CONFERENCE REPORTS

Summarized Proceedings of a Symposium on Electronic Devices at Helium Temperatures—London, November 1960

Abstract

A one-day symposium on electronic devices which work at helium temperatures was held jointly by the Low Temperature Group and the Electronics Group of The Institute of Physics and The Physical Society on 15th November, 1960. The emphasis was on devices which could be used in electronic computers. Recently there have been considerable advances in the research on Crowe cells and cryotrons. Both devices can be switched at high speed ($\sim$ 10–15 *ns) and the factors governing their performance are fairly well understood. There have been equal advances in the development of a helium refrigerator of great reliability and efficiency. With cryotrons, the conditions for reproducibility are far less stringent than with the Crowe cell and, as four terminal devices with current gain, they offer great flexibility to computer designers, being capable of use both in the store and in logical components. The p–n junction, tunnel diode, and cryosar are all based on semiconductors and all work at helium temperatures. They could be very useful ancillary devices in computers based on superconductors or, on the other hand, computers could be based on these devices entirely and the use of liquid helium is then unnecessary. However, taking into account the low heat dissipation and close packing feasible with superconductive devices* (10^7 *bits in a 35 cm cube), where fast computing is concerned the cryotron offers great advantages. It is, moreover, a device of universal application throughout a computer which may demand a new approach to logical design and the layout of the machine.*

Introduction

Eight papers were read at this symposium; they were 'An introductory survey' by Dr. D. H. Parkinson (Royal Radar Establishment), 'Superconductors' by Dr. J. M. Lock (Royal Radar Establishment), 'Crowe Cells' by Dr. E. H. Rhoderick (Services Electronics Research Laboratories), 'Cryotrons' by Dr. D. R. Young (I.B.M., Poughkeepsie, U.S.A.), 'Work on cryotrons at the N.P.L.' by Dr. J. S. Hill (National Physical Laboratory), 'p–n junctions at low temperatures' by Dr. A. K. Jonscher (G.E.C. Research Laboratories), 'Computers of the future' by Dr. J. S. Gill (Ferranti Ltd.), and 'The cost of using helium devices' by Dr. E. Mendoza (Manchester University). This report summarizes their contents and the subsequent discussions which tended to centre on the use of devices in computers.

The first part of this report deals with superconductors and devices based on them, the second part with low temperature devices based on semiconductors, the third with liquid helium refrigeration and consequent problems, finally some appreciation of the future outlook is given.

Devices based on superconductors

From the time when superconductivity was first discovered in 1911 thoughts have turned to possible applications of the phenomenon of zero resistivity. The first ideas concerned the generation of high magnetic fields in superconducting solenoids which has received renewed attention recently. Since then there have been many applications of superconductivity most of which have remained inside low temperature laboratories. The superconducting bolometer was developed during the war by Andrews as a detector of infrared radiation and has continued to receive attention. Other examples are superconductive amplifiers of very high sensitivity (e.g. de Vroomen and Van Baarle 1957), the superconducting galvanometer (Pippard and Pullan 1952) capable of detecting 10^{-5} ampere in a resistance of 10^{-7} ohm, besides various switching devices (e.g. Templeton 1960).

The cryotron was first described by Buck (1956) and was soon followed by the Crowe cell (Crowe 1957). These two devices and particularly the cryotron have received much attention. Two rather similar devices, the persistatron (Buckingham 1957), and the persistor (Crittenden 1957) have also been proposed though there has been little recent work on them. The Crowe cell and cryotron work in quite different ways; to appreciate their operation and the significant differences, it is first necessary to outline the relevant features of the superconducting transition itself.

A superconductor is a metal such that below a well-defined temperature, the transition temperature T_c, all traces of electrical resistivity are non-existent. This sharp transition is not only characteristic of pure metals, but also impure metals and alloys provided they are sufficiently ordered. Thus well annealed tin specimens containing 2% of indium can have transitions only about one thousandth of a degree wide, even though such an impurity concentration is sufficient to increase the normal resistivity just above the transition to 1000 times that of the purest tin. This feature is significant for superconducting devices where a reasonably large normal resistance is required. Roughly one-third of all the metallic elements are superconductors above about $0 \cdot 1°$ K. None of the monovalent metals or alkaline earth metals are superconductors. There are many superconducting alloys some of which have components which are themselves not superconductors.

In the superconducting state the resistance of the material is zero. The most sensitive test of this point is provided by the Crowe cell itself in which the persistent current shows no observable decay over long periods of time. It can easily be shown that the resistance in the superconducting state must be less than 4×10^{-14} of its normal value at the most. Below T_c, the normal resistance can be restored by applying a high enough external magnetic field, the critical field H_c, which plotted as a function of temperature is parabolic (see Shoenberg 1952). The destruction of superconductivity by an applied field can be sharp, e.g. $0 \cdot 1$ gauss wide, and forms the basis of operation for the cryotron.

It follows from the property of zero resistance that in the superconductive state the value of B, the magnetic flux, in the material cannot change if the external field is changed. Eddy currents induced on the surface of the metal just compensate for any change of external field; such currents are 'super-currents' and flow without decay. However, the interesting feature of superconductors is that not only is dB/dt zero but so also is the value of B. Thus if a specimen is cooled in a magnetic field from above the transition, the flux is suddenly pushed out completely as it passes through the transition temperature. This is the Meissner effect shown first by Meissner and Ochsenfeld (1933). There is a similar effect if the external field is slowly reduced through the critical value H_c at constant temperature.

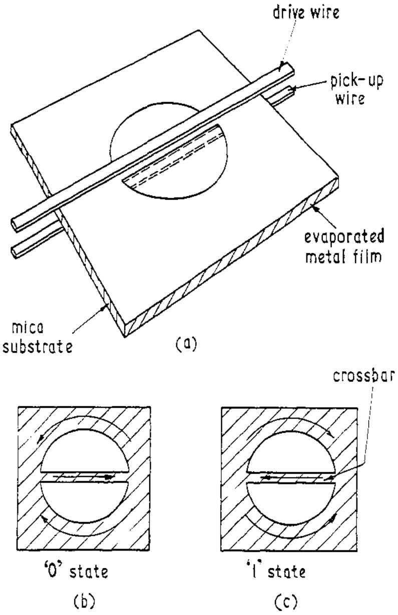

Fig. 1. Diagram of Crowe cell.

When the material is superconducting, the state with $B = 0$ can be regarded as that of thermodynamic equilibrium, and the critical field curve can be treated as the equilibrium curve between the normal and superconducting phases. One can then use simple thermodynamic reasoning to show that the superconducting phase always has lower entropy than the normal phase and is thus more ordered.

The surface currents, responsible for the expulsion of the magnetic flux from a superconductor flow in a surface layer, typically about 1000 Å thick, which extends to the depth to which magnetic fields penetrate, the penetration depth δ. For specimens of thickness similar to δ, such as the films used in Crowe cells and cryotrons, there are two immediate consequences. First the diamagnetic susceptibility falls below the bulk value $1/4\pi$, from which it can be shown that the critical field is considerably increased.

The critical current is also affected in such thin specimens. In bulk specimens the critical current is just sufficient to produce the critical field at the surface of the wire. For films thinner than the penetration depth the critical current is less than that required to produce the critical field at the surface. This is in contrast to the increased critical field and can be shown to be due to the form of the magnetic field and related current distribution through the thickness of the film.

This brief outline of the features of the superconductive transition is adequate for the consideration of the Crowe cell and cryotron.

The Crowe cell consists of thin tin specimens usually evaporated on to mica in which there are two D-shaped holes, back to back, Fig. 1(*a*). It is usually made by leaving a clear circle in a first evaporation and then depositing the 'cross-bar' in a second evaporation. The two states of a cell (0 or 1) are represented by the sense of the persistent super-currents which can be made to flow round the D-shaped holes as in Figs 1(*b*) and 1(*c*). Drive and sense wires are arranged above and below the cell. The whole assembly may be made by evaporation on to a single substrate, with insulation between successive conductors being effected by evaporated layers of silicon monoxide or other suitable material. Alternatively the film with the D's may be put down first on one side of a mica sheet with the drive wire on the other. The sense wire may then be evaporated on to a second sheet which is then accurately aligned with the first.

The mode of operation can be demonstrated in terms of Fig. 2 where the current induced in the cross-bar is shown corresponding to drive current pulses. The induced currents flow in the cross-bar and film so as to oppose any penetration of flux into the film, i.e. through the D's. Assuming unity coupling, during the rising edge of a drive pulse, AB, the cross-bar current, PQS, rises until it reaches the critical value at Q (determined by the thickness of the film), when the flux penetrates. During the rest of the rising edge a pulse is generated in the sense wire. At Q the cross-bar becomes normal and heat is generated in it. When the drive pulse reaches a constant value, the cross-bar current falls according to the L/R time constant of the cross-bar and the

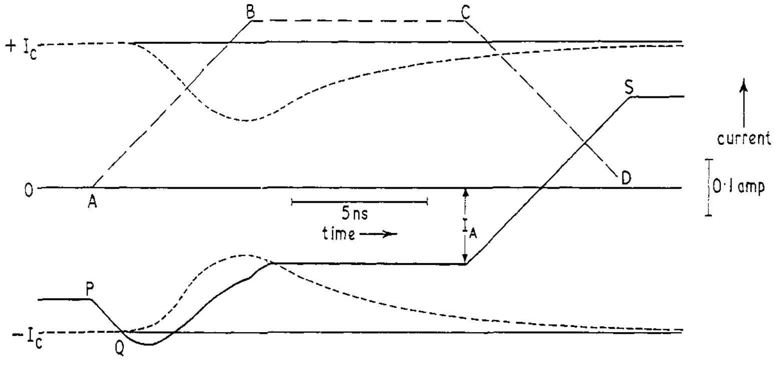

Fig. 2. Switching of Crowe cell.
——— crossbar current, ------ critical current,
— — — drive current.

return path through the film, and eventually reaches the critical value again. The value of the critical current will itself have been reduced owing to the heat generated in the cross-bar. The peak BC of the drive current should be longer than the time constant L/R and the time constant for the dissipation of heat to the substrate. When the drive pulse is removed CD, the cross-bar current, reflects the change and a supercurrent is left circulating in the cross-bar. The operation with drive pulses of opposite sign, half pulses and repeated pulses of the same sign follows logically.

Typical Crowe cells are about 2 mm in diameter with cross-bars about $0\cdot 2$ mm wide and 1000 to 2000 Å thick. They have been made successfully with both lead and tin evaporated on to both glass and mica. The fastest operation has been with those using tin evaporated on to mica, where pulses as short as a few nanoseconds have switched cells with cross-bars of the order of 900 Å thick. In general Crowe cells can be switched with pulses 10–15 ns long and with current amplitudes of about 100 mA. The corresponding sense wire signals are about 10 mv. It has been shown that information can be stored for long periods of time and remain intact against many half-level pulses. Thus the cell is suitable for use with a coincident current drive system.

The Crowe cell is a passive device and the output from one Crowe cell cannot drive another. In any computer with a store based on this cell, the logic would have to be done using other devices. To utilize the high switching speed, the read and write circuits must be arranged so that wires cross the store once only. Fortunately, owing to the small size of the cell, some 10^7 bits could be contained in a 35 cm cube, and the transit time for a pulse to reach the store, cross it once and return to the generator is easily made compatible with the switching speed. A coincident current selection system for writing and reading has been devised, based on the cryosar. The sense signals have also been shown to be capable of switching Esaki diodes (see below) from which a read out register would be constructed. These systems have been described by Lock, Parkinson and Roberts (1961).

It has also been shown that heat dissipation in the store is not a critical problem; a repeated switching rate of 50 Mc/s seems possible. The mechanism of the return of normal resistance in the cross-bar has been studied to some extent. Thermal propagation of the normal phase along the cross-bar plays some part and has at least led to the development of another bistable device, the calotron, which had been described by Broom and Rhoderick (1960); whether this could be used in computers is doubtful.

The Crowe cell, however, suffers from one serious drawback, the tolerances which must be set on the critical current of the cross-bar, on the magnitude of the stored current and on the drive currents when used in coincident current manner, are very tight, and at the best are about 7% to 8% for each (Peacock 1961). This feature may well prevent the Crowe cell having any useful future.

In its original form the cryotron consisted of a straight superconducting wire around which a second superconductor with a higher transition temperature was wound as a small solenoid. The field generated by the solenoid was sufficient to destroy superconductivity in the straight wire, but not in the solenoid itself. Such a device could be used rather as a simple Post Office relay, but is obviously far too slow for use in a modern computer. The cryotron has been developed to consist simply of two thin strips of different superconductors of different width crossing each other at right angles, as shown in Fig. 1 of the accompanying article by Dr. D. R. Young (this will be referred to again as (D.R.Y.)) One strip of width W_c, is the control wire and is usually of lead, while the other of width W_g, is the gate and is usually of tin; W_c is considerably less than W_g. Such an arrangement would usually be made by evaporating the strips on to a glass substrate, but interleaved with an evaporated insulating layer of silicon monoxide. In use, it is operated just below the transition temperature of tin (e.g. $2\cdot 9^\circ$ K) which is far below the transition temperature of lead. The tin gate remains superconducting for currents below its critical current I_c. The strip immediately below the control wire can be made normal if a current through the control wire is sufficient to create the critical field H_c of the gate. Suppose the smallest current to do this is i. Then if i is less than I_c the cryotron has current gain $g = I_c/i$ or a supercurrent I_c in a circuit can be switched by a control current i. Now ignoring in the first place any effect of the ground plane, $H_c = \alpha i/W_c$ where α is a constant and the gate current $I_c = i_c W_g$, where i_c is the critical current per unit width.

Hence we can write

$$g = \frac{\alpha i_c W_g}{H_c W_c} = \frac{H_i}{H_c}\frac{W_g}{W_c}$$

where H_i is the surface field produced by the current i_c per unit width in the gate. We can also write $g = f(t, T) W_g/W_c$, where t is the thickness of the film and T is the temperature of operation. If the film thickness is reduced, f decreases and so g is impaired. On the other hand, when the gate is driven normal the largest possible return of resistance is required which implies the use of the thinnest possible films. These requirements are conflicting and there is an optimum thickness of about 3500 Å. As originally made the current gain of the crossed strip cryotrons was very far short of the theoretically possible values. There have been two factors which have completely changed this situation. First the use of a ground plane (Young 1959), and second the elimination of edge effects in the gate (Delano 1960).

When a strip conductor runs parallel to a superconducting ground plane at a distance small compared with its width the image, in the form of supercurrents in the ground plane, modifies the current distribution and the field between the strip and plane. Between the strip and plane the field is virtually doubled and made more uniform, elsewhere the field is reduced to zero. The gate current is made more uniform across its width and consequently the gate critical current is increased. Likewise the resistance restored in the gate is virtually confined to a strip of length W_c.

Edge effects arise with evaporated films because there is always some sort of penumbra at the edge where the film gets thinner and where there can be many defects. Imperfections change the transition temperature and a change in thickness will change the critical field, both leading to ill-defined transitions. In fact, removing the edges of a film by mechanically trimming it produces a very well-defined and sharp magnetic transition at a lower field. Similarly the temperature transition is also sharpened. Trimming the edges does not affect the critical current appreciably. Annealing, in which the grain size in the films is made more uniform, also improves the transitions. Reduction of the critical field obviously increases the current gain.

Cryotrons which perform in a manner near to the theoretical can now be made. Removal of the edge effects also greatly improves the reproducibility. Gains as high as 10 have so far been achieved though 3 or 4 is quite enough for most purposes. The time constant for switching L/R is governed by the inductance L of the circuit loop involved and the value of the restored resistance R. Time constants as small as approximately 10 ns have been observed. Where the highest speed is required the restored resistance must be high and hence ω must be large; in consequence current gain has to be sacrificed. Control currents of the order of 500 mA are adequate, depending on how close the operating temperature is to the superconducting transition in tin.

The time constant can be shortened by increasing the restored resistance which also reduced the mismatch to a typical superconducting strip transmission line. To this end the 'in-line' cryotron has been studied recently. Here the control and gate wires are parallel and the section of gate which is made normal is very much larger. This arrangement is discussed in the accompanying article (D.R.Y.).

Cryotrons can be used in digital computers in a number of ways; the following are three examples. First, they may be connected as cross-coupled flip–flops as was originally proposed. Second, they can be used as simple switches where a supercurrent is switched into one of two paths, each path being sensed by another cryotron. Third, Haynes (1960) has described an ingenious way in which the information is stored as a circulating current in a circuit loop, Fig. 3. A, B and C are cryotrons; a persistent current in the loop abcd represents 1 and no current 0. To set up a 1, current is applied to wire D and a pulse to E, the gate of B becomes resistive and the current in D is diverted through abcd. Removal of the current from E leaves the current in D still flowing through abcd. The external current supply to D is then cut off leaving a circulating current in the loop abcd. Sensing a 0 or 1 can be carried out by applying a current to wire F, the sense line, and also a pulse to the 'read select line' G. Current in G makes the gate A resistive, and if there is no circulating current in abcd the current in F is diverted through the path efgh which contains the gate of cryotron C. If there is a circulating current in abcd, the current in F cannot flow and is diverted to a parallel superconducting line not shown, so controlling a digit register cryotron which will record the stored 1. Units such as in Fig. 8 are repeated in square array throughout the store. Reading and writing simultaneously but on different parts of the store is possible; reading is also non-destructive.

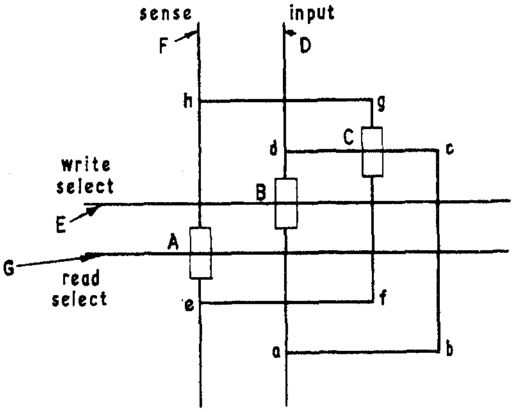

Fig. 3. Cryotron persistent current store.

Tolerances on cryotrons are not at all severe, provided the current gain is greater than 1.

Devices based on semiconductors

The devices of immediate interest are: the p–n junction of which the Esaki or tunnel diode is a particular case, and the cryosar. It ought to be possible to make transistors work satisfactorily in liquid helium. In the accompanying paper by Dr. A. K. Jonscher, there is given the general pattern of behaviour of germanium and silicon p–n junctions as the temperature is lowered. The Esaki or tunnel diode (Esaki 1958) is a particular case of the p–n junction where the level of doping in the two halves is very high. In the p-type material enough acceptors are present to depress the Fermi level into the valence band while in the n-type there are enough donors to raise the Fermi level into the conduction band, Fig. 4(a). Suppose the overlap of the band edge is Δ.

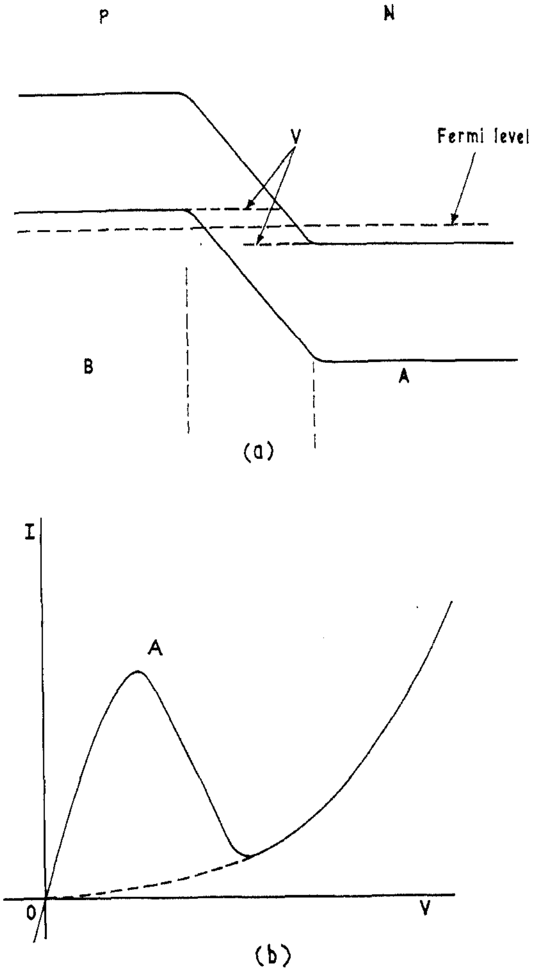

Fig. 4. Esaki diode characteristics.

With no voltage applied across the junction electrons can pass from the Fermi level in A to that in B and vice versa by tunnelling across the junction. This is non-classical process (see, for example, Purcel 1960) and for it to be appreciable the junction must be very narrow. With a small voltage applied across the junction in either direction a current will flow. However, when voltage $V = \Delta/e$ is applied in the forward direction the band overlap will be destroyed and the currents will tend to zero. For greater voltages the overlap is completely destroyed, the situation is comparable with a normal p–n junction with the corresponding current–voltage characteristic. The important part of the characteristic is the region of negative resistance, separating the two parts of the characteristic representing stability and in principle these two states could be used to represent a 0 or 1 in a computer circuit. They represent two different impedances, consequently the circuits would have to be arranged to sense the impedance of the device. By biassing an Esaki diode to a point such as A in Fig. 4(*b*) a very small voltage pulse, such as that from a Crowe cell, is required to drive it to the second part of its characteristic. This has been demonstrated and hence Esaki diodes could be the basis of an output register for a store composed of Crowe cells.

The cryosar (McWhorter and Rediker 1959) is a simpler device relying on the avalanche effect in a semiconductor. Suppose a sample of germanium which contains n-type impurities is cooled and a potential is applied across it. At low enough temperatures phonon scattering of the current carriers is negligible and impurities remain as the chief source of scattering. Provided the concentration of impurity is not too great then between collisions current carriers can absorb enough energy from the potential field to ionize impurity atoms on collision. Thus when the field is high enough the number of carriers increases very rapidly with time and avalanching of carriers occurs. With germanium at helium temperatures a symmetrical current–voltage characteristic is produced as in Fig. 5. The 'corners' such as at X and Y can be fairly sharp; compare with Fig. 3 of the paper by Dr. A. K. Jonscher.

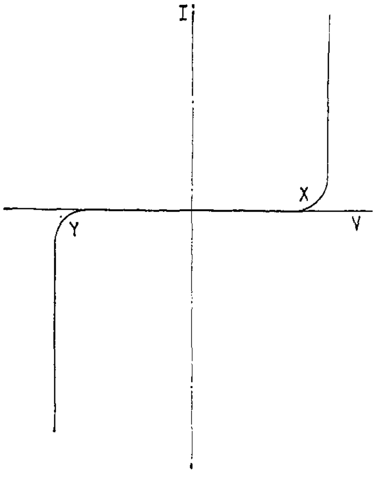

Fig. 5. Cyrosar characteristics.

Helium refrigeration

There is a natural reluctance with computer engineers to consider the computer based on cryogenic devices using liquid helium. The first good reason for this is that the refrigerating device must be utterly reliable and must run reliably for many thousands of hours continuously (1 year = 8760 hours). Laboratory helium liquefiers have not been sufficiently reliable by two orders of magnitude. A second reason is that building computer circuits at room temperature is bad enough, for many circuits have to be adjusted finally by trial and error, to have to cool to helium temperatures during building would be an almost insufferable difficulty. Once built, the computer itself must be reliable and withstand repeated coolings. 'Trouble shooting' at a late stage would also be very difficult. There are replies to all these objections.

Recently the reliability of helium refrigerators has increased markedly. A first prototype machine designed by A. D. Little for continuous closed circuit operation has 1000 hours operation to its credit without any adjustments whatever. (A later report suggests that wear in the driving compressor stopped operations at approximately 2500 hours.) This is within an order of magnitude of what is required. The machine has been described by MacMahon and Gifford (1960).

The principle of operation can be seen by reference to Fig. 6; there R is a regenerator connected as shown to a cylinder containing a displacer X. A and B are inlet and outlet valves respectively, both at room temperature. To begin the cycle imagine the lower end of R cold, the system at 1 atmosphere, and B closed. When A is opened to the high pressure source gas at approximately 300 lb/in^2, gas enters the space P above X and fills the refrigerator. Gas reaching the lower end of R is cooled. When pressure has been built up, X moves upwards, gas is displaced from P through R to Q and is cooled in R. Extra high pressure gas is drawn in through A during this process. A is now closed and B opened. The high pressure gas exhausts through R, cooling it in so doing and carrying heat from the low temperature chamber (Joule effect, and compare Simon expansion liquefier). The displacer finally moves downward and the last cold gas passes out from Q through R. B can now be closed and the cycle repeated. This system is not as efficient thermodynamically as the normal expansion engine; this is offset, however, by the use of a regenerator instead of heat exchangers. Moreover, the only moving part which is cold is the displacer which does not do any work and the only valves are at room temperature. It is easy to see that the regenerator could be placed inside the displacer itself, so combining the cylinder and regenerator unit. For the production of helium temperatures two models of a three-stage machine have been developed, the larger has a refrigerated space of about 1 foot cube and the smaller a space of about four inches cube. Obviously this machine is in its early stages of development and the present promising results show that the first objection to the use of helium can be removed.

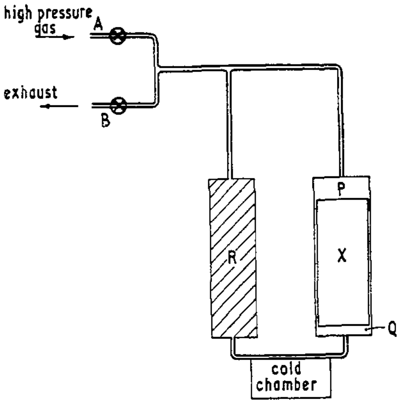

Fig. 6. Principle of helium refrigerator.

The second objection arises from thinking in terms of conventional computers in which there are many different types of circuit element. Computing circuits based on cryotrons are very suitable for design by computers and contain fewer individual components. Complete circuits would have to be designed and produced in one set of evaporations. In future computers of large size and speed it will be necessary to pack circuit elements in large numbers into very small volumes. According to the devices used, techniques of 'microminiaturization' and 'solid circuitry' or sheets deposited by evaporation will have to be used. Whether cryotrons are used or not we are soon to be faced with the necessity of producing complete circuits which work properly at once and need no adjustment. 'Trouble shooting' and replacement of sections of the computer even when cold are not insufferable difficulties provided the computer is designed with these things in view. Remote handling techniques for dealing with circuits at helium temperatures are quite feasible.

As far as cost is concerned, from what is known of the present complete Collins type of liquefiers it is likely that $50 000 should cover a complete installation to deal with a 10^7 bit store. This is not very different from the cost of an air conditioning plant to keep a large modern computer of similar storage capacity at room temperature.

The future outlook

The use of electronic computers is so widespread that it would be difficult to list all the many types of problem to which they are applied. There is no doubt whatever that eventually computers will be used to control all the major industrial processes and most of the minor ones too, most transport problems, traffic by air, sea and land, communications, language translations; besides the more obvious design problems. The field of application is so vast that the electronic computer will, and is indeed having, an impact on our life which is far greater than that of nuclear energy. Unfortunately, this is happening with less publicity and far fewer people are aware of it.

It is likely that large central computers having been set-up will themselves have to be interlinked to exchange information when necessary. This will magnify time of flight problems and consequently computers will have to be capable of dealing with several problems at once, 'switching attention' from one to the other while waiting for data to come in or for the answers to parts of the problem.

Of the devices which have been discussed the cryotron stands out as a device which commends itself for use in fast computing. If it were not for the need to use helium its future would be completely assured; meanwhile since this symposium it is now reported that I.B.M. hope to have a computer based on this device working in 1963.

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