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THE COHERER AS A STORAGE ELEMENT

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ABSTRACT

[illegible] need for more economical storage [illegible] a simple storage and switching element [illegible] playing [illegible] developments [illegible] are discussed. [illegible] Various potential [illegible] discussed [illegible] eliminated to avoid possible difficulties in [illegible]

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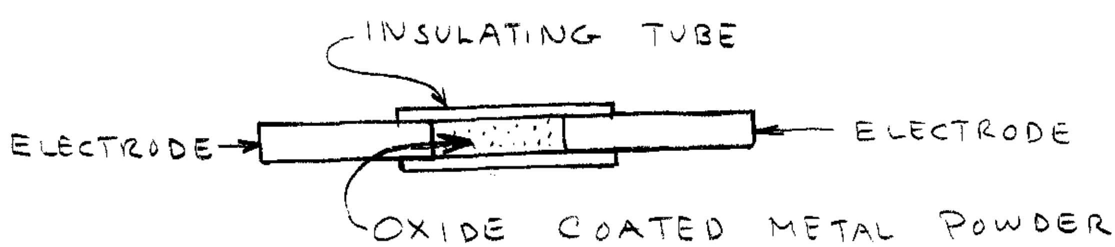
1. Introduction

A computer having 10,000 elements corresponds to the number of neurons in a flatworm. McCulloch[1] has estimated that if a computer were built to have the same number of elements as there are neurons in the human brain - 10^{10}, a skyscraper would be required to house it, the power of Niagara Falls to light the filaments, and the Niagara River to cool it. If the vacuum tube can be replaced by a cheaper, simpler, and more durable device, the reliability and feasability of larger computers would be improved.

Elements which do not require filament power are in various stages of development, such as the transistor, bi-stable magnetic cores, and ferroelectric storage. Electrochemical elements using chemical deposition, electrolytic polarization, hydrogen-electrode polarization, anodic-film polarization, and alteration of surface tension, have received attention. Another surface effect, the coherer, has shown more promise than the various electrochemical effects. The coherer is essentially a tube containing a metal powder with two electrodues touching the powder. The powder has an oxide coating which is normally non-conducting, but which breaks through to make a permanent low resistance path when the coherer is subjected to a certain minimum firing voltage. The path is broken by application of a mechanical shock. The coherer was originally used in early radio communication as a detector. The coherer action is present in many common electrical connections such as commutators, switches, and electric plug connectors.



ELEMENTARY COHERER

FIG. 1

1. W. S. McCulloch, "The Brain as a Computing Machine" Elec. Engin. Vol. 68, PP. 492-497, June 1949.

Two principal advantages of the coherer are its simplicity and that it retains the stored information when the power is shut off. It only requires power for storing and reading out the information. An elementary coherer is shown in Figure 1. Coherers have recently been investigated as switching and storage devices at the Mellon Institute, Harvard Computation Laboratory, and the IBM Research and Development Laboratory at San Jose.

2. Early History of the Coherer.

The early history of the coherer, which was used in early radio communication, is shown in Table I in an abbreviated form. For more details refer to:

J. J. Fahie, A History of Wireless Telegraphy, Second Edition, Revised; Edinburgh and London; 1901. PP 194-200, 204-210, 228, 249-253, 292-304, 306-316.

A. J Fleming, The Principles of Electric Wave Telegraphy and Telephone, New York: 1919. PP 364-385.

After the introduction of crystal diodes, triode detectors, and amplifiers, the coherer was forgotten in radio communication. However, the coherer effect continued to be of interest in relation to contact problems in commutators, slip rings, switches, plugs, and relays. These later investigations can be found in the following references:

Ragnar Holm, Electric Contacts. Stockholm, 1946. PP 352-358.

American Society for Testing Materials, Bibliography and Abstracts Electical Contacts 1835-1951. Philadelphia: 1952.

American Institute of Electrical Engineers, AIEE Lightning Reference Book, New York, 1937. References on oxide lightning arresters.

Years	Country	Investigator	Development
1835	Germany	Munck	Described increase of conductivity of mixture of tin filings, carbon and other conductors from passage of electric discharge.
1852	England	Varley	Observed high resistance of loose metallic powder was decreased during a thunderstorm.
1866	England	Varley	British Patent 165 for telegraph lightning protector.
1878	England	Hughes	Found that tube of filings of zinc and silver was sensitive to electric sparks at a distance.
1884	Italy	Calzechi - Onesti	Experimented with metal powder loosely packed in a tube.
1890	France	Branly	Extensive experiments resulting in a specific coherer design using metal powder. Also found coherer effect at single junction of oxidized wires.
1890	Germany	Rupp	Established decohering by continuously rotating the filings.
1892-3	England	Turner, Croft, Forber and Minchin	Extensive theoretical discussion and experimenting with the Branly tube. Developed modifications.
1894-7	England	Lodge	Employed coherer with clockwork decoherer.
1894-7	Italy	Marconi	Developed sensitive coherer for use in wireless telegraphy with relay tapper decoherer.
1895-7	Russia	Popoff	Developed coherer for detection of radio waves. Bell tapper decoherer.
1896	England	Brown and Neilson	Carbon granule coherer.
1896	England	Jervis-Smith	Powdered carbon coherer and telephone.
1898	France	Blondel	Side pocket adjustable sensitivity coherer.
1899	France	Tommasina	Decohering by mounting on telephone. Carbon coherer requiring less shock for decohering. Mercury to break coherer. Magnetic decohering with magnetic filings
1899	England	Fleming	Nickel filings in box on electromagnet.
1899	England	Brown	Decohering by superimposing an alternating field.
1900-01	Italy	Castelli	Self-decohering coherer using mercury drops.
1902	Italy	Solari	Improved mercury coherer.
1899-1900	India	Bose	Extensive experimental studies. Verified existence of anti-coherers.
1902	England	Lodge and Muirhead	Steel disc to paraffin oil to mercury coherer which decoheres by rotation.
1900-1904	U. S. A.	Guthe and Trowbridge	Theory of surface moisture film in coherer action.

TABLE I
THE EARLY HISTORY OF
THE COHERER

3. Present Status of Theory.

The action of coherers is not well understood. The most well-known theory at present is that of Ragnar Holm. According to Holm's theory, coherer action results from a puncturing of an oxide film between conductors. The breakdown of the film occurs when the electrostatic field in the oxide layer becomes so strong that the free electrons in the lattice structure are able to gain sufficient energy to further ionize the lattice. The resulting avalanche of free electrons in the oxide layer apparently causes the temperature to rise above the melting point, and a metal filament forms between the particles. A coherer which has been fired is returned to its high resistance state by mechanical shock which breaks the chains of particles. Holm agrees that there are cases where coherer action takes place without sufficient energy to melt the metal.

There are other theories which may possibly lead to a better understanding of coherers. When Cu_2O has a perfect lattice structure, the resistivity is 10^9 ohm-centimeters. In the non-stoichiometric form with excess oxygen, Cu_2O can have a resistivity of 100 ohm-centimeters. Thus, a change in the ratio of oxygen to the metal in an oxide can give the order of magnitude of the change in resistance of a coherer. It is not known whether such a change can be initiated by the forming current. It is more likely that CuO predominates on the bronze and copper spheres used in coherers.

It may be possible that the coherer action is essentially the same as dielectric breakdown. If so, a knowledge of the critical temperature separating electronic and ionic conduction would help determine which mechanism applies. A theory developed by Zener to explain dielectric breakdown applies to the conductivity of n-type semi-conductors but not to dielectric breakdown. This alternative theory has been applied by Shockley to "hot" electrons in germanium. This involves the interaction of electrons with the optical modes of crystal vibration. The electron waves have energies between the conduction band and the valence band, a region which has received little attention. Although this Zener current has some features consistent with cohering action, so far it has not been possible to ascertain its applicability on account of the coherer action involving a transient effect, while the available theoretical curves for the Zener current are for steady-state conditions. The following references contain material on these alternative theories:

Ragnar Holm, Electric Contacts, Stockholm (1946). PP 96-143.

H. Frohlich and J. H Simpson, "Intrinsic Dielectric Breakdown in Solids", Advances in Electronics II (1950). PP 185-219.

A. R. von Hippel, "Dielectrics Made to Order", Electronics, 24, June 1951. PP 126-8.

D. A. Wright, Semi-Conductors, London (1950). PP 24-49.

N. F. Mott and R. W. Gurney, Electronic Processes in Ionic Crystals, Oxford (1948). PP 152-201, 249-268.

W. Shockley, "Hot Electrons in Germanium and Ohm's Law", Bell System Technical Journal, 30, October 1951. PP 990-1034.

4. Recent Developments.

a. Mellon Institute

The Mellon Institute has investigated the formation of chains in the coherer powder, calculated the energy required for decoherence, and estimated the temperature and filament sizes corresponding to the melting of metal to form the chains in the coherer. They have conducted extensive tests of firing voltage, and fired resistance as a function of the metal and the size of the cell. Metallic elements have been classified into the following classes: (a) coherable, (b) non-coherable, and (c) conducti

They point out that the advantage of coherers in computers is that they stay in either of its two stable states without the application of power. The extent of application as a computer element may depend upon the speed of transfer, particularly decoherenc They consider that research on decohering and obtaining uniform firing potentials and uniform coherred resistance values is worthwhile only if coherers can be successfully used in ganged switching and storage devices. A binary-to-octal converte was developed and a coherer oscillator was demonstrated. Supersonic and magnetic attempts to decohere were unsuccessful, except one special magnetic system.

b. Harvard Computation Laboratory

Two-element and multi-element coherers were constructed. Three-element coherers for control units were investigated and were found unreliable. Combinations of two-element coherers were made into parallel control circuits, series choice circuits, and pyramid switching circuits.

c. IBM, San Jose

A physical research program was established to learn more about the physics of coherer action and to obtain statistical data on various types of coherers. Two effects have been found: the "packing" effect and the "time delay" effect. Packing of powder at the bottom of a coherer tends to lower the firing voltage. This time delay effect means that coherers can be made to fire at a lower voltage if the lower voltage is applied for a longer time.

The effects of atmospheric pressure, temperature, and electrode configuration have been investigated. Data on the effect of a magnetic field on the firing voltage of nickel powder was obtained. Various metal powders were investigated, of which the best are bronze, nickel, and aluminum bronze.

Recent experimental and theoretical work is available in the following report: H. E. Singhaus, "Preliminary Progress Report on the Coherer Investigation Program", IBM Report 203.001.026.

5. Coherer Techniques.

Various techniques of firing, reading and decohering have been tried. The principal methods, both the successful and the unsuccessful ones, are included in the following sections to help the engineer interested in coherers to understand both the advantages and disadvantages of different techniques.

a. Firing of Coherers

Since coherers consist of hundreds of metal spheres having oxide coatings of varying thickness, the path may be different for each firing. This means that there will be a statistical variation of the firing voltage such as is shown in Figure 2. It is desirable to design coherers so that the mean deviation of the firing voltage is small so that a reading voltage can be used which is well below the minimum firing voltage.

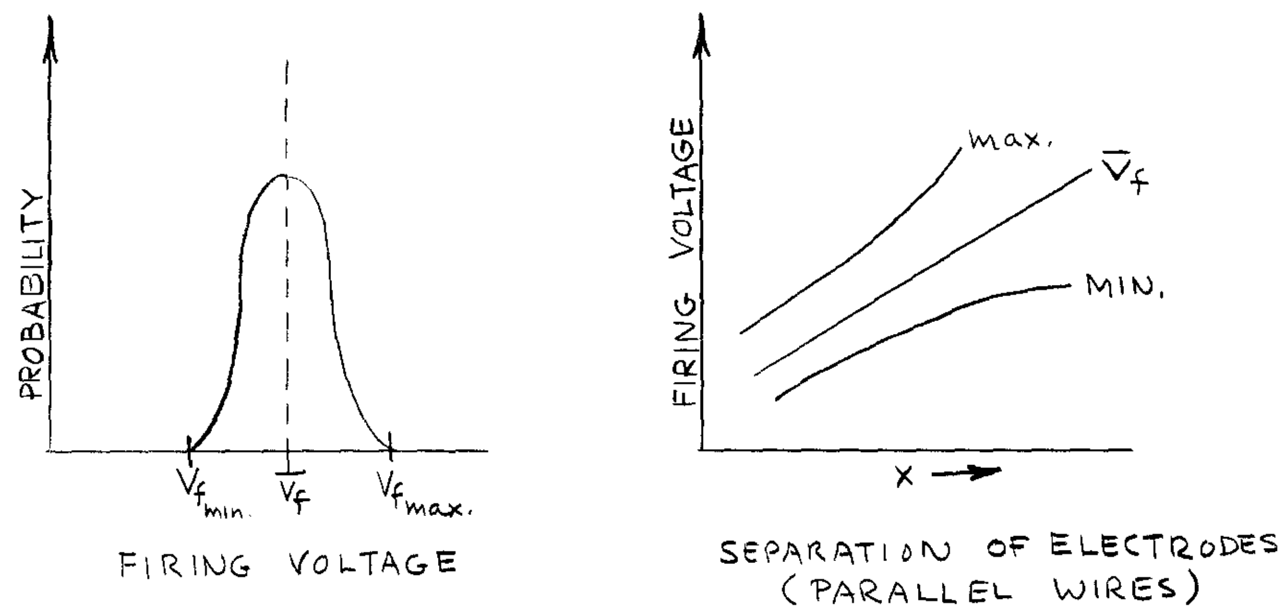


FIGURE 2.- Probability of Coherer Firing at Voltage V. and the Variation with Electrode Separation.

Several methods of firing coherers are considered, as follows:

(1) Direct Current Firing of Coherers.

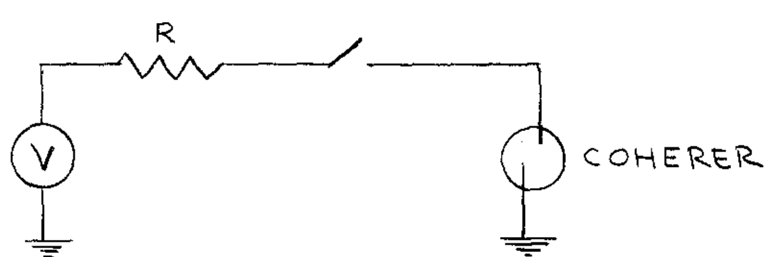


FIGURE 3.

The direct current firing of coherers is accomplished by direct switching of a d-c voltage source of high enough voltage across the coherer, as is shown in Figure 3. Data on firing voltage for various material and spacing are available in the following reports:

IBM, San Jose, Code 203.001.026.
Mellon Institute Reports.

(2) Transient Firing of Coherers.
Troubles in design of coherers can result from firing of coherers on transient voltages occurring at the opening of switches. The transient voltages can be analyzed into their Fourier components, which reduces the problem to that of radio frequency firing.

(3) Radio Frequency Firing of Coherers.
The firing of coherers with radio frequency voltage source eliminates the need for a direct connection, since firing can be accomplished through a capacitor, as is shown in Figure 4.

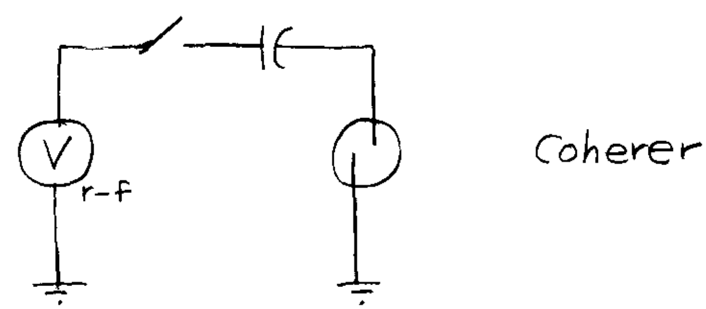


FIGURE 4.

This permits a certain isolation of elements such as the following three-electrode coherers in Figure 5.

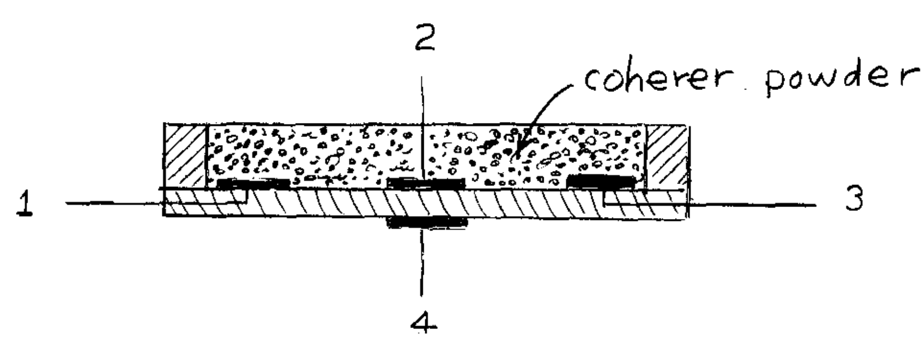


FIGURE 5.

Thus, if 1 or 3 are tied to ground an r-f voltage on 4 will cohere paths 1-2 or 2-3 by going through the coupling capacity between 2 and 4. In r-f firing stray capacitances can cause serious difficulties.

(4) Parallel Coherers

If coherers are simply put in parallel, all the current would go through the first one to fire. To insure that all coherers in parallel bank fire, they can be isolated by either resistances or capacitors, as is shown in Figure 6.

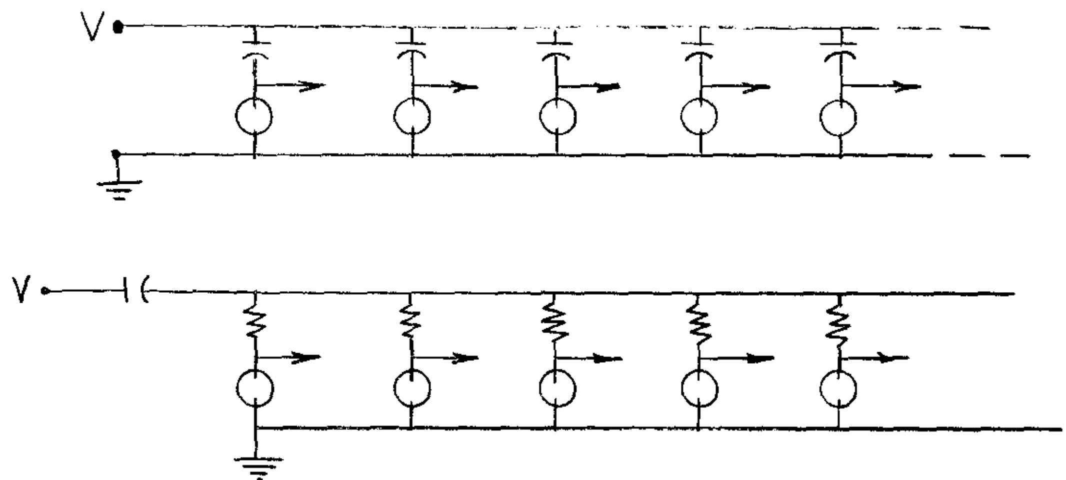


FIGURE 6

(5) Firing of Coherers from Ferroresonant Storage Matrix

A possible way of using a coherer storage matrix is to fire the coherers on the read-out pulses from a ferroresonant storage matrix. The firing of coherers through a ferroresonant core element has been demonstrated by W. Christopherson.

b. Reading of Coherers

By switching a reading voltage across the coherer, a current will flow if the coherer has previously been cohered. The reading voltage must be sufficiently lower than the minimum firing voltage of Figure 2 to avoid false readings due to the reading voltage firing the coherer. Most proposals for reading coherers use electronic switch tubes or relays to read out the stored information. A method has been proposed for parallel read-out of a row of coherers through phantom wound magnetic cores.

c. Decohering

(1) Mechanical Shock Decohering.

The basic method of restoring coherers to their high resistance state is to "decohere" them by the mechanical shock of a relay or solenoid. Coherers are not economical for decohering separately. They become economical when a matrix of m x n elements are decohered by a single solenoid or relay. Various proposals to provide for separate decohering of individual elements are described in the following paragraphs.

(2) Supersonic Decohering

The Mellon Institute reports unsuccessful results. The coherer was mounted on a barium titanate electromechanical transducer with resonant frequencies of 200 kc. The coherer was fired with a d-c potential. Application of 500 volts r-f signal to transducer produced no decoherence. The r-f radiation field cohered the powder.

(3) Audio Frequency Decohering

Proposals have been made for mounting coherers on a loudspeaker core, but no reliable designs have been developed.

(4) Magnetic Decoherence

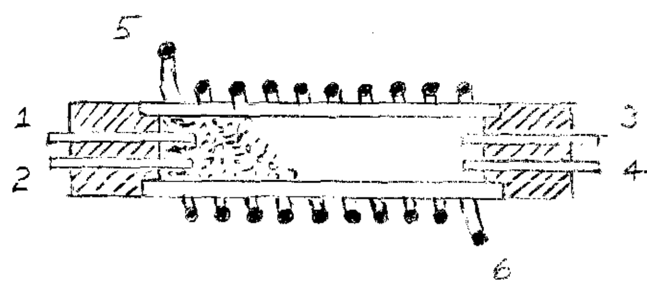


FIGURE 7

The coherer of Figure 7 has two sets of electrodes, 1-2 and 3-4. A magnetic material, such as nickel powder is used in the coherer. To decohere, a direct current is connected to the coil 5-6, which moves the powder to electrodes 3-4, thus decohering and switching to the alternate terminals. After firing 3-4, running current in opposite direction is supposed to move powder back to 1-2.

The Mellon Institute has reported a successful magnetic decoherer with one set of electrodes, where the powder is returned by gravity.

Attempts to use the $F = e\,[E + V \times B]$ interaction between the current in the cohered chain and a crossed magnetic field were unsuccessful.

(5) Capacitor Discharge Decoherence

The discharge of a capacitor across the terminals of some types of coherers will cause a transient short circuit current to explode the cohered chain in the powder. Although this system works, there is danger of sending transients through the nearby elements.

(6) Coherer Oscillator

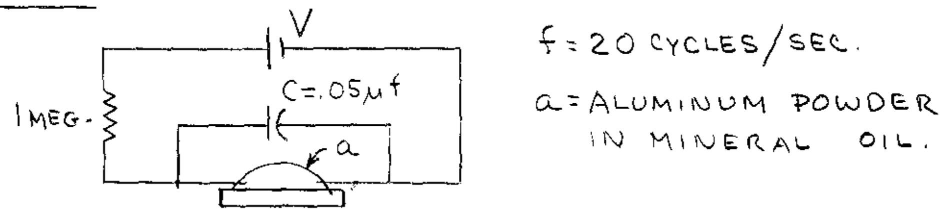


FIGURE 8

The capacity discharge of coherers leads to the coherer oscillator of Figure 8, which has been demonstrated at the Mellon Institute. The wave shape had an irregular, step-wise manner, apparently corresponding to individual elements and groups of elements firing.

6. Application of Coherers

The principal places where the economy of the coherer can be utilized is for storage where a matrix of coherers can be decohered with one solenoid or relay. Coherers can be developed as logical circuit elements for special cases not requiring separate decoherence.

a. Storage

(1) Coherer Matrix Storage

Figure 9 is an example of matrix storage in which the input pulses are applied to switch A. A and B are synchronized in time to cover the matrix. When a pulse enters A, the coherer is fired through a neon bulb or diode rectifier (to eliminate back circuits). For reading, a constant voltage is applied to D while C and D are switched. When the switches C and D connect a fired coherer, the current through the dropping resistors R gives a voltage pulse at terminal P-n.

(2) Punched Card Coherer Storage

A coherer matrix has been investigated where the elements match a punched card as shown in Figure 10. The card to be transferred is placed over the matrix and charged brushes are run across, cohering the elements under punched holes. Later, the card can be duplicated by running brushes across the matrix, obtaining a current through a relay or tube corresponding to each fired coherer.

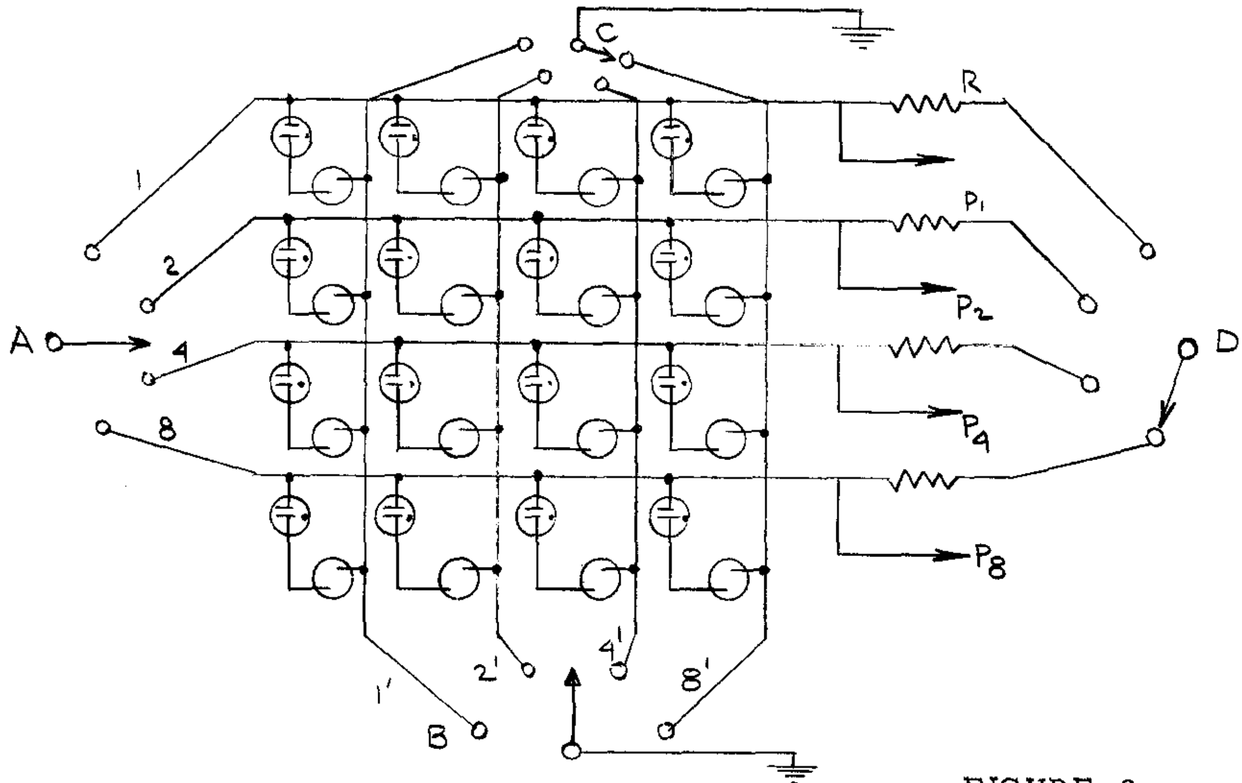


FIGURE 9

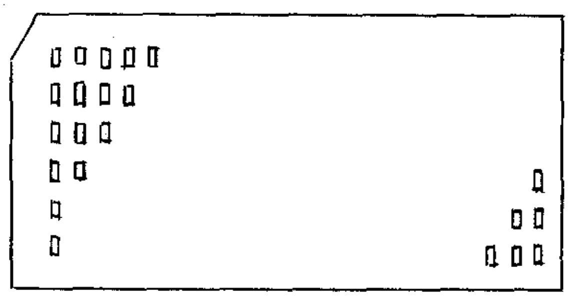


FIGURE 10

b. **Logical Circuit Elements**

(1) **Coherers for Logical Circuit Components**

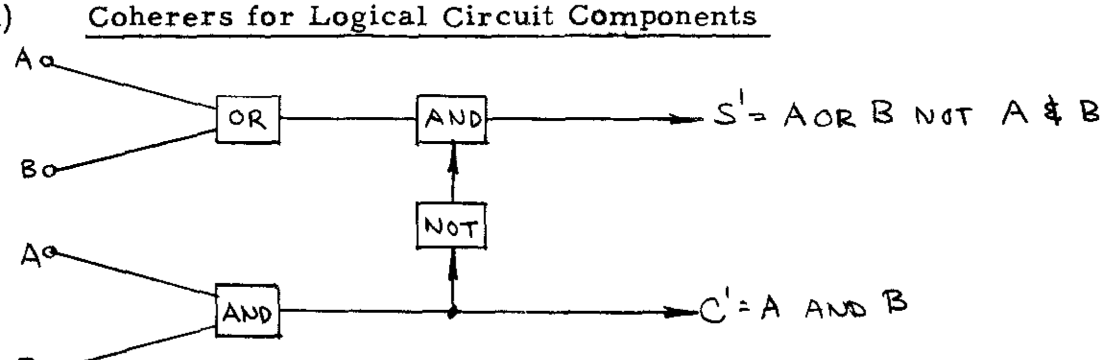


FIGURE 11

A sketch of a binary half adder is shown in Figure 11 to illustrate how binary calculations could be made if three types of coherers could be developed:

(1) logical AND
(2) logical OR
(3) logical NOT

The operation of such logical circuits may be complex if an economical way to decoherer single elements is not found.

(2) Choice Circuit

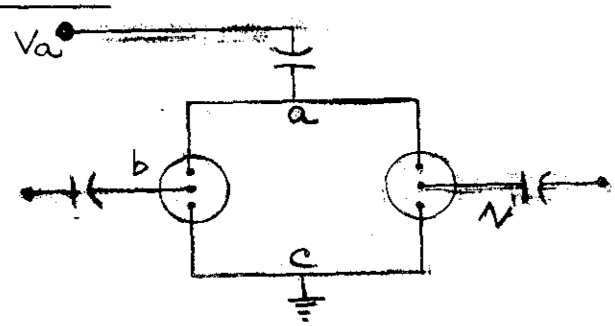


FIGURE 12

In the double two-element coherer of Figure 12, a is to be connected to b or b'. If a pulse is applied to b first, before a pulse is applied at a, then a is connected to b'.

(3) Pyramid Switching Circuit

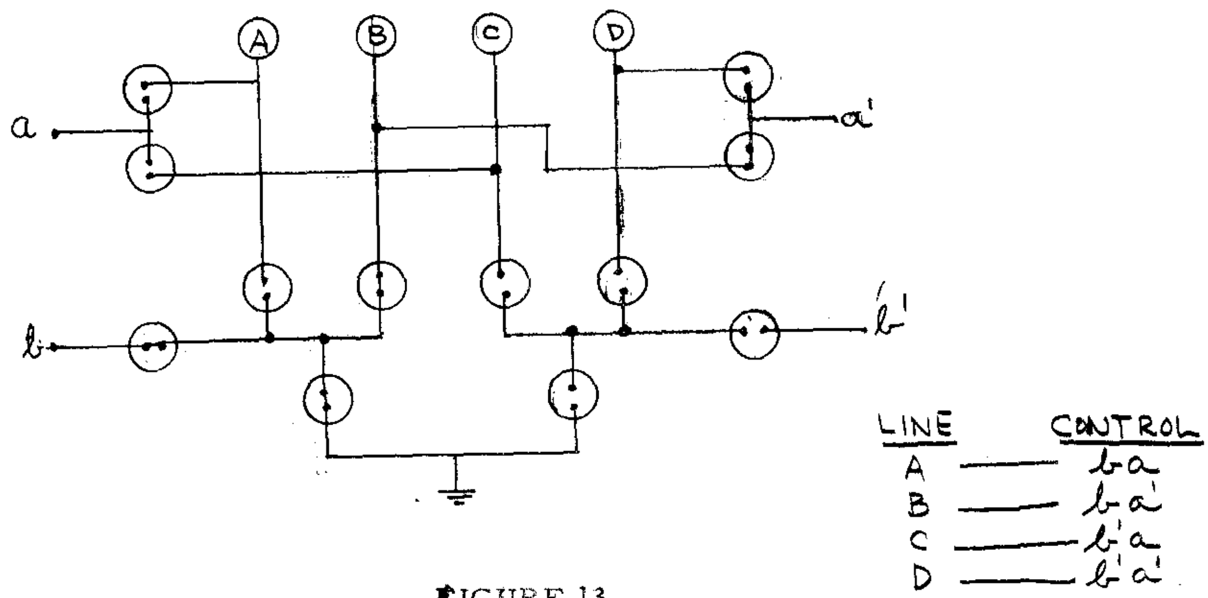


FIGURE 13

It is desired to connect A, B, C to [illegible] the switching circuit of Figure 13. This [illegible] pulses of a magnitude to fire two coherers, but [illegible] a or a'.

(4) Binary-to-Octal Converter

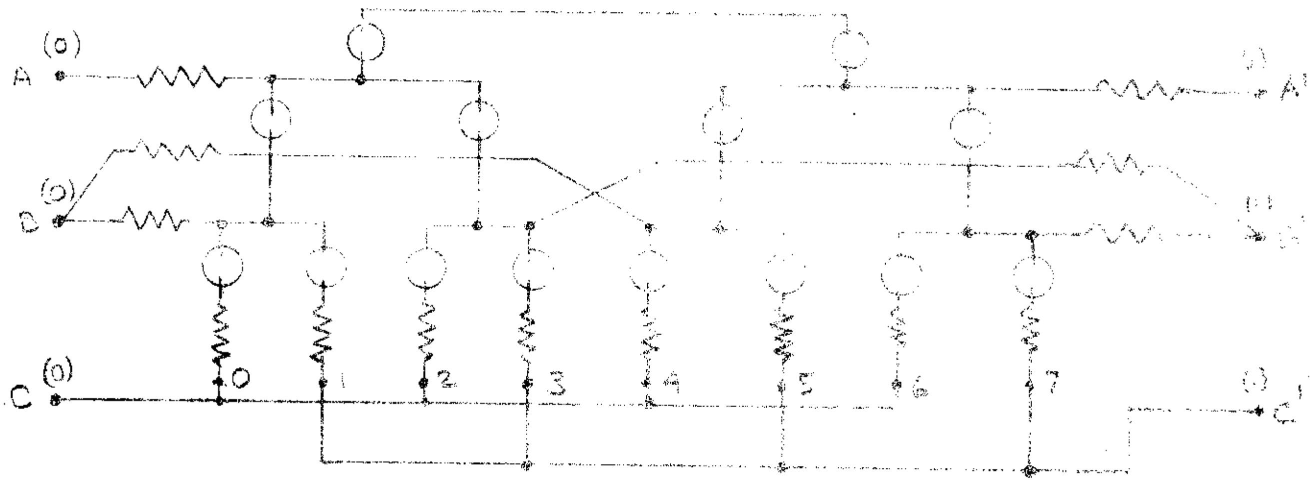


FIGURE 14

A voltage sufficient to fire one coherer but not two is applied to A (A'), B (B'), C (C') in sequence to the circuit of Figure 14. Thus 010 would leave output resistor 2 connected to ground. This system has been operated manually at the Mellon Institute. They were unsuccessful in using 3-element coherers.

(5) Series Connection of Three-Element Coherers

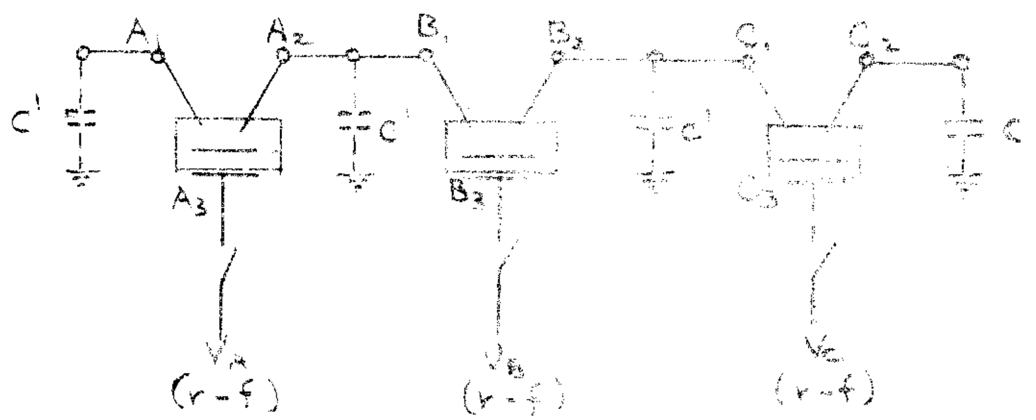


FIGURE 15

Switching on V_1 (r-f) would sometimes fire coherers A and/or C in Figure 15. This trouble can be eliminated by tying terminals B1 and B2 to ground for r-f by adding capacitors C. Where a bank of coherers use the same box of powder, there are serious problems of firing between rows and columns.

(6) Separation of Controlling Circuit from Controlled Circuit

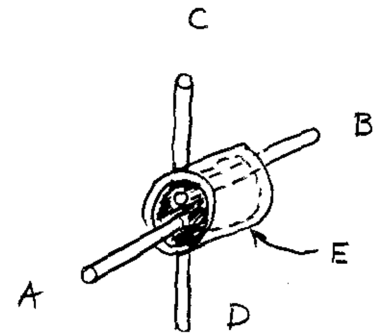


FIGURE 16

Terminals A, B, in Figure 16 are the controlled electrodes, and protrude into the powder; C, D are the controlling electrodes which are separated from the filings by the dielectric E. The difficulties with this system stem from r-f fields that can propagate on wires A and B to cause trouble in adjacent elements.

(7) Four-Element Coherer

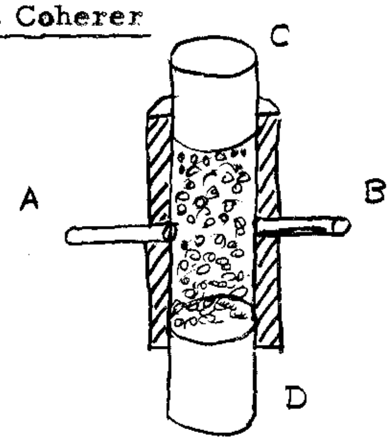


FIGURE 17

Branley in 1890 observed that connection of any two of the elements A, B, C, and D in Figure 17 resulted in coherence of the whole mass of filings when a spark gap oscillator was used. No recent experiments are known to have been made as yet to check the microwave behavior of coherers.

(8) Three-Element Control Coherer

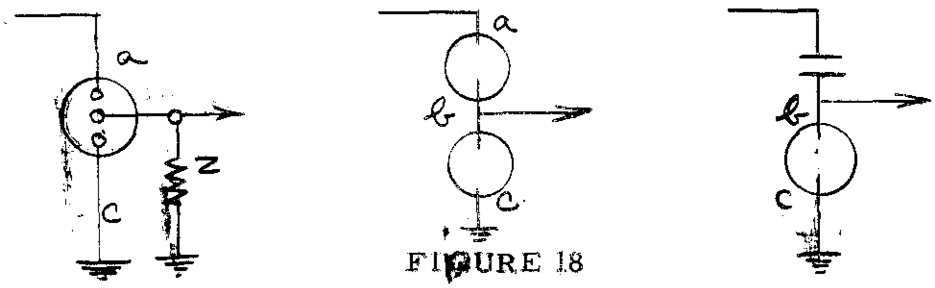


FIGURE 18

In Figure 18, a is the control electrode. Electrode b is connected to ground by applying a voltage to a. The chain sometimes bypasses b. At Harvard it was found that connection of b and c by a high impedance improves results, but is not perfect. Use of two separate 2-element coherers is more reliable. The first coherer can be replaced by a small capacitor.

(9) Anti-Coherer as Logical Circuit Element

Since potassium, arsenic, lead and lead peroxide increase in resistanc in an electric field, they are potential negation devices. It is not known if the increase in resistance is reliable enough for practical application.

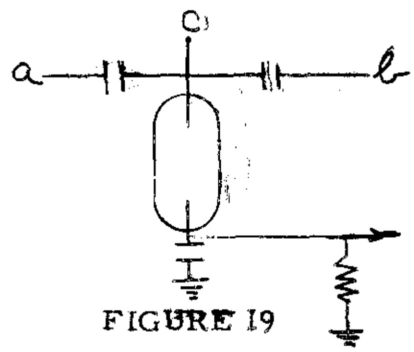


FIGURE 19

If an anti-coherer were developed such that a pulse on a or b in Figure 19 would increase the resistance to an applied voltage on c, the following table would apply:

a	b	Res	Output
0	0	L	1
0	1	H	0
1	0	H	0
1	1	H	0

This is equivalent to the Sheffer stroke in logic:

$a/a = \bar{a}$ not a

7. Conclusions

The simplicity of the coherer makes it very [illegible] the fact that it will hold information without use of [illegible] power requirements of large scale computers. The [illegible] limits coherers to storage matrices and switching [illegible] coherers are decohered at the same time. This [illegible] class of logical circuit elements which must [illegible]

There are several features which could [illegible] due to lack of understanding of the fundamental [illegible] have been found empirically which have a small mean deviation of [illegible] the lack of understanding of the mechanism of coherer firing could [illegible] which might be unstable after small design changes were made for [illegible] The influence of impurities in the oxide on the metal spheres is not well [illegible] to establish processing specifications for the coherer powder. [illegible] coherers have been fired by a series pulses below the minimum [illegible] voltage. This means that there is a product of time and voltage effect or [illegible] which must be investigated. The increase of the mean deviation for [illegible] gaps indicates potential trouble with multiple coherer units [illegible] In view of these potential difficulties, it is recommended that the [illegible] action be more thoroughly explored and checked by suitable experiments.