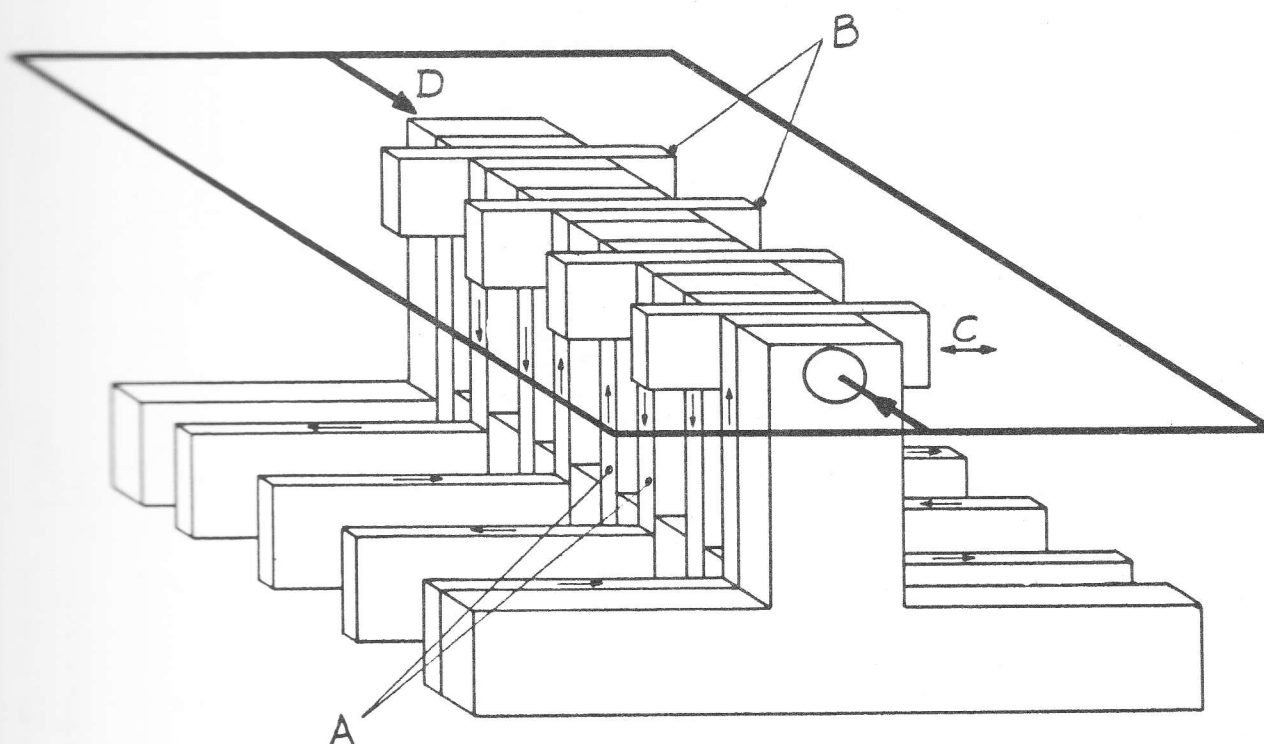
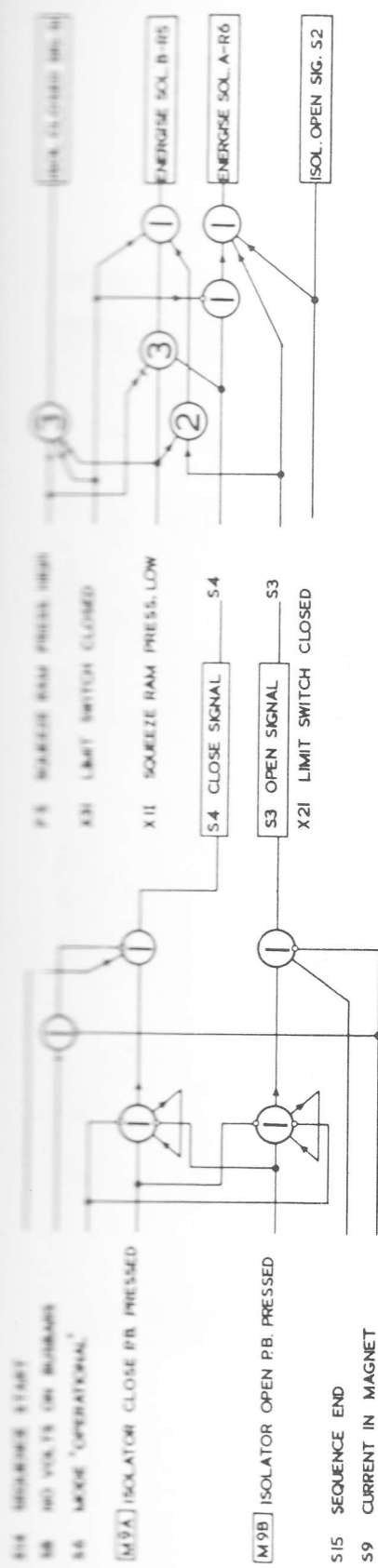


Figure 7. Diagram of 200 kiloamp isolator (actual height about 2 ft) showing principle of operation. (A) Vertical cantilever conductors clamped at lower end. (B) Bridging pieces capable of sliding in direction shown at (C) connect two adjacent verticals or separate them with insulation. (D) Heavy arrows and frame represent contact squeezing system operating at "switching line".

### 2.3 Water Cooling System

The water cooling system comprises the bulk of the equipment of the Magnet Laboratory. This system is capable of forcing 4,000 gallons per minute of chemically pure water through a magnet at 200 p.s.i. It operates in a pulsed manner to match the nature of the power received from the h.p.g. The water travels in a closed loop, rapidly during a pulse, between a cold storage tank, through a magnet to a hot storage tank (see Figure 9); and slowly during the period of recharging the h.p.g., from hot storage, through a heat exchanger back to cold storage.

During the rapid part of this cycle, the flow is powered by means of compressed air stored in a 7-foot diameter spherical reservoir and released to the space above the water in the cold water storage tank by means of an electrohydraulic servo controlled 3 in. air valve. The servo system is in turn controlled from an electronic variable function generator whose function may be tailored more or less by trial and error to obtain the desired water flow law. In this way water may be conserved and matched to the magnet power law. Control of water flow by throttling

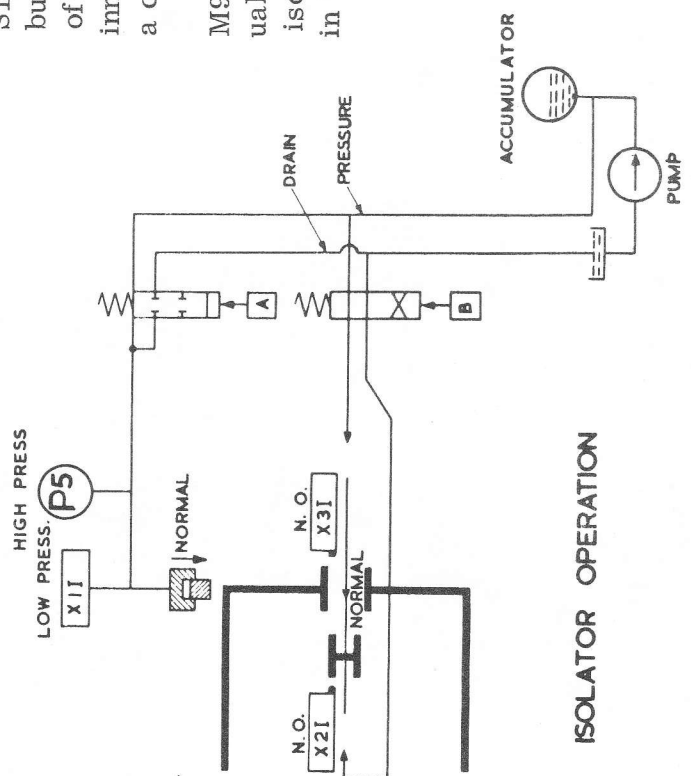


The lower diagram is a schematic of the isolator. The heavy lines represent the incoming and outgoing current paths. The isolator may be closed by insertion of bridging bars (shown as an "H" sideways) and application of squeeze pressure shown diagrammatically as a small ram above the upper current lead. X21 and X31 are limit switches which send a "1" when activated by the bridging bars. X11 is a switch which sends a "1" when the squeeze ram is released.

Solenoids A and B operate the hydraulic control valves in the direction shown when signals R6 and R5 respectively are "1".

S14 and S15 are normally "0", but change to "1" for a period of about 3 seconds at the beginning and end respectively of a current pulse.

M9A and M9B are the only manual controls associated with the isolator and are effective only in "non op" mode.



### ISOLATOR OPERATION

Figure 8. Isolator Logic Diagram

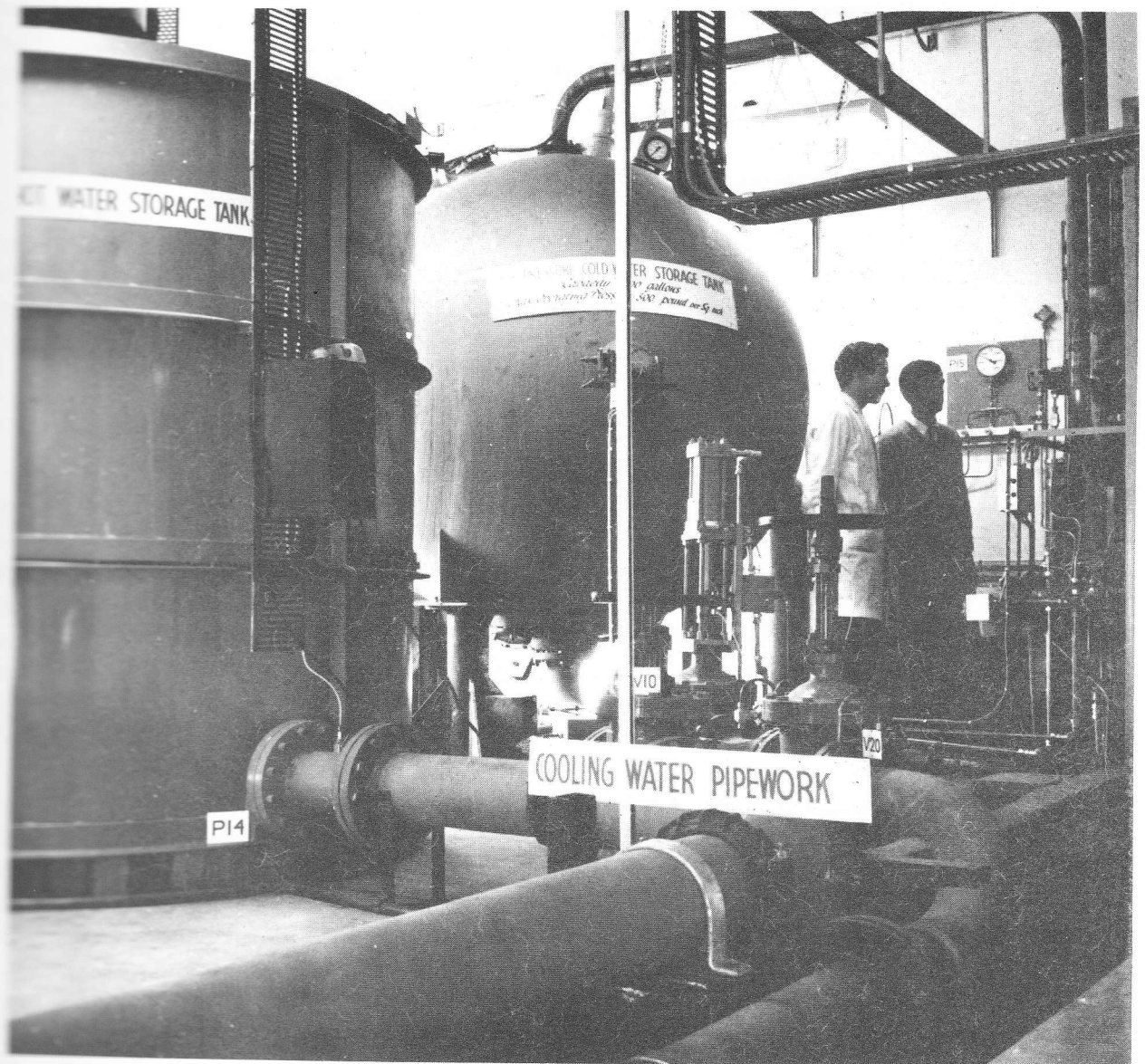


Figure 9. The cold storage tank (spherical), hot storage tank and some of the piping and valves.

air flow is to be preferred to direct throttling of the water. Firstly, the size of the valve to be servo operated is smaller for air throttling. Secondly, one obtains a smooth water flow free from the danger of water hammer, and thirdly, there is a slight thermodynamic advantage gained from air throttling in that the energy dissipated in the throttle is returned to the air causing further expansion. However, a simple on-off water valve is required to prevent initial flow by gravitation and to finally halt flow after a pulse when compressed air still in the cold reservoir would otherwise maintain it. This valve is hydraulically operated and is equipped with a hydraulic device which limits the closing rate thus preventing water hammer.

A feature of the A. N. U. cooling system is the conservation of compressed air. After a pulse, a high pressure multistage centrifugal pump is used to pump the water in 5 minutes or so from hot storage through heat exchanger to cold storage. In so doing, compressed air is displaced through a bypass valve back into the compressed air reservoir. This feature, besides being an economical way to compress air, ensures the minimum time between pulses.

### 2.3.1 Dissolved air

Building a water circulating system where water and compressed air were in contact for appreciable times was not engaged upon before considerable thought was given beforehand to the problem of dissolved air in the water. This was particularly pertinent because of the possible deleterious effects of oxidation upon the many electrical contacts within a Bitter solenoid. However, it was clear that this danger could be reduced by ensuring chemically pure water and in any case in principle an impermeable membrane could always be inserted in the cold storage tank to separate air and water. A theoretical study based on the known diffusion properties of air in water revealed that there was a great dependence on the mean exposure time of water molecules to the regions close to the water surface adjacent to the compressed air. The study, appearing in detail in Appendix I, may be summarised by Figure 10, where it will be seen that short exposure times, characteristic of rapid eddies of small dimensions, favour rapid solution. Consequent to this study, return water from the heat exchanger was introduced into the 6 in. diameter outlet pipe of the cold storage tank rather than directly into it in order to reduce eddy velocities at the surface. Ideally, by means of flow dispersing vanes, it should be possible to reduce surface velocities to the order of magnitude of the rate of change of water level, but because such devices are bound to interfere with the rapid efflux of water from the cold storage vessel, they have not been considered. It is thought that the rate of change of level has a limiting effect because of viscous effects at the tank walls (see Figure 11). It was thought that surface velocities during the slow refilling of the cold store would be somewhere between the efflux velocity from the 6 in. pipe and the rate of rise of level, i. e. somewhere between 45 ft/min and 1/2 ft/min. Assuming a surface exposure distance of 1 ft (vessel radius 3 ft), it was therefore concluded that exposure times should be between one or two seconds and 2 min. Recent measurements (Figure 10) on the system indicate that actual values of exposure time are between 1 and 2 min.

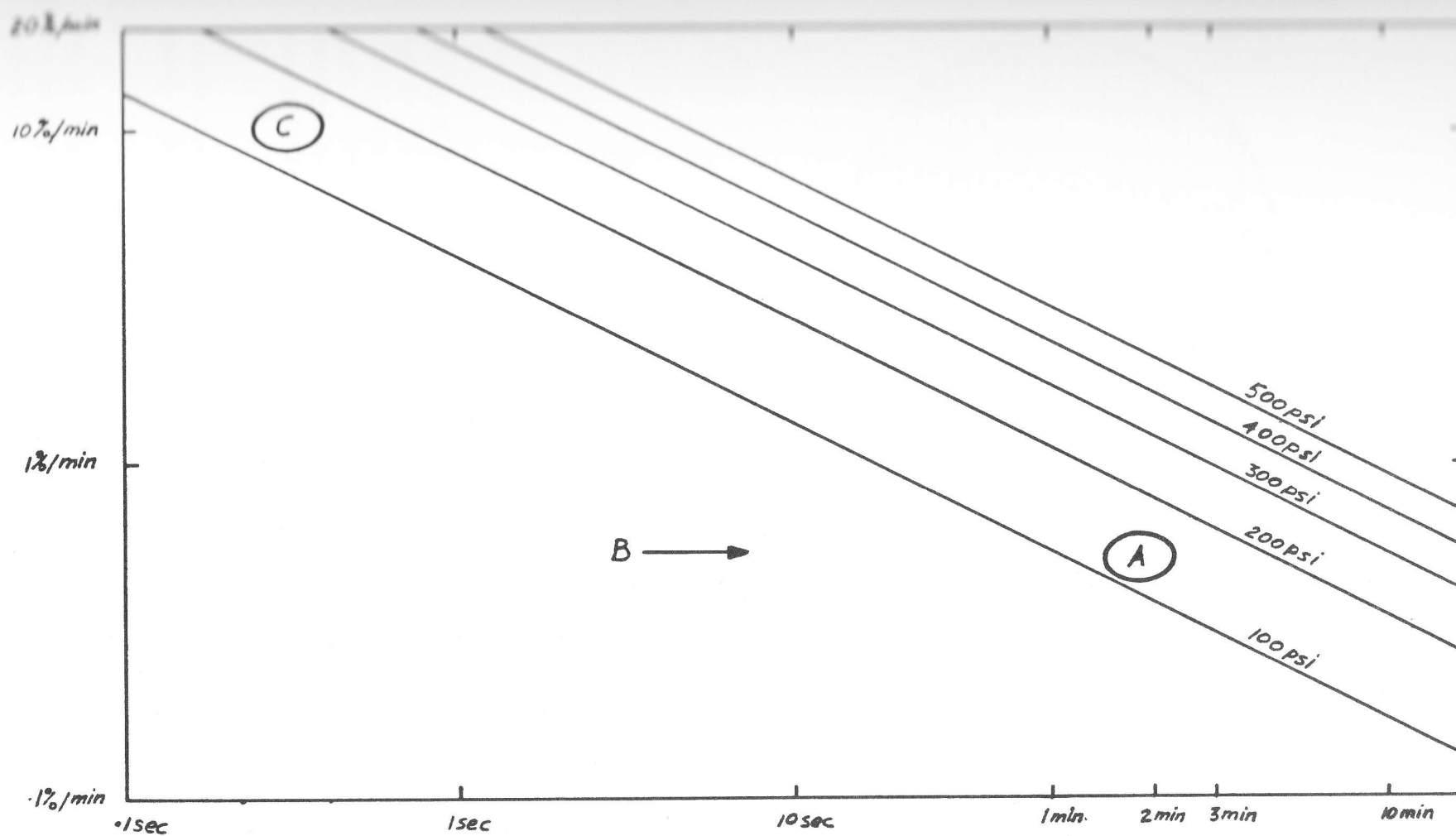


Figure 10. Rate of solution of dissolved gas in water vs. mean exposure time of water molecules to surface layer. Rate of solution is expressed as percentage of saturated value at atmospheric pressure per minute.

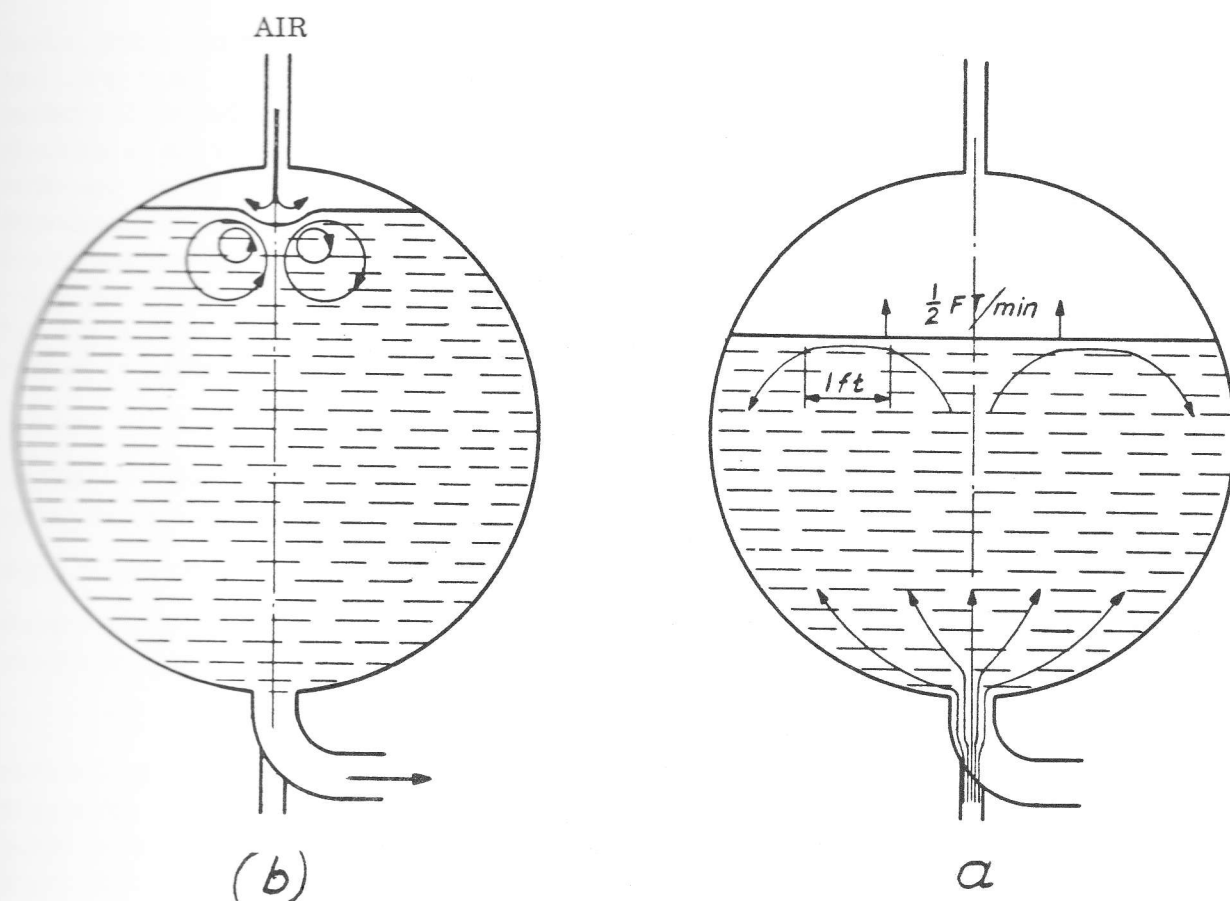


Figure 11. Diagrams illustrating probable flow eddy currents in cold store (a) during slow filling (pump back) and (b) during pulsing.

During the rapid flow pulse through the magnet, conditions are quite different in the cold storage vessel. Apparently the rapid entry of compressed air induces surface turbulence giving a 20-fold increase in rates of solution and a corresponding exposure time of only  $1/4$  second or so. This effect is worsened no doubt by the fact that it is customary to begin a pulse with the cold stored water at atmospheric pressure. The small air space above the water has therefore first to be pressurised, causing the initial air velocity to be quite high for a short time.

Despite the high rate of solution during a pulse, the duration is comparatively short and the total quantity of air introduced is in fact about the same as during the slower more docile part of the cycle.

The initial development of the magnet cooling system was based on an assumed average figure for air solution of 0.5% per minute during a working day's cycling. The percentage figure refers to the percentage of the equilibrium air concentration at atmospheric pressure and ambient temperature. On this

basis, 100% corresponds to approximately 8 p.p.m. (by weight) of dissolved oxygen and 16 p.p.m. of nitrogen. (The laboratory acquired a biological dissolved oxygen meter calibrated to this scale which has proved most useful in understanding the mechanism of air solution.) It was planned to provide a vacuum deaerator capable of reducing the air concentration overnight to a low value. The simplest way of operating this deaerator was to draw off from the hot water storage tank a continuous flow for treatment and to return the deaerated water to a different part of the same tank. Provided there was good mixing in the storage tank, the air concentration there should fall exponentially overnight, the time constant being simply volume of water stored/rate of treatment.

In our case the stored volume was approximately 1000 galls so that by selecting a treatment rate of 10 g.p.m. one should obtain a time constant of under two hours. **Starting from 100%** therefore, it was hoped that in 12 hours overnight (6 time constants) the air concentration would be reduced to  $(\frac{1}{e})^6$  or  $\frac{1}{4}\%$ .

Furthermore, it was calculated that this same deaerator operating during the day should be able to limit the concentration to 50% (with air dissolving at 0.5% per min).

The important consideration, however, was to be able to reduce concentration rapidly at the commencement of shut down periods and in this regard the selection of a treatment rate of 10 g.p.m. seemed adequate. Without adequate knowledge of the mechanism and rate of air solution and its effects, it seemed imprudent to outlay any more money on this or any alternative method of lowering air concentration.

In practice we have measured average air solution rates of over twice the assumed figure of 0.5% per minute. This we believe is partly due to turbulence introduced during pulsing as already explained. Over 400 pulses have been taken by the magnet since August 1966 and so far no ill effect has been noticed on the electrical or cooling characteristics of the magnet. We are, however, designing a plastic membrane and hope to introduce it at a later date.

### 2.3.2 Water purity

Water purity is monitored by means of a conductivity cell and meter and is generally below 1 micro mho per cm. Materials used in contact with the water have been selected for their resistance to corrosion in the presence of oxygen. Thin-walled (up to 16 s.w.g.) pipes and vessels are generally stainless steel. Large pipes 6 in. diameter are mild steel with an internal formaldehyde coating. The interiors of 6 in. valves and the cold storage tank (a pressure vessel) are similarly lined. The use of corrosion resistant materials and linings has been extended to include the compressed air reservoir and connecting pipe work to the cold storage vessel. This has been done to prevent scale being produced in a region where it may easily be blown into the water and finally block the small cooling holes in the magnet (typically 1/8 in. diameter or less).

A commercial demineralizing plant is in use having a capacity of 100 gals per-hour and a special oxygen resistant element.

### 2.3.3 Design considerations

The essential elements of the water cooling system and their sizes are shown in Figure 12. The capacities of the storage tanks are related to the energy storage capacity of the h.p.g. If the maximum of 500 megajoules is released (no matter at what power level), the temperature rise in the 160 or so cubic feet of available water will be 9°C. However, when allowance is made for margins at either end of a pulse (to ensure a power pulse always occurs within the period of a water pulse), and for reduced capacity in cases where high pressures are required, as will be explained later, a more likely figure for the water temperature rise through the magnet is 20°C or 30°C. Higher average water temperature rises are not advisable because hot spots in a magnet are always likely to increase local water temperature rises considerably; because for economical heat transfer in the heat exchanger and associated heat sink, magnet inlet water temperatures may be as high as 30°C; and because boiling within the magnet is to be avoided due to the resulting unstable heat transfer coefficient.

Pipe sizes in the pulse circuit have been selected as a compromise between cost and friction drop over the length involved (dictated by the geometry of the building).

The design performance is given in Figure 13. Here, available pressure at a magnet is plotted against flow for two particular values of pressure in the cold storage vessel. Constant flow pulses are visualised during which the air valve is throttled in such a manner as to maintain constant pressure in the cold storage vessel despite the consequent drop in pressure in the air reservoir. Obviously the cold storage vessel's pressure can be maintained only as long as it is lower than the air reservoir pressure. The quantity of water ( $Q$ ) transferred before equality of pressure occurs depends on the dimensions of the air reservoir (volume  $V$ ), the initial pressure ( $P_0$ ) within it, and the pressure being maintained in the cold storage vessel ( $P_2$ ). Analysis shows that for adiabatic conditions in both vessels,  $Q = \frac{V}{\gamma} \left( \frac{P_0}{P_2} - 1 \right)$ . ( $\gamma$  being the ratio of specific heats of air at constant volume and constant pressure.) The capacity of the air reservoir, 230 cubic feet, has been chosen so that all the water may be expelled from the cold store when the pressure is maintained there at half the initial air reservoir pressure. The lower curve on Figure 13 refers to this condition when  $P_0$  is at its design maximum of 500 p.s.i. The upper curve is for a higher  $P_2$  in which case the quantity of water transferred is reduced to half.

### 2.4 System Control

The safe, efficient control of the equipment described necessarily occupied a great deal of the designer's attention. It is gratifying, but at the same

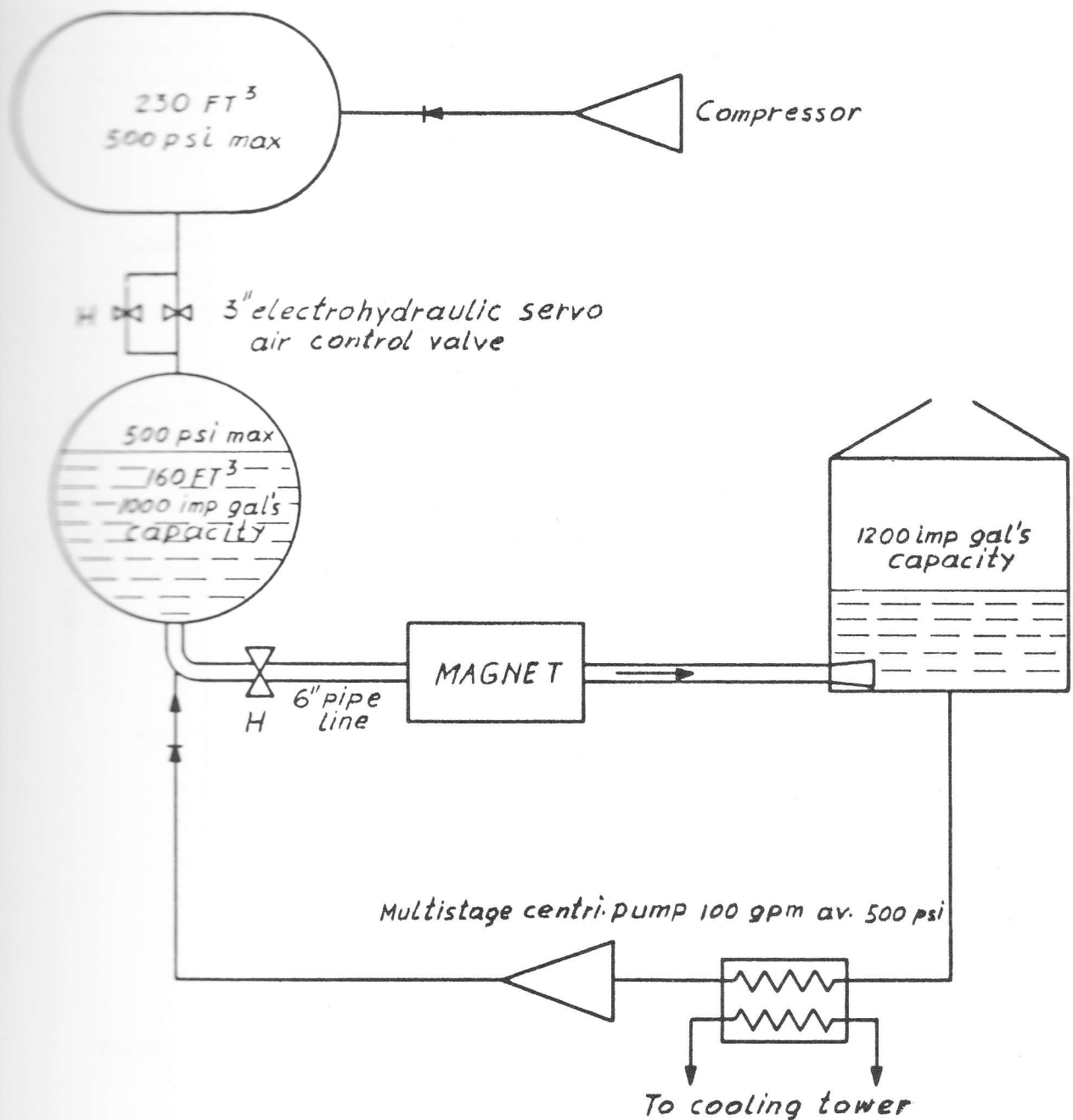


Figure 12. Diagram of water cooling system showing essential components, capacities, pressures. Valves marked "H" are operated on and off hydraulically.

time sobering, to realize that in the first few months of operation most of the safety routines provided were at one time or another called upon to prevent a dangerous situation developing. However complex the system may appear, it has shown its worth and in fact has since been added to rather than reduced.

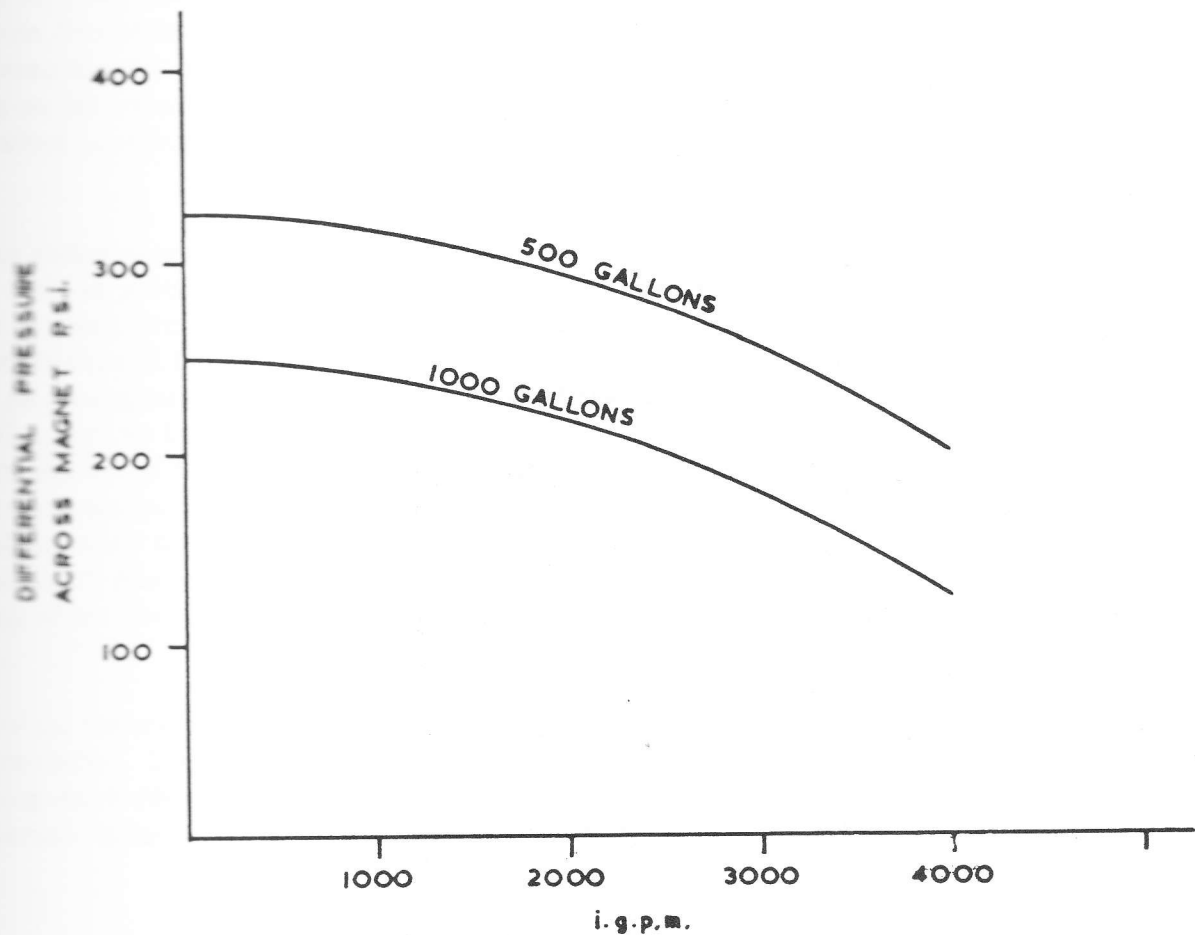


Figure 13. Pressure available at a magnet vs. constant flow for two particular values of initial pressure in the cold water storage vessel. Upper curve, 500 imp. gals. transferred; lower curve 1000 imp. gals. transferred.

The control problem may be divided into two broad sections: the gallery of control; and the technical means of achieving it. It will be mainly the former that will be discussed here since it is this that lends purpose and consistency to the latter.

### 2.4.1 Policy

At the time of conception of the Magnet Laboratory, the h.p.g. and electrolytic variable resistor were going concerns. It was imperative that the magnet laboratory control system interfere as little as possible with the existing h.p.g. system and it was just as imperative that the h.p.g. system should not be orientated towards any particular user but should remain capable of the maximum flexibility. Under these circumstances there was little choice other than to create for the magnet laboratory, an independent system, relying as little as possible on information from the h.p.g. system and even possessing built-in protection against possible malfunctioning of that latter system.

As has already been described, the electrolytic resistor was endowed with an additional latch feature which converted it into a circuit breaker as well as a current regulator. This resistor therefore presented a curious problem: its current regulating feature was traditionally an integral part of the h.p.g. system but its circuit breaking capability, being the only means of de-energising the magnet in an emergency, was an essential part of the magnet control system. The policy solution was as follows: it was the responsibility of the h.p.g. to provide the magnet current asked for; it was the magnet laboratory's responsibility to ensure that this current was within safe limits with due regard to the quantity of cooling water flowing, and to cause the circuit breaker feature to trip should the safe limits be exceeded. The latch mechanism was therefore tied into the magnet system, the rest of the operation of the electrolytic resistor remaining tied to the h.p.g. system.

As far as automatic operation was concerned, the policy was that all the operations for a water pulse, together with essential monitoring should be automatic. The reason for this was solely on account of safety and efficiency. During pump-back (the slow return part of the cycle) however, operations were entirely in the operator's hands except with regard to certain safety overriding features.

### 2.4.2 Operating modes

It was recognised that on many occasions water pulses alone would be required, without necessarily involving the h.p.g. control system. There would also be occasions when individual components would be required to operate without involving the full sequence of events of a water pulse. These occasions would occur during testing and maintenance. To make provision for this need, the policy was expanded to include two modes of operation: "mode op" and "mode non-op". The later was a non restrictive mode where every item could be individually operated provided such operations were basically "safe". For example in "mode non-op" the isolator could be opened or closed at will, the only restrictions being that it could not be closed on live busbars or opened when carrying current.

Another example was the water valve, which could be operated at will except that it automatically closed when the water level in the cold storage

vented was very low. This was to prevent compressed air being blown through the water system and into the hot storage vessel. An additional back up protection was that concurrently the hot storage vessel was opened to atmosphere. These restrictions were quite basic and always in force in either mode. Each operable item had a set of similar basic restrictions which were always in force.

In contrast "mode op" was quite restrictive. In this mode, items operable in a pulse were under automatic control only. The term "safe" now had a wider scope because in this mode it was possible to receive electric power from the h. p. g.

The idea of two modes could only be pursued, of course, if it were made impossible to receive h. p. g. power while in "mode non-op". Provision against this happening was incorporated in the policy of pulse initiation. The view was taken that the h. p. g. could initiate a pulse at will but it was the magnet laboratory control system's responsibility to accept the power only when it was safe to do so and when it was required. (In practice of course power is delivered when required, but the safety of the magnet should not be dependent on this being always so.) The magnet laboratory's control system does this by compiling automatically a check list of all essential conditions to be fulfilled prior to a pulse. It requires then a warning signal from the h. p. g. two seconds before the h. p. g. initiates a power pulse. This signal is used to initiate water flow and to close the isolator switch. When the system has established that the isolator is closed and that water flow is adequate, the latch mechanism is primed, thus allowing the electrolytic resistor to be raised to the conducting condition. An essential item on the check list is that the mode must be "mode op". Only when all items on the check list are fulfilled will the control system accept the warning signal from the h. p. g. To aid communication, a "ready" signal is sent to h. p. g. control at this time also.

#### 2.4.3 Normal sequence

During normal current pulsing, the mode is, of course, set "mode op" and the following sequence of events occurs. We will assume a current pulse has just occurred and we shall follow events up to the initiation and through the execution of the next current pulse. The operator, by push button control, starts the high pressure pump and opens the "bypass valve" which allows displaced compressed air to return to the air reservoir. The pump is automatically switched off by a float switch in the cold water storage reservoir. At the same time a "level correct" signal is registered in the automatic check list.

Sometime during this "pump back" stage another "level correct" check list signal will have been registered indicating that there is sufficient room available in the hot storage tank to receive a full pulse of water.

The operator will close the bypass valve by push button and open a vent valve allowing the small quantity of compressed air left in the cold store

to escape to atmosphere. The equipment is now in a "standby" condition. Only two items will normally be required to complete the check list, and the water, not being in contact with compressed air, will remain at a steady level of air concentration (or slightly decreasing with time due to the evolution of small air bubbles in regions rendered supersaturated after the reduction in pressure to one atmosphere).

Items not yet mentioned which will by now have been registered on the checklist are:

--gauge pressure in cold store zero (necessary to eliminate excessive side loads on the gate water control valve while opening, a situation which might cause excessive and variable delay).

--air valve ready--indicating the function generator is ready to begin its cycle.

--hydraulic pressure okay--essential because of the dependence of operations on hydraulic power.

--three manually-operated valves in correct position.

--air pressure in reservoir satisfactory

--water temperature satisfactory

--isolator switch open

--busbar and circuit breaker insulation satisfactory

--magnet resistance satisfactory

The last two items are included to check that odd items such as tools or wires have not been left in dangerous positions, and to check the state of the insulators in the electrolytic resistor which are subject to immersion in caustic soda.

The remaining two items on the checklist are:

--vent valve closed

--operator's confirmation that all is ready including the experimenter--indicated by pressing a "ready" push button (this confirmation is automatically lost should any item on the check list subsequently disappear prior to the initiation of a pulse).

Once an operator has completed the list, a "ready" signal is sent to the h.p.g. control and the magnet laboratory's control system will now accept

an initiating signal from the h. p. g. When this arrives, the following events occur automatically:

- the function generator commences cycling, in a half second or so opening the air valve and pressurising the cold storage reservoir.

- the water valve opens

- the isolator closes

Normally in two or three seconds all these operations have been completed and a substantial quantity of cooling water is flowing. The control system checks that this is so and then inserts the latch in the circuit breaker mechanism just prior to the rising of the tank of electrolyte.

#### 2.4.4 Protection against faults

Should the latch be inserted too late, the tank will not follow the cam and the circuit breaker will remain open throughout the time of the pulse.

On the other hand should the latch be inserted, but for some reason the tank be considerably late in rising, the latch will again be withdrawn. These two features prevent serious lack of synchronism between the current and water pulses.

The occurrence of any of the following during a pulse will cause the circuit breaker to trip:

- magnet temperature too high

- water flow too low compared with electrical power input

At the end of a pulse, the completion of the electrolytic resistor control cam cycle initiates an "end of cycle" signal which opens the isolator and closes the water valve (the function generator controlling the air valve by this time having completed its cycle). At the same time the circuit breaker latch is withdrawn and the system is ready for "pump back".

#### 2.4.5 Control hardware

Practically all the logic circuitry for the magnet laboratory system is comprised of identical modules each of which may be made to perform the logic functions of "and" or "or" and which contain a driver stage used to energise indicating lights and relays. The modules, made at the A. N. U., use silicon transistors mounted on plug-in printed circuits.

Mimic displays are used extensively. An inexpensive, reliable and flexible method for constructing mimic diagrams has been developed at the Magnet Laboratory which makes use of ink drawings on special drawing material. Figure 14 shows the control panels and instruments.

## 2.5 Instrumentation

Instrumentation provided in the laboratory (apart from experimenters' instrumentation) includes a float driven potentiometric contents gauge in each reservoir and a back-up pressure-operated contents gauge in the hot water reservoir; a propeller driven water flow meter (the propeller producing electrical pulses at a rate proportional to flow); a multichannel temperature indicator using thermistors; insulation and magnet resistance meters, various pressure gauges, magnet voltmeter, a magnetic field meter employing a field pick-up coil and an electronic integrator, and a multichannel galvanometer recorder.

## 3. The Future

Undoubtedly the main work of the laboratory at this stage must be oriented towards building and putting into operation as soon as possible the 300 kilogauss magnet. Many physicists from Australia and overseas have indicated that they would wish to experiment in such a field and have expressed the opinion that this venture is of great value to science.

The main purpose of the existing 165 k. g. magnet is therefore to establish a working laboratory as soon as possible and to give us experience with the sort of problems likely to be met with the larger magnet.

Experiments in solid state physics have been carried out with the present magnet by Monash University's Physics Department under the direction of Professor Street. The results of these experiments will be published in the scientific literature in due course. Other experiments are planned for the near future and it is anticipated that as facilities increase the 165 k. g. magnet will come into almost full time operation.

Design of the 300 kilogauss magnet has not yet been finalized. It is expected that this magnet will weigh about 3 tons and require a total power of some 30 MW., divided approximately in the ratio of 2:1 between outer and inner solenoid respectively. The solenoids will be connected electrically in parallel, requiring 200,000 amperes at 150 volts. It is hoped to have the magnet operational towards the middle of 1968.

Some effort is being channelled into solving the problem of more precise magnet current control. It is anticipated that eventually magnetic field stability of 0.1% will be required. There are three ways this might be practically achieved: by controlling the h. p. g. field; by providing a set of radially moveable inner brushes on the h. p. g. which would convert the h. p. g. into a variable voltage machine; or by a series resistor.

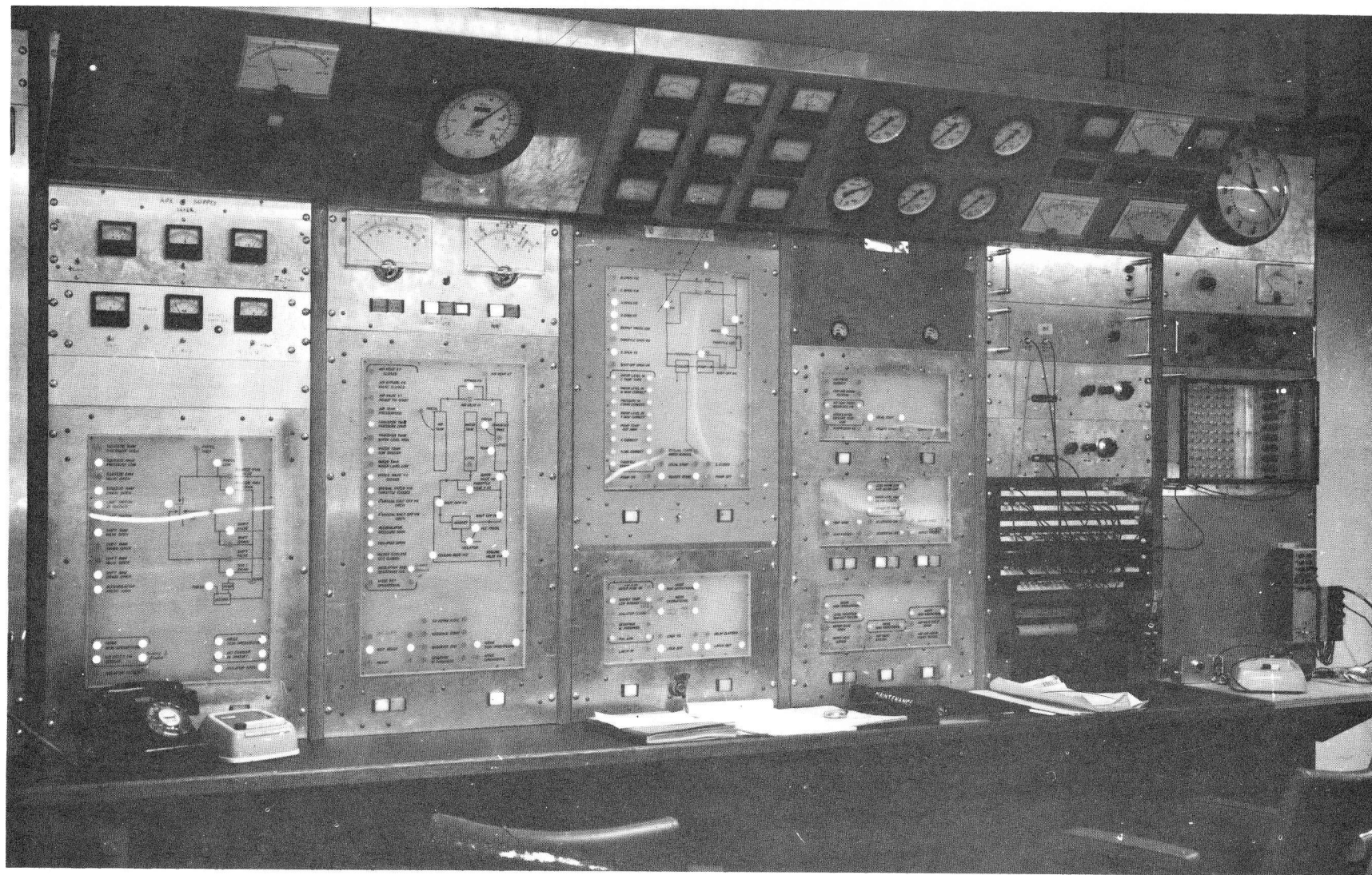


Figure 14. Control panels and instruments, showing mimic diagrams, ultra-violet galvanometer recorder (5th panel from right), air valve function generator (6th panel), meters and gauges overhead.

The last method is now being used, but a h.p.g. current feed back would have to be employed to obtain the accuracy called for. The first method is not applicable when powers exceed 40 MW or so because the inductance of the h.p.g. field windings will not allow a rapid enough increase in field to compensate decreased rotor speed without seriously exceeding their voltage rating. The second method is the most promising offering as it does fast response and high efficiency. R. A. Marshall of this department, who developed the original brush gear for the h.p.g., is at present working on this solution.

#### 4. Conclusion

Although the A.N.U. Magnet Laboratory is in its infancy, it holds promise, given the chance, of making significant contribution to science. If it is successful, it will be by virtue of the present monopoly it holds on large power sources and by the calibre of the researchers it is able to attract in this present developing stage. It is therefore, like most scientific ventures, a gamble and being just that, is prone to falling victim to the attitude which questions its worth in favour of ventures having more recognisable returns. It is hoped that this attitude will not prevail and that the project will meet with the support it needs to become a resounding success.

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## APPENDIX I

### The Mechanism of Solution of Air in the Cold Storage Vessel

Consider first a vessel partially full of water containing no dissolved air and having absolutely no motion. If the rest of the vessel is now filled with compressed air we may consider that the surface layer of the water instantaneously dissolves air up to the equilibrium concentration level given by Henry's Law.

Henry's law applied to our case states that the equilibrium concentration of dissolved oxygen or nitrogen in water at a certain temperature is proportional to the partial pressure of the gas in contact with the water.

Migration of the dissolved gas beyond the surface layer is a process of diffusion, the basic equation of which is

$$J = -D \frac{\partial c}{\partial x}$$

where  $J$  is the diffusion flux, for example, gms of dissolved gas crossing unit area per second (the area being parallel to the water surface);

$c$  is the local instantaneous concentration of dissolved gas, for example, in gms per c. c.

$x$  is the distance co-ordinate normal to the surface (in cms) and

$D$  is the diffusion coefficient whose value has been taken for the components of air as

$$D = 10^{-4} \text{ cm.}^2/\text{sec}$$

The result of the diffusion process is that the saturated surface layer grows in depth and one may gauge the rate of growth by defining a boundary depth  $Z$  such that from the air-water interface to depth  $Z$  the water is substantially saturated, for example it is at or close to the equilibrium concentration level, and beyond  $Z$  the concentration is substantially zero.

It can be simply shown that  $Z$  is of the order of magnitude

$$Z = \sqrt{D t_e}$$

where  $t_e$  is the time the water surface has been exposed to the compressed air.

Substitution of representative values will show that when there is no motion in the water the relative amount of dissolved air entering the water is insignificant.

$$\text{e.g. if } t_e = 10 \text{ mins}$$

$$Z \approx 1/4 \text{ cm,}$$

which must be compared with an average depth of remaining uncontaminated water of approximately 80 cms.

Let us now consider the case where there is motion within the water of the form of non turbulent eddy currents of a circulatory nature about horizontal axes. There may be a number of these currents circulating in different directions. We are interested in those which have the air-water interface as a boundary. Each of these may be considered as disturbing the surface over a length  $y$  and width  $x$ , the characteristic surface velocity (in the  $y$  direction) being  $v$  (see Figure 15).

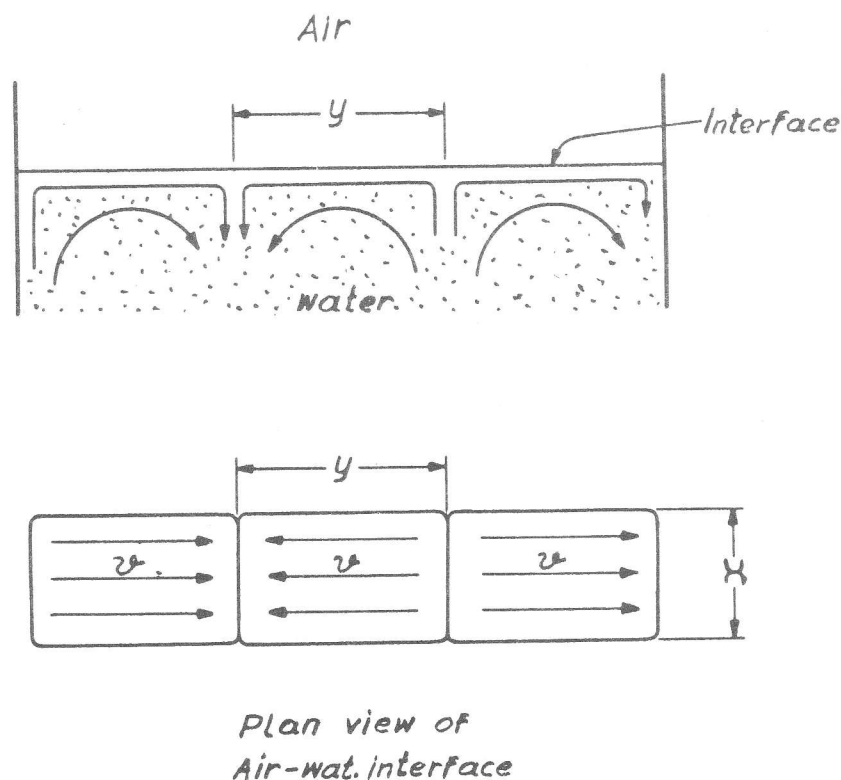


Figure 15. Idealized eddy currents illustrating terms used in the analysis.

The exposure time for a surface particle will therefore be

$$t_e = \frac{y}{v}$$

When a surface particle finally submerges after time  $t_e$ , we may consider that the water to a depth  $Z$  below it has reached saturation. We will assume that this saturated layer mixes thoroughly with the rest of the water before being exposed to the surface again.

In time  $t$  therefore the total surface area exposed will be

$$A_e = vt \times \left( \frac{A}{xy} \right)$$

where  $A$  is the area of the interface surface,  $\frac{A}{xy}$  being the number of eddy systems disturbing the surface.

The total volume of water reaching saturation is therefore

$$\begin{aligned} V_s &= A_e z \\ &= \frac{vtA}{y} \sqrt{Dt_e} \\ &= \sqrt{\frac{D}{t_e}} \cdot At \end{aligned}$$

The average rate of increase in concentration over water volume  $V$  is

$$\frac{\Delta C_{av}}{t} = \frac{V_s C_s}{V} = \sqrt{\frac{D}{t_e}} \cdot \frac{C_s}{h}$$

where  $C_s$  is the equilibrium (saturated) concentration and  $h$  is the characteristic depth of water ( $= \frac{V}{A}$ )

Figure 10 is a plot of this equation for various air pressures, the water temperature being about  $20^\circ\text{C}$  and  $h \approx 1$  meter. The ordinate  $\frac{dC_{av}}{dt}$  is for any component of air in terms of percentage of saturation at atmospheric pressure.

It will be seen that during pump-back, measured values of  $\frac{dC_{av}}{dt}$  for oxygen imply  $t_e \approx 1-2$  min. which as explained in the text is about as large as one can expect with ideal flow re-entry geometry.

During pulsing  $\frac{dC_{av}}{dt}$  was found to be very high indicating short exposure times consistent with small rapid eddies.