Electron emission depends not only on a steady flow of electrons to the cathode from the external circuit, but also on the presence of very special conditions at the cathode surface, including impurity elements which lower the work function and allow the electrons to escape. The surface condition appears, by every evidence gathered over nearly fifty years, to be subject to inevitable deterioration as the impurity elements boil off or otherwise escape. And there is no sure mechanism for putting them back. So, sooner or later, the emission falls off and the tube goes dead. Much can be done to arrest the deterioration, as in the case of the 40-year submarine cable repeater tube. But the life expectancy of this tube (about 0.02 per cent failures at 1,000 hours) was achieved *in spite of* the fact that it uses cathode emission, not *because* of it. As a result, the tube is used so far under normal ratings, and is so painstakingly put together that its use can be justified only in very special circumstances.

Contrast this with the "million-hour transistor" postulated above. It achieves long life expectancy without overdesign or costly production methods. This is possible because the charge emission process in a transistor is fundamentally different from that in a vacuum tube. The transistor emitter is self-replenishing, indefinitely. Transistors do burn out, of course, for a large number of other reasons; and they do lose their amplifying function if they are overheated. But they do not fail due to exhaustion. Tubes do.

At the moment this difference appears to be fundamentally rooted in the principle of operation of the two devices. If further investigation confirms this view, we may then be sure that long life (which means unvarying ability to amplify) will always be easier to get in a transistor than in a vacuum tube. The conclusion then is evident. We should use transistors, now, where long life and ruggedness is important. We should use tubes in the many areas where transistors, for the present anyway, can't handle the job.

Perhaps, then, we can conclude with the observation that the two devices have a lot to learn, one from the other. In such a situation, fast and easy communication from one group of technical workers to another is essential to rapid progress. The Professional Group on Electron Devices, a single group having cognizance of both devices, is in an ideal position to foster this communication through its conferences, its TRANSACTIONS, and through the PROCEEDINGS OF THE IRE.

The Cryotron—A Superconductive Computer Component*

D. A. BUCK†

Summary—**The study of nonlinearities in nature suitable for computer use has led to the cryotron, a device based on the destruction of superconductivity by a magnetic field. The cryotron, in its simplest form, consists of a straight piece of wire about one inch long with a single-layer control winding wound over it. Current in the control winding creates a magnetic field which causes the central wire to change from its superconducting state to its normal state. The device has current gain, that is, a small current can control a larger current; it has power gain so that cryotrons can be interconnected in logical networks as active elements. The device is also small, light, easily fabricated, and dissipates very little power.**

THE CRYOTRON PRINCIPLE

BEFORE describing the cryotron as a circuit element and potential computer component, the basic physical phenomena underlying its operation will be described.

Superconductivity

Superconductivity was discovered in 1911 by H. Kammerlingh Onnes at Leiden, three years after he succeeded in liquifying helium. While extending electrical resistance measurements to this new low-temperature region he found that the resistance of mercury drops suddenly to zero at 4.12°K. Soon many other materials were shown to display this same unusual behavior. Niobium becomes a superconductor at 8°K, lead at 7.2°K, vanadium at 5.1°K, tantalum at 4.4°K, tin at 3.7°K, aluminum at 1.2°K, and titanium at 0.5°K. In addition to 21 elements, many alloys and compounds are superconductors with transition temperatures ranging between 0 and 17°K.[1,2]

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[1] D. Schoenberg, "Superconductivity," Cambridge University Press, Cambridge, England; 1952.
[2] F. London, "Superfluids," John Wiley & Sons, Inc., New York, N. Y., vol. 1; 1950.

The resistivity of many superconductive materials is relatively high at room temperature, especially those which have high transition temperatures, such as niobium, lead, tantalum, etc. It is interesting that relatively poor conductors become superconductors at low temperatures whereas good conductors such as gold, silver, and copper do not. The resistivity of superconductive materials drops as they are cooled. Just above their superconductive transition, the resistivity is between 10^{-1} and 10^{-3} of their room temperature resistivity, depending on the purity and mechanical strain in a particular sample.

Below the superconductive transition the resistivity is exactly zero. That it is truly zero is vividly demonstrated by an experiment now in progress by Professor S. C. Collins at M.I.T. wherein a lead ring has been carrying an induced current of several hundred amperes since March 16, 1954, without any observable change in the magnitude of the current.

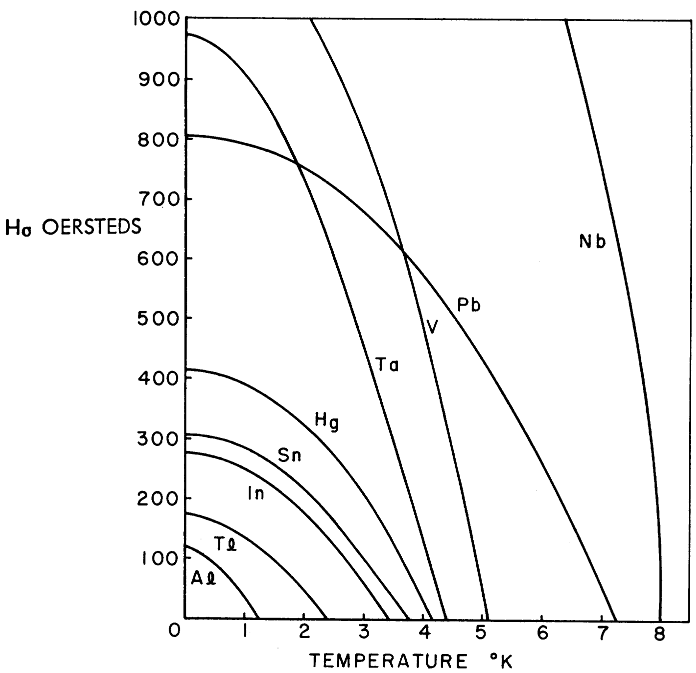

Fig. 1—Threshold magnetic field vs temperature for several common superconductors.

Destruction of Superconductivity by a Magnetic Field

The foregoing discussion of the superconductive transition is valid only in zero magnetic field. With a magnetic field applied, the onset of superconductivity occurs at a lower temperature. If the intensity of the magnetic field is increased, the transition temperature is still lower. A plot of the transition temperature as a function of the applied magnetic field is more or less parabolic in shape, levelling out as absolute zero is approached. Such a plot for several common elements is given in Fig. 1.

If the temperature is held below the transition temperature for one of these materials, the resistance of that material is zero. Its resistance will remain zero as a magnetic field is applied until that magnetic field reaches a critical value. Above this value the normal resistance returns. If the field is lowered, the resistance disappears.

Raising and lowering the magnetic field thus controls the resistance of the material in the magnetic field by causing it to shift from its superconducting state to its normal state and back without changing the temperature. In Fig. 2, this operation corresponds to moving up and down on a vertical (constant-temperature) line which has its lower end in the superconducting region and its upper end in the normal region. If the operating line is moved to a lower temperature, the magnetic field required to reach the normal region is greater. For each of the materials which becomes superconducting, there is a temperature about 0.2°K below the zero-field transition which allows operation with rather small magnetic fields—between 50 and 100 oersteds. For lead, this temperature is about 7.0°K, for tantalum about 4.2°K, for tin about 3.5°K, for aluminum about 1.0°K.

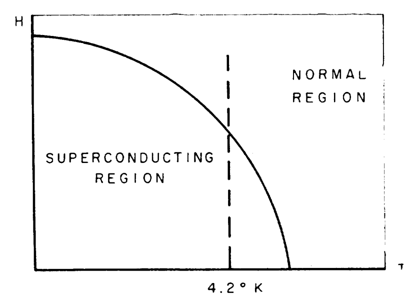

Fig. 2—Threshold magnetic field as a function of temperature for a superconductor.

Tantalum has been used in many of the early experiments at M.I.T. because 4.2°K is the boiling point of helium at a pressure of 1 atmosphere and therefore the temperature of most storage tanks for liquid helium. Higher temperatures (up to 5.2°K) involve raising the pressure on the liquid helium bath; lower temperatures (down to about 1.0°K) involve lowering the pressure. At 4.2°K, then, experiments do not involve sealing of the lead-in wires.

In a typical cryotron, the resistance being controlled is in the form of a straight piece of wire about 1 inch in length. The magnetic control field is generated by current in a single-layer winding which is wound over the central wire (Fig. 3, top). The central wire is analogous to the plate circuit of a vacuum tube and the control winding is analogous to the control grid. In this case, the plate resistance is zero in the cutoff region and rises rapidly as grid-current cutoff is reached.

Superconducting Control Winding

The control winding is made of a superconducting wire which has a relatively high transition temperature. Niobium (formerly called columbium) is used because it has a very high transition temperature and can be drawn into fine wire which is strong. Lead or lead-plated wire is a second possible control-winding material.

At the temperature used, the control winding remains a superconductor at all times, and would remain so even in magnetic fields much higher than those being used to control the central wire. Therefore, there is no resistance in the control winding. A magnetic field, once established, needs no further energy for its support; the control current is maintained against zero back voltage. Similarly, all interconnecting wire is also superconducting.

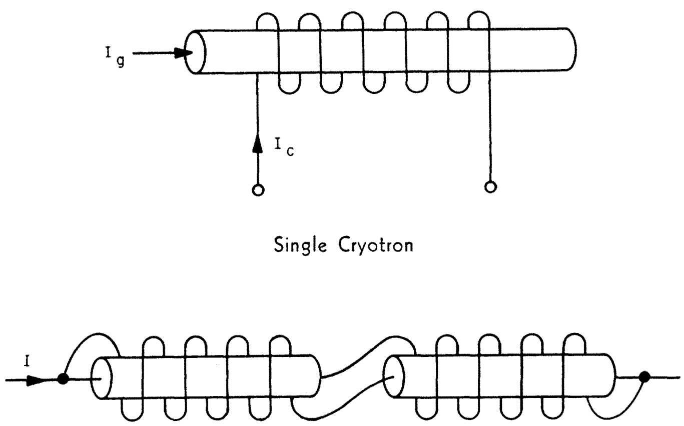

Fig. 3—Cryotron bistable element (flip-flop).

The Cryotron as a Device

Static Characteristics

The resistance of the central wire of a typical cryotron is plotted as a function of current in the control winding in Fig. 4. The central wire is called the gate circuit. This particular cryotron is made by winding a single layer of 0.003-inch insulated niobium wire over 0.009-inch bare tantalum wire. The insulation on the niobium is heavy Formvar. The finished winding has 250 turns per inch. In the midportion of the winding, the magnetic field due to a current is 124 oersteds per ampere. When the control current of Fig. 4 is translated into magnetic field intensity, the highest transition field is seen to be about 40 oersteds.

As current in the tantalum gate circuit is increased, the transition control current becomes lower. This effect is due to the additional magnetic field at the surface of the tantalum wire created by the gate current. This field, commonly called the self-field of the wire, limits the amount of current which can be carried by a superconductor. The effect was, in fact, discovered shortly after the discovery of superconductivity when Onnes and his coworkers (1913) tried to make a powerful electromagnet out of their newly discovered zero-resistance materials. When the current in their superconducting solenoid reached a certain critical value, its resistance suddenly reappeared. When the discovery was made that magnetic fields cause restoration of resistance, it was quickly seen by Silsbee (1916) that the limit on the current that can be carried by a superconductor is due to the magnetic field created by that current. The magnetic field, H, at the surface is given by:

$$H = \frac{I}{\pi d}$$

where

H is in ampere-turns per meter
I is in amperes
d is in meters.

If H is given in oersteds, I in amperes, and d in mils (thousandths of an inch) this becomes

$$\underset{\text{oersteds}}{H} = \frac{175.5}{d \text{ mils}} I.$$

It will be noted that the transition characteristics are very sharp for high gate currents. The additional sharpness is a peculiarity of the measuring technique wherein a current is passed through the gate circuit and the voltage across the gate circuit is measured. When resistance suddenly appears, I^2R loss in the gate circuit causes heating which lowers the critical field and speeds switching.

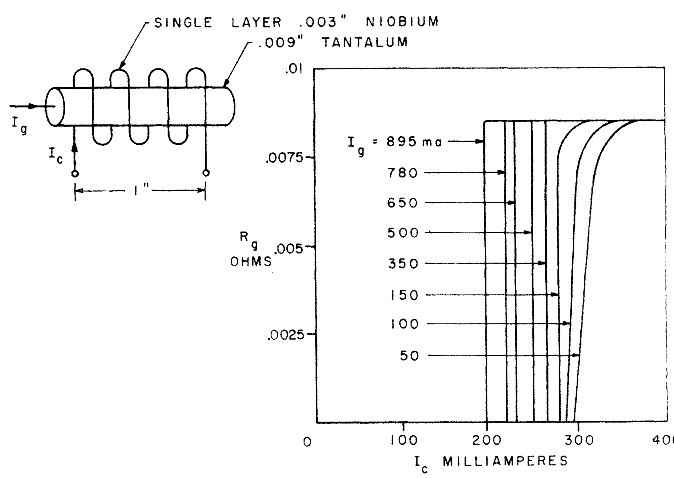

Fig. 4—Cryotron gate resistance vs control current.

The magnetic field due to the control winding is along the axis of the central wire while the self-field of the wire due to its own current is tangential to the wire. The two fields thus add in quadrature and the resulting net field is the vector sum of two fields. Results indicate that the superconducting central wire reaches its critical field when the net field reaches a certain value, regardless of which way the net field points in relation to the center line of the wire. In one experiment, the curves of Fig. 4 were reproduced exactly for all four combinations of positive and negative control and gate current. There is no reason to suspect that there would be anisotropy in the critical field for different orientations of the net field with respect to the wire axis as long as the control field is longitudinal, especially since the wire is polycrystalline. Thus the cryotron has an interesting property as a circuit element. Control is independent of the sign of the control current—it depends only on the magnitude. Furthermore, when the gate circuit is ON, that is, in its superconducting state, current can flow in either direction, unlike a vacuum tube which can pass current only in one direction.

Current Gain

Because the two fields add in quadrature, the self-field of the wire has less effect on the threshold control current at low gate current than it does at high gate current. The locus of threshold control current points as a function of gate current is an ellipse. The ratio of major axis to minor axis of the ellipse is the ratio of the magnetic field produced by a current in the control winding to that produced by the same current in the gate circuit. This ratio is also called the current gain of the cryotron. If the current gain were less than unity, it would not be possible to control one cryotron with an identical cryotron because more current would be required to bring the second cryotron to its control-current threshold than the first cryotron could handle through its superconducting gate circuit.

The control field is related to the control current by the number of turns per inch in the control winding, and the self-field is related to the gate current by the diameter of wire used in the gate circuit. Current gain, K, is simply given by:

$$K = \pi d \frac{N}{L}.$$

For a given pitch control winding and a given gate wire diameter, the current gain is specified. Fig. 5 is a plot of lines of constant K as a function of winding pitch and gate wire diameter. For the cryotron whose characteristics are plotted in Fig. 4, $K=7$. The current gain actually observed for a given cryotron is often less than calculated, presumably due to the constriction of supercurrents by small normal regions which nucleate about flaws in the wire surface. Control-current threshold points thus form a locus in the gate current-control current plane which lies on an ellipse of smaller major-to-minor axis ratio.

Power Gain and L/R Time Constant

The input power to a cryotron, exclusive of eddy current and relaxation losses, is the product of the energy stored in the magnetic field of the control winding and the frequency at which the control winding is energized:

$$P_{\text{in}} = \frac{fL_cI_c^2}{2}.$$

The input power is reactive. In an oscillator circuit the input inductance can be resonated with a linear capacitor to minimize input losses. In computer pulse circuitry, however, the control windings are untuned. The entire amount of power is therefore dissipated.

The output power of a cryotron can be approximated as follows: Consider a cryotron amplifier delivering square waves of equal on and off periods to a resistive load. The gate circuit shunts the current when superconducting and allows part of it to flow through the load when normal. Maximum power transfer occurs when the load resistance, R_L, is made equal to the normal resistance of the gate circuit R_g. Under this condition, average load power is given by:

$$P_{\text{ave}} = \frac{I_g^2R_L}{2}.$$

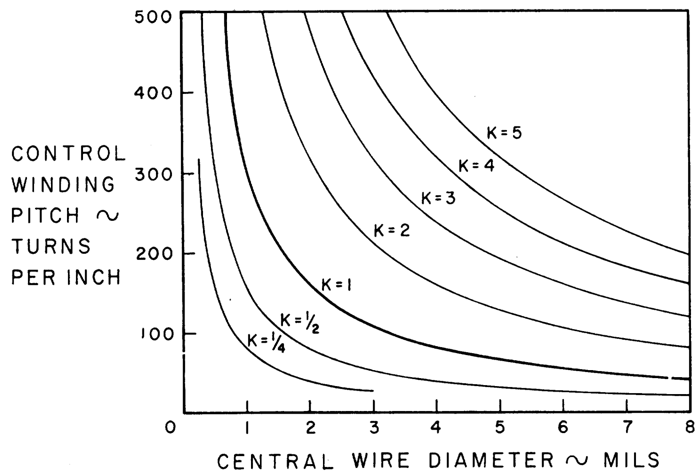

Fig. 5—Current gain vs control winding pitch and central wire diameter.

Power gain, G, can be approximated by:

$$G = \frac{\text{power out}}{\text{power in}} = \frac{I_g^2R_L}{fL_cI_c^2} = \frac{1}{f}\left(\frac{I_g}{I_c}\right)^2 \frac{R_g}{L_c}.$$

In the pulse circuits of the following section on cryotron computer circuitry, the gate current of one cryotron becomes the control current of another; $I_g=I_c$. For this condition, the frequency at which the power gain becomes unity is:

$$f_{\max} = \frac{R_g}{L_c}$$

which is the reciprocal of the L/R time constant of the circuit. The L and R are on different cryotrons, but since large numbers of identical cryotrons are involved, one can speak of the L/R time constant of a given cryotron as being the fundamental time constant of the circuitry.

If a given cryotron is made longer while holding the pitch of the control winding constant, the resistance and inductance increase together such that the L/R time constant is not affected. The L/R time constant is thus independent of cryotron length.

If the diameter of a given cryotron is made smaller while holding the pitch of the control winding constant, the resistance increases inversely as the diameter squared, while the inductance decreases directly as the diameter squared. The L/R time constant thus dedecreases as the fourth power of the diameter.

The current gain of the cryotron drops if the diameter is made smaller while holding the pitch of the control winding constant because the current-carrying capacity of the gate circuit decreases directly with the diameter. If the current gain is to be held constant by increasing the pitch of the control winding proportionately as the diameter is made smaller, the inductance remains constant and the L/R time constant decreases as the square of the diameter. One thus pays rather dearly for current gain. Cryotron computer circuitry, discussed below, is operated with a minimum of excess current gain.

The resistivity of the normal state varies over several powers of ten among the various superconductors. The L/R time constant varies inversely as the resistivity. An increase in speed of circuit operation can therefore be achieved by alloying superconductors to increase resistivity.[3]

Circuit speed can also be increased by using a hollow central wire. Superconductivity is a skin effect, penetrating but a few hundred atom layers, and therefore the core of a wire can be removed and the wire will still have zero resistance in its superconducting state. The resistance in the normal state, however, will be higher by the ratio of the original cross sectional area to the new cross sectional area. The core need not actually be removed, provided it is made to have a relatively high resistivity. Wire with a high resistivity core and a superconducting shell can be fabricated by vapor plating.

Eddy Currents

It has been shown by Faber[4] that the delay τ, due to eddy currents in the destruction of superconductivity of a wire by a longitudinal magnetic field is:

$$\tau_e = \text{const}\,\frac{\mu d^2 H}{\rho(H - H_c)}$$

where H is the external magnetic field, H_c is the threshold magnetic field and ρ is the resistivity. The switching time varies directly as the square of the diameter and inversely as the resistivity, and is a function of the amount by which the threshold magnetic field is exceeded.

As the circuits of the following section are speeded up by making cryotron diameters smaller, there will be a speed range where eddy currents become important. Lowering the diameter still further and increasing the pitch proportionally should then increase the speed as the inverse square of the diameter, since both circuit L/R time constants and eddy current time constants decrease proportionally. The observed time constants of the free-running multivibrator of the next section are of the same order of magnitude as the calculated L/R circuit time constants. Eddy current effects should become important during the next order of magnitude increase in speed.

The transition from normal to superconductor also involves delays and a somewhat different switching mechanism.[5,6] A supercooling effect is important. A nucleus of superconducting material forms at one spot on the wire surface, sweeps around the wire, and then grows along the wire. Extrapolation of slow velocity data on tin rods in fields just barely below the threshold field indicate that in cryotron operation, velocities of the order of tens of centimeters per microsecond ought to be encountered with a current gain of two. As soon as a superconducting path is established over the surface of the wire, the cryotron is in its superconducting state —even if the center of the wire requires additional time to become superconducting. While it is not anticipated that this transition will be a major source of delay, it is interesting to note that this delay is one which depends on the length of the cryotron.

As circuit speeds are increased by increasing the resistance of the central wire, thereby shortening L/R circuit time constants and minimizing eddy current effects, a fundamental limit to the ultimate speed exists in the form of relaxation losses. The exact frequency region in which these losses will become predominant is not known, but from experiments with superconducting coaxial cable and waveguide resonators, an estimate is available which places the limit between 100 and 1,000 megacycles.

Cryotron Computer Circuitry

The low impedance level of cryotron circuitry dictates a high-impedance power supply (current source) with circuit elements connected in series. Each element allows the current a choice among two or more paths only one of which is superconducting; all of the current flows through the superconducting path. The current encounters zero back voltage except when the paths are changing. The standby power is therefore zero. Several circuits, representative of those found in digital computers, are described below.

Flip-Flop

A bistable element, one of the most common in a digital computer, can be made using two cryotrons. The two gate circuits are each in series with the control winding on the other and the two paths are in parallel (Fig. 3,

[3] B. Serin, "The Magnetic Threshold Curve of Superconductors," ch. VII, "Progress in Low-Temperature Physics," edited by C. J. Gorter, Interscience Publishers, New York, N. Y.; 1955.

[4] T. E. Faber, "The phase transition in superconductors II. Phase propagation above the critical field," *Proc. Roy. Soc. A*, vol. 219, pp. 75–88; 1953.

[5] A. B. Pippard, "Kinetics of the phase transition in superconductors," *Phil. Mag.*, vol. 41, p. 243; 1950.

[6] T. E. Faber, "The phase transition in superconductors III. Phase propagation below the critical field," *Proc. Roy. Soc. A*, vol. 223, pp. 174–194; 1954.

bottom). If the current is established in one of the two paths, that current makes the alternate path resistive. Current in one path, once established, will therefore continue to flow indefinitely in that path.

Two additional cryotrons can be added to the circuit, one in series with each branch, in order to place the flip-flop in the desired state. A pulse on one of the two input cryotrons momentarily places a resistance in that side. Both sides are then resistive, and the current divides between them. If the power supply current is not larger than twice the critical current of the cryotrons, both sides of the flip-flop will become superconducting. One side of the flip-flop has a resistance inserted by the input cryotron, however, and the current thus chooses the other side. Once the current builds up in the other side, it makes the side on which the input cryotron is being pulsed resistive, and therefore the pulse in the control winding of the input cryotron can be removed; the current will continue in the new path.

Two more cryotrons can be added to the circuit for sensing the state of the flip-flop. Placed with their control windings each in series with one of the two sides of the flip-flop, one of the read-out cryotrons is resistive and the other is superconductive. The gate circuits are joined and a read-out current pulse is applied at the junction. The read-out pulse will choose one path or the other, depending on the state of the flip-flop. The flip-flop with read-in and read-out cryotrons is shown in Fig. 6.

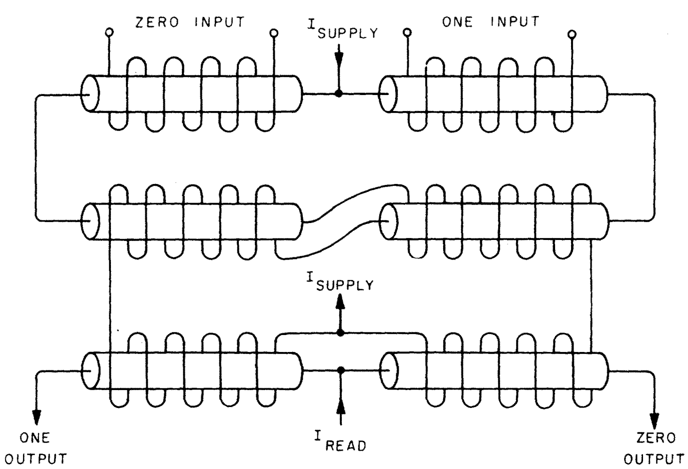

Fig. 6—Cryotron flip-flop with read-in cryotrons and read-out cryotrons.

Any number of input cryotrons can be added in series with those already described (Fig. 7) to set the flip-flop to one state or the other. Connected as such, they are OR gates; any one of them acting alone can set the flip-flop. Similarly, additional cryotrons can be added with their gate circuits in parallel with the control winding of the input cryotron already described, behaving as AND gates (Fig. 8). The flip-flop set current is bypassed through one or more of these parallel gates unless all of them are resistive. This latter connection involves superconductors in parallel, in which case the current divides inversely as the inductance of the parallel paths.

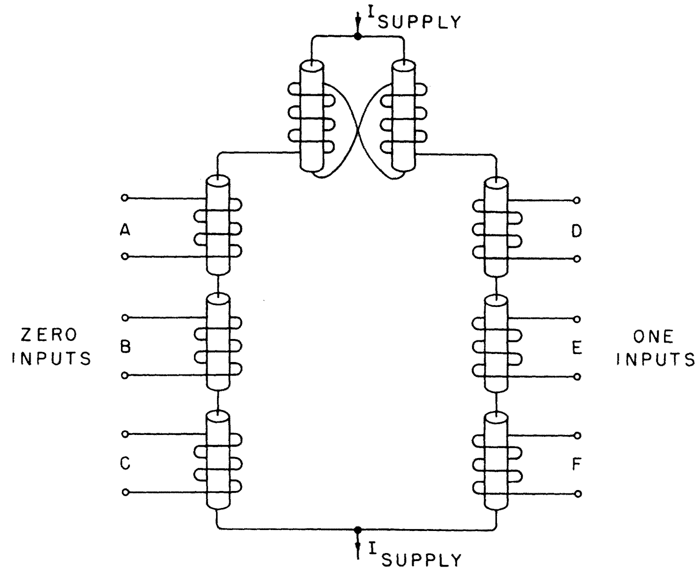

Fig. 7—Cryotron flip-flop with OR gates in both sides.

Additional read-out cryotrons can be added in series with those already described. Since their control windings are superconducting, the additional cryotrons do not add any resistance to the flip-flop. The additional inductance increases the L/R time constant of the circuit, however, lengthening the transition time between states.

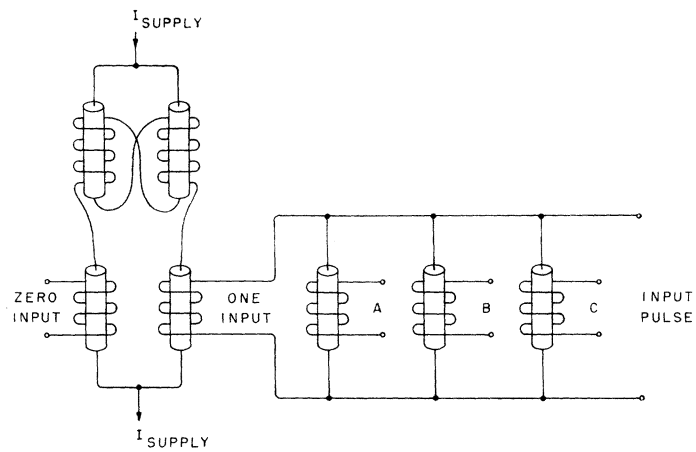

Fig. 8—Cryotron flip-flop with AND gates in one side.

Multivibrator

Three flip-flops made of one-inch pieces of the cryotron stock whose characteristics are given by Fig. 4 have been studied in a multi-vibrating circuit (Fig. 9). The read-out cryotrons of flip-flop A are connected in

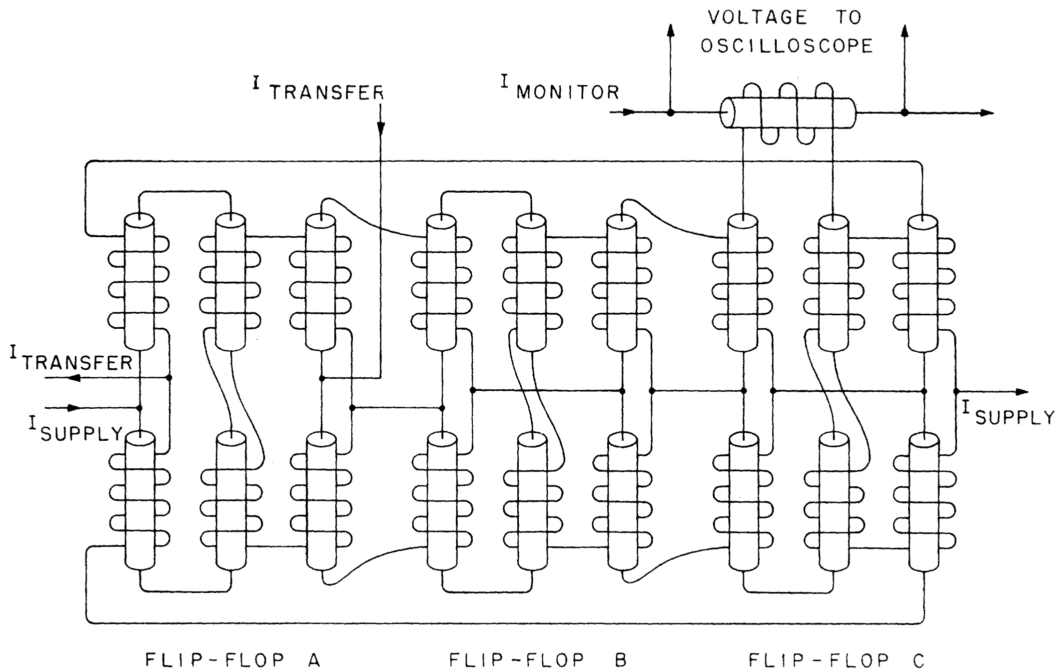

Fig. 9—3-flip-flop cryotron multivibrator.

TABLE I

SEQUENCE OF MULTIVIBRATOR FLIP-FLOP STATES

	Time Period								
Flip-flop	0	1	2	3	4	5	0	1	2
A	0	0	0	1	1	1	0	0	etc.
B	0	1	1	1	0	0	0	1	etc.
C	1	1	0	0	0	1	1	1	etc.

such a way as to set flip-flop *B* to the state opposite that of *A*. A similar connection between *B* and *C* causes *C* to assume the state opposite to that of *B*, and a similar connection between *C* and *A* causes *A* to assume a state opposite to that of *C*. Since there are an odd number of stages, the ensemble free-runs through the sequence given in Table I.

ZERO is defined as conduction through the upper cryotron of the flip-flop pair and ONE is defined as conduction through the lower.

The time taken for transition from one time period to the next is a function of the transfer current. If transition occurs at a fixed threshold current value, the final value of the rising current in a given control winding determines the fraction of the L/R time constant required to reach that threshold value. If the final value is (a) times the threshold value, the time required to reach the threshold is given by: $t = L/R \ln (a/a-1)$. The particular multivibrator circuit described completes the round-trip through its six time periods at the rate of 100 to 1,000 times per second depending on transfer current. The higher frequency gives individual time periods of 167 microseconds duration.

To monitor the transitions of one of the flip-flops, an additional cryotron gate is added with its control winding in series with one side of the flip-flop. A current source is connected to its gate circuit. When the control current is zero, the gate circuit is a superconductor and the voltage is zero. When the control current reaches the threshold value, the gate circuit becomes resistive and develops a voltage which is amplified and displayed. Typical values are: $R = 0.01$ ohm, $I = 100$ ma; $V = 1$ millivolt. The true current waveform is not preserved by the monitoring gate due to its inherent nonlinearity plus the sharpening of its transition due to I^2R heating as it becomes resistive.

Multiterminal Switch

Distributing a pulse among several wires can be accomplished by a cryotron switch (Fig. 10). Information is fed into the switch from cryotron flip-flops, here represented by toggle switches. One flip-flop causes the odd or even rows of the switch to be resistive, a second flip-flop causes odd or even pairs to be resistive, a third flip-flop causes odd or even fours to be resistive, and so on. A single path survives as a superconductor, and all of the read current follows that path and thence to the load. With the flip-flops set as shown with binary input 101, row 5 is selected. This particular switch can thus be used as a binary-to-octal converter.

Binary Adder

The principles embodied in the flip-flop and switch can be used to design the stages of a binary adder. The task to be done by each stage is represented by Table II.

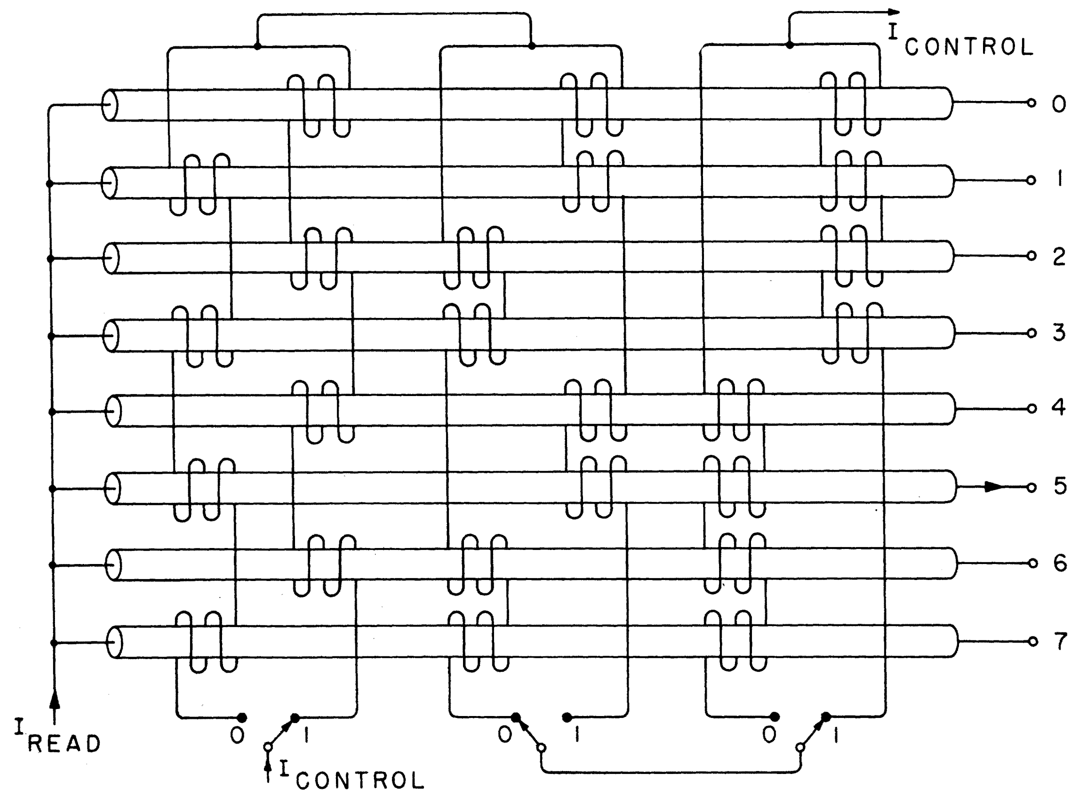

Fig. 10—8-position cryotron switch.

TABLE II
BINARY ADDITION TABLE

Input A	Input B	Carry In	Sum	Carry Out
1	1	1	1	1
0	1	1	0	1
1	0	1	0	1
0	0	1	1	0
1	1	0	0	1
0	1	0	1	0
1	0	0	1	0
0	0	0	0	0

The (n)th digits of the two numbers to be added are combined with the carry from the $(n-1)$th stage to form the (n)th digit of the sum and the carry to the $(n+1)$th stage. Since there are eight possible combinations of the three inputs, an accumulator design can center about the eight-position switch already described. The three inputs operate the control windings and the eight output leads, one of which carries current, can actuate cryotron gate circuits which set up paths to determine sum and carry digits. Fig. 11 shows such a stage. The carry input actuates either the upper four rows or lower four rows of the switch, thus eliminating one of the control-winding pairs. The eight gates which operate the sum flip-flop are connected with four in series in each of two parallel paths. The element which is caused by the switch to be resistive diverts the current to the path opposite itself setting the sum flip-flop to its proper state. A similar group of gates develops the carry for the following stage. Note that all circuits are in series from a current source power supply.

The foregoing binary adder design is described to illustrate the way in which switches and gates can be interconnected. A design having fewer cryotrons per stage is available wherein the carry is handled by a lattice network shown in Fig. 12. The label beside each of the six control windings indicates when it is to be energized. The $A=B=0$ and $A=B=1$ windings can each be made of two cryotrons in a parallel AND circuit and then directly excited from the A and B flip-flops, or the current necessary to excite them can be derived from a four-position cryotron switch. The latter method has an advantage since $A=B$ and $A\neq B$ currents are useful in forming the sum digit. After the current has passed through the $A=B=1$ and $A=B=0$ coils in the carry network, the two coil ends can be combined to provide a current $A=B$. This involves the outputs of two of the four output terminals of the 4-position switch. The other two output terminals can be tied together directly to provide a current if $A\neq B$. The sum digit can then be simply formed in the following way.

Note that the sum is ONE if $A=B$ and the carry in is ONE; ZERO if $A=B$ and the carry in is ZERO; ONE if $A\neq B$ and the carry in is ZERO; ZERO if $A\neq B$ and the carry in is ONE. The $A=B$ and $A\neq B$ currents can therefore be used to route the carry input currents to the proper side of the sum flip-flop. Fig. 13 is a schematic

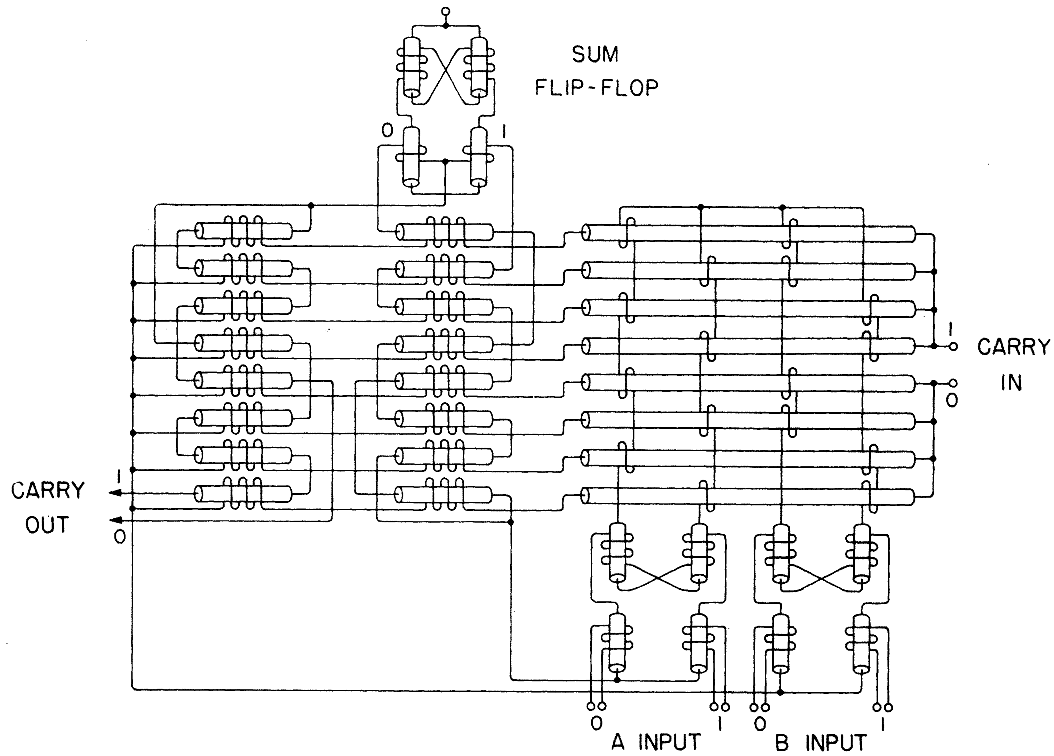

Fig. 11—One stage of a binary adder.

drawing of such a stage of an accumulator, abbreviated in that the *A* and *B* flip-flops are not shown, nor is the transfer link from the sum flip-flop back to the *A* flip-flop shown (used during accumulative addition and subtraction). In this design one notices the convenience of interconnecting cryotrons without regard to dc levels, very much as relay contacts are placed in relay computer circuitry.

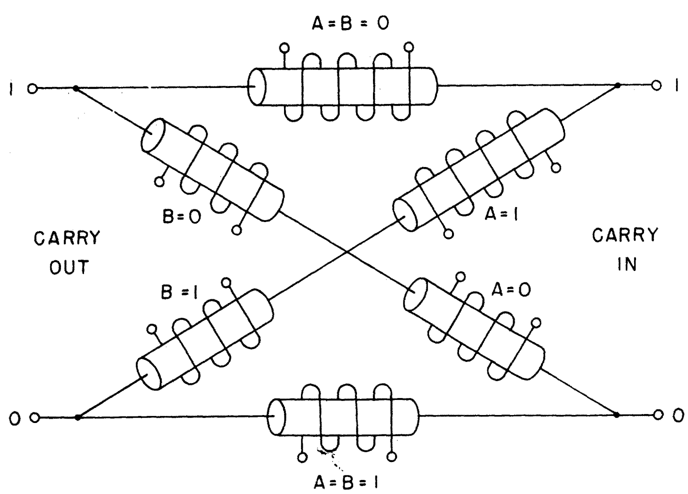

Fig. 12—Carry network.

Stepping Register

Stepping registers are commonly used for receiving digital information in serial form at one pulse repetition frequency and after a predetermined number of binary bits have been stored, shifting the information out at a different frequency. A second common use for shifting registers is to accomplish the conversion between digital information in serial and parallel form. The stepping registers in common use are made of vacuum tubes, transistors, or magnetic cores. Cryotrons can also be used in the same service. Each stage of the shift register consists of two cryotron flip-flops with read-in and read-out cryotrons. One transfer circuit sets the second of the two flip-flops of each stage to correspond to the state opposite that of the first. The coupling link to accomplish this is similar to the one described in the above section discussing the multivibrator, which interconnects stages of the multivibrator. A second transfer circuit sets the first flip-flop of each stage to correspond to the state opposite that of the second flip-flop of the stage to its left. A line of such stages serves as a shifting register, capable of shifting digital information to the right. Information (ONE's or ZERO's) fed into the first flip-flop in synchronism with the second of the two transfer pulses (called ADVANCE *B* pulse), will advance through the stepping register one stage for each pair of transfer pulses, ADVANCE *A* and ADVANCE *B*, which are displaced in time. Fig. 14 shows two stages of a cryotron stepping register. Parallel output gates are not shown.

Coincident-Current Circuits

Many interesting circuits can be made of cryotrons with two or more control windings wound over each other in such a way that the net magnetic field affecting

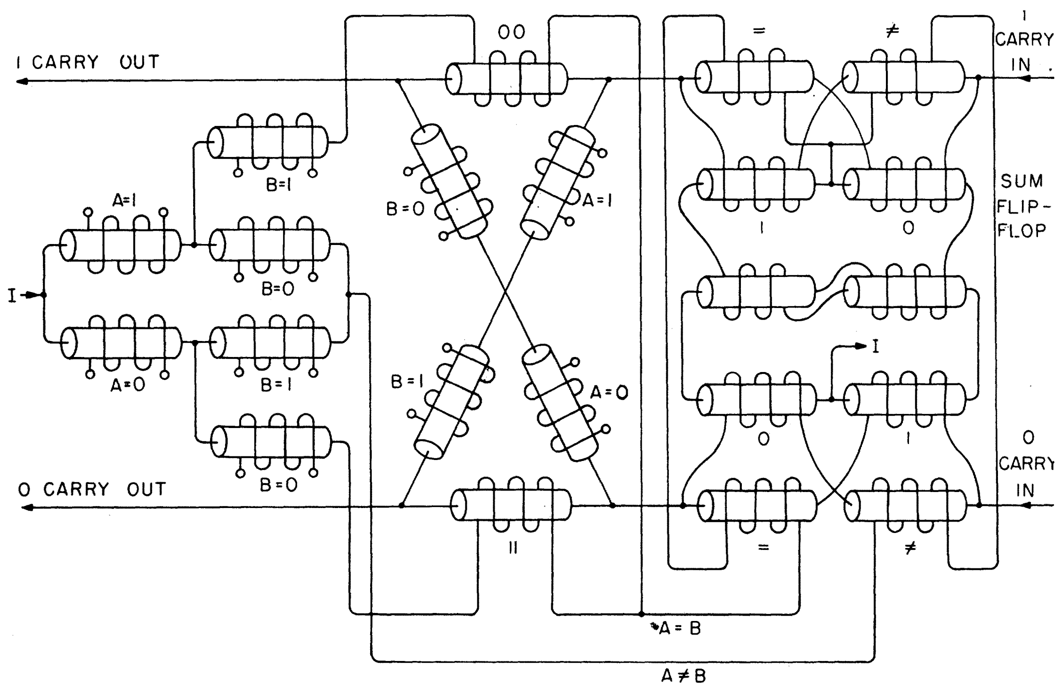

Fig. 13—Binary accumulator stage.

the central wire is due to the sum of the magnetic fields of the individual windings. The dc cryotron characteristics of Fig. 4 are sufficiently sharp in their transition between superconducting and normal states to allow the transition to result from the sum of two half-amplitude fields or even three one-third-amplitude fields. A coincident-current circuit of this type is useful for the selection of cryotron flip-flops placed at the intersection of the rows and columns of a matrix. A one-half-amplitude pulse is applied to the flip-flop control windings along a row, and a similar pulse to the flip-flop control windings along a column. The flip-flop at the intersection of that row and column can thus be placed in one of its two states; all other flip-flops in the matrix are unaffected.

If two such control windings are operated in opposition in such a way that the magnetic field of one subtracts from that of the other, a gate circuit of the "exclusive OR" type is available, wherein a flip-flop is set if either pulse A or pulse B occurs, but not if they both occur. Operation in this manner takes advantage of the fact that control depends on the magnitude of the controlling field and not on its polarity.

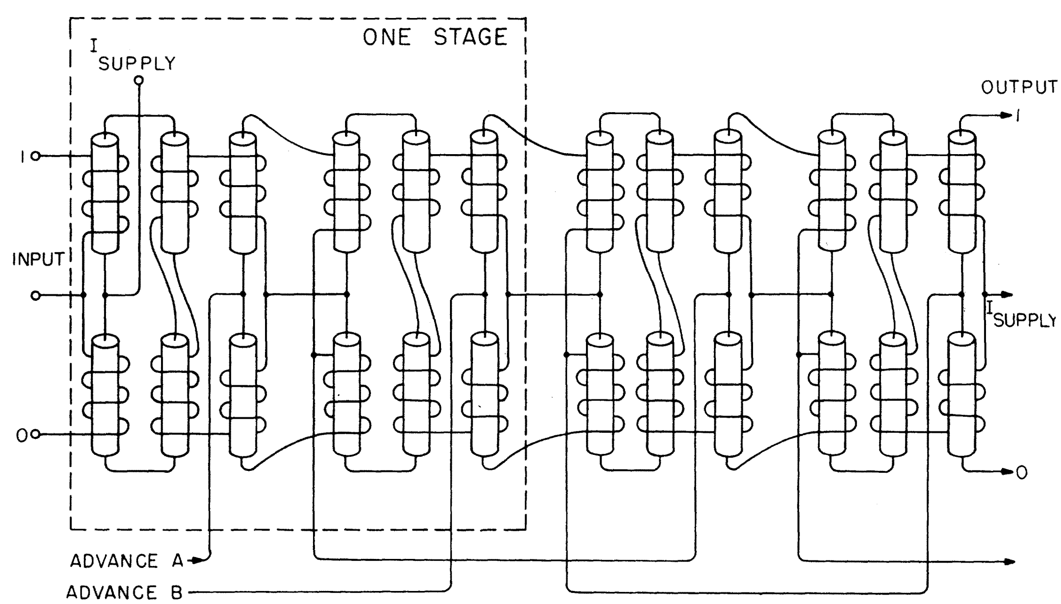

Fig. 14—Two stages of a cryotron stepping register.

Engineering a Cryotron System

Low-Temperature Environment

The most unusual requirement of a cryotron system is that it operates at a temperature near the absolute zero. Ten years ago this requirement would have precluded serious thought of such a system. Today, however, such an operating temperature is relatively easy to achieve.[7] This change is mainly due to the work of Samuel C. Collins whose helium liquefiers revolutionized the field of low-temperature physics. Arthur D. Little, Inc. of Cambridge, Mass., has built seventy Collins helium liquefiers of a 4-liter-per-hour capacity. The liquefier at M.I.T. liquefies 27 liters per hour. Storage of liquid helium has also improved. Commercially available double Dewars which use liquid nitrogen in the outer Dewar lose less than one per cent of their liquid helium per day.

The heat dissipated by a cryotron system causes evaporation of the helium. If the average power dissipated per cryotron is 10^{-4} watt, an estimate based on present experimental units, a 5,000-cryotron computer would dissipate one-half watt. The latent heat of vaporization of liquid helium at 4.2°K is 5 calories per gram,[8] its density is 0.1257, and therefore one-half watt corresponds to an evaporation rate of 0.93 liter per hour. A continuous system which recycles helium would be most economical for a stationary installation; a ten- or twenty-liter charge at the time of launching would suffice for portable systems.

The temperature of a liquid helium bath can be controlled by controlling the pressure of the bath. Table III gives the boiling point of helium at various pressures.

TABLE III
Boiling Point of Helium

Pressure mm Hg	Temperature °K	Pressure mm Hg	Temperature °K
0.001	0.657	720.0	4.156
0.01	0.791	730.0	4.170
0.1	0.982	740.0	4.184
1.0	1.269	750.0	4.198
10.0	1.743	760.0	4.211
100.0	2.638	770.0	4.225
200.0	3.067	780.0	4.239
300.0	3.368	790.0	4.252
400.0	3.605	800.0	4.266
500.0	3.803	900.0	4.40
600.0	3.975	1000.0	4.52
700.0	4.127	1500.0	5.03
710.0	4.141	1720.0	5.20

Below 2.19°K, the so-called *lambda-point*, liquid helium exhibits unusual properties which may prove useful in a cryotron system. A second phase of liquid helium appears which acts as a second fluid free to move through the first fluid with no friction. This zero-viscosity component is able to conduct heat with zero temperature gradient. It thus flows intimately in and around any structure immersed in it and allows rapid conduction of heat away from the structure. If heating is a problem in a cryotron system, operation in this temperature region should provide a solution. It is interesting, incidentally, to watch a liquid helium bath being pumped down. It may boil rather vigorously until the temperature drops below 2.19°K at which point the surface becomes perfectly still; heat is conducted through the liquid and liberated at the surface rather than on the container walls which causes boiling.

Physical Construction

Fig. 15 shows some experimental cryotron circuits. They are mounted at the ends of three-foot cupro-nickel tubes for immersion in a liquid helium storage vessel. Power supply and signal wires come up through the center of the tube. The experiments read chronologically from the large probes on the right which were used for dc characteristic measurements to the three-flip-flop multivibrator circuit on the left which contains nineteen active elements. A closeup of the latter experiment is shown in Fig. 16. The individual elements are those whose dc cryotron characteristics are given by Fig. 4. Spotwelding has been used to interconnect niobium and tantalum wires. Nickel lugs, while not superconducting, have proven useful for mounting. They both spotweld and solder nicely and careful design minimizes the resistance they introduce. The feasibility of using superconductive etched-wiring boards is under study. In these, lead would form the superconductive paths.

Many materials are used in the construction of circuits to operate in liquid helium. Ordinary wire insulation (enamel, silk, glass, Formex, Formvar, etc.) shows no sign of failure after repeated immersion. One experiment using wooden coil forms glued together with Duco cement was successful. Scotch electrical tape, while it freezes, seems to hold well. Commercially available feedthrough and standoff insulators have been used without any sign of cracking. Metals in general are much stronger at extremely low temperatures. Some are relatively good thermal insulators (stainless steel and cupronickel) and may be used for mechanical support. There is no basis for the common impression that everything falls apart just below JAN specifications (−85°C).

Input, Output, and Power Supply

Input pulses to cryotron circuits involve current amplitudes which are easily achieved in the terminal equipments commonly associated with digital computers. Since the voltage level is low, input of information to a cryotron system involves no unusual problems.

Connecting the output pulses of a cryotron system to terminal equipment, on the other hand, is difficult due to the low power level of the cryotron circuitry. Power cryotrons can be designed to increase the power level,

[7] C. A. Swenson and A. G. Emslie, "Low-temperature electronics," Proc. IRE, vol. 42, pp. 408–413; February, 1954.
[8] W. H. Keeson, "Helium," The Elsevier Pess, Inc., New York, N Y.; 1942.

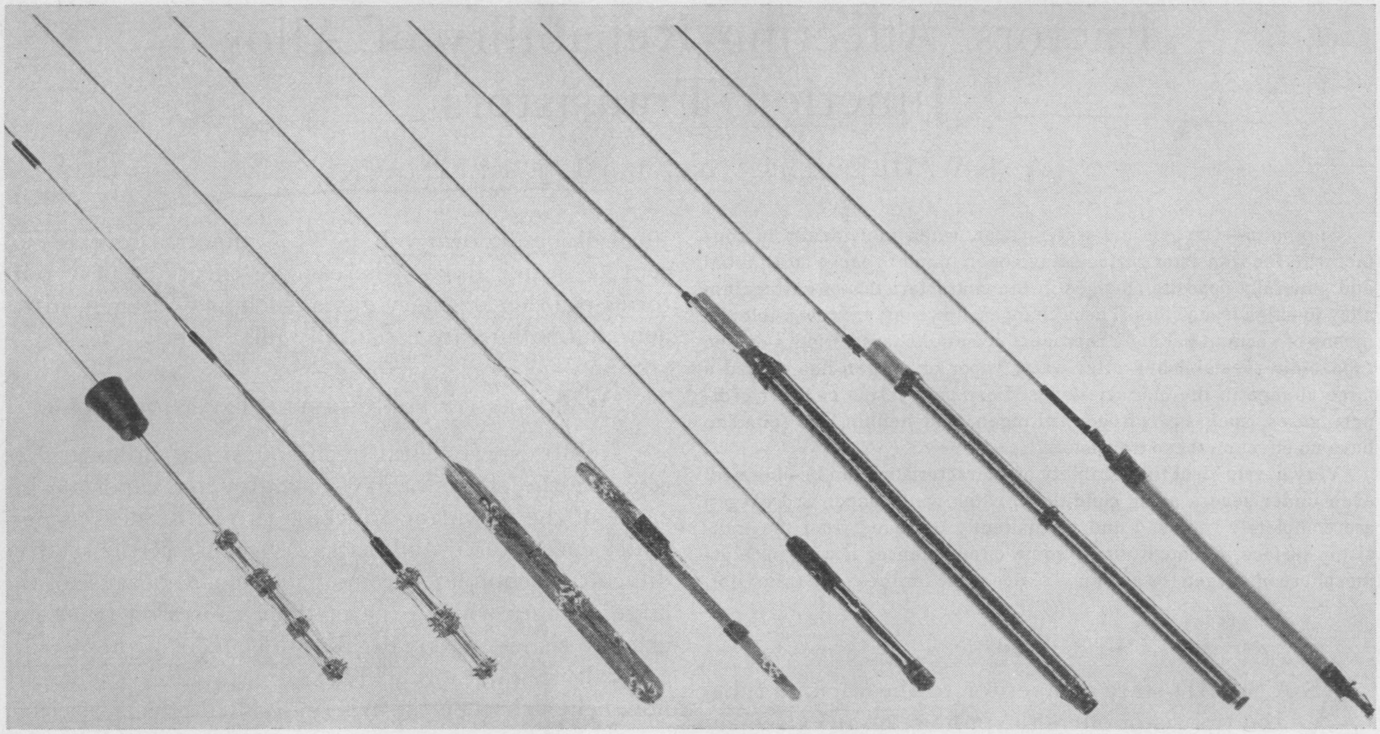

Fig. 15—Experimental cryotron circuits.

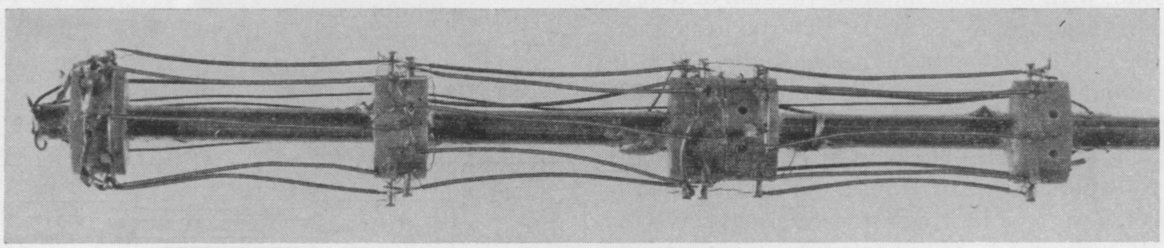

Fig 16.—3-cryotron-flip-flop multivibrator.

but it appears that vacuum-tube or transistor amplifiers are necessary to bring the level up to that of most output equipments. Magnetic amplifiers with superconductive control windings are an interesting possibility for power amplification.

Power supplies for cryotron systems are easy to achieve. The low impedance of the circuitry dictates a current-source power supply. A battery with a series resistance is adequate.

Conclusion

The cryotron in its present state of development is a new circuit component having power gain and current gain so that it can be used as an active element in logical circuits. It is easily and inexpensively fabricated from commercially available materials and its size is small. Extrapolating the volume occupied by the present experimental circuits to larger numbers of components indicates that a large-scale digital computer can be made to occupy one cubic foot, exclusive of refrigeration and terminal equipment. The power required by such a machine extrapolates to about one-half watt, once again excluding refrigeration and terminal equipment. The reliability of cryotron circuitry is not known, but it is anticipated that operation in an inert helium atmosphere at a temperature near to absolute zero where chemical activity and diffusion processes are essentially stopped promises a high degree of reliability. The circuit noise level is similarly not known, but due to the low temperature, very little thermal fluctuation noise is anticipated. The device is at present somewhat faster than electromechanical relays, but far slower than vacuum tubes and transistors. A program is under way to increase the speed.