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FLUID LOGIC DEVICES: A REVIEW

by

C.J. Charnley and R.E. Bidgood

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DEPARTMENT OF PRODUCTION AND INDUSTRIAL ADMINISTRATION

Fluid logic devices

A review

- by -

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Summary

Background study of work connected with this report entailed the collection of a large number of specialised and general technical publications concerning the techniques and applications of fluid computing. General conclusions from these investigations are that, in Russia and America, this science is very advanced and considered to be of great significance, especially where pure fluid logic devices are concerned. The purpose of this survey is to enable the reader to assess the quality and magnitude of work done by other academic institutions, and also to show with what importance this science is viewed elsewhere.

It must be realized, however, that general description and discussion of available bibliography is the only assessment possible, as work of a military nature has not been released.

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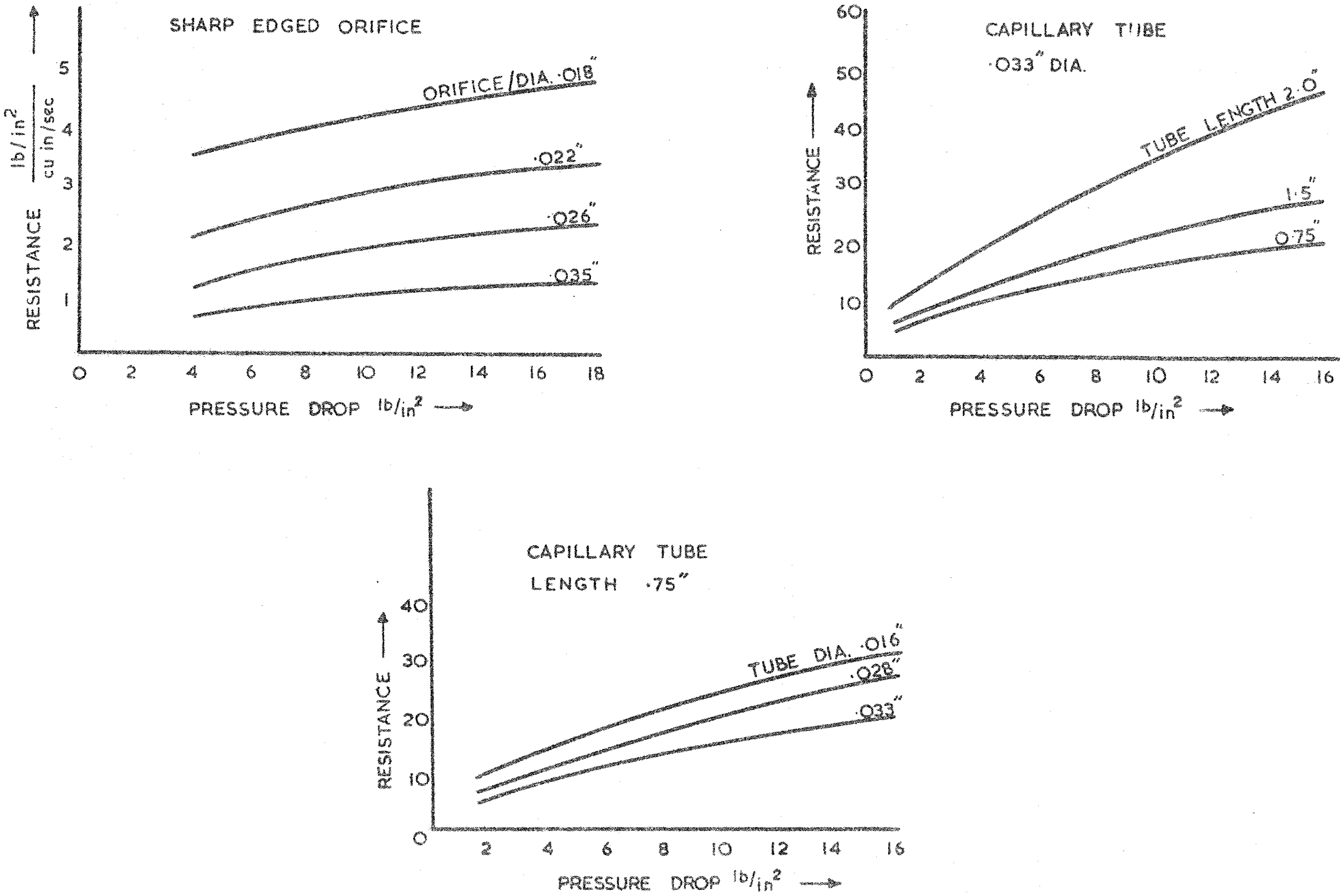


FIG. I. VALUES OF RESISTANCE FOR CAPILLARY TUBES AND SHARP EDGED ORIFICES.

Introduction

Pneumatic-electric circuit analogy

Most of the earlier work dealt with analogue elements and much useful information has been obtained as to the fundamental properties of fluid circuits. Perhaps the most valuable is the simple expression of pneumatic parameters in the electrical form, such as resistance, capacitance, and power. This work has enabled direct comparisons with electric circuits and, as a result, the design of pneumatic circuitry has been much simplified. The analogy cannot be too strict, however, as pneumatic parameters are non-linear, but first order accuracy is considered sufficiently reliable for design purposes.

Analaguous Physical Quantities

		Pneumatic	Electric
Quantity	Q	Molecule (in^3)	Coulomb
Time	t	Minute	Second
Potential	P	lbf/in^2	Volt
Rate of flow	$q = \frac{dQ}{dt}$	moles/min (in^3/min)	Coulomb/sec(Ampere)
Resistance	$R = \frac{P}{q}$	$\frac{lbf/in^2}{moles/min}$ $\frac{(lbf/in^2)}{(in^3/min)}$	$\frac{Volt}{coul/sec}$ (Ohms)
Capacitance	$c = \frac{1}{p}\int q\,dt$	$\frac{moles}{lbf/in^2} = \frac{in^3}{lb/in^2}$	$\frac{Coulomb}{Volt}$ (Farad)
Power	$W = P.q$	$\frac{lbf}{in^2} \cdot \frac{moles}{min}$ $\left(\frac{lbf}{in^2} \cdot \frac{in^3}{min}\right)$	$\frac{Volt\ coulomb}{sec}$ (Watt)

Pressure - A pressure gauge or manometer can be considered as a pneumatic voltmeter.

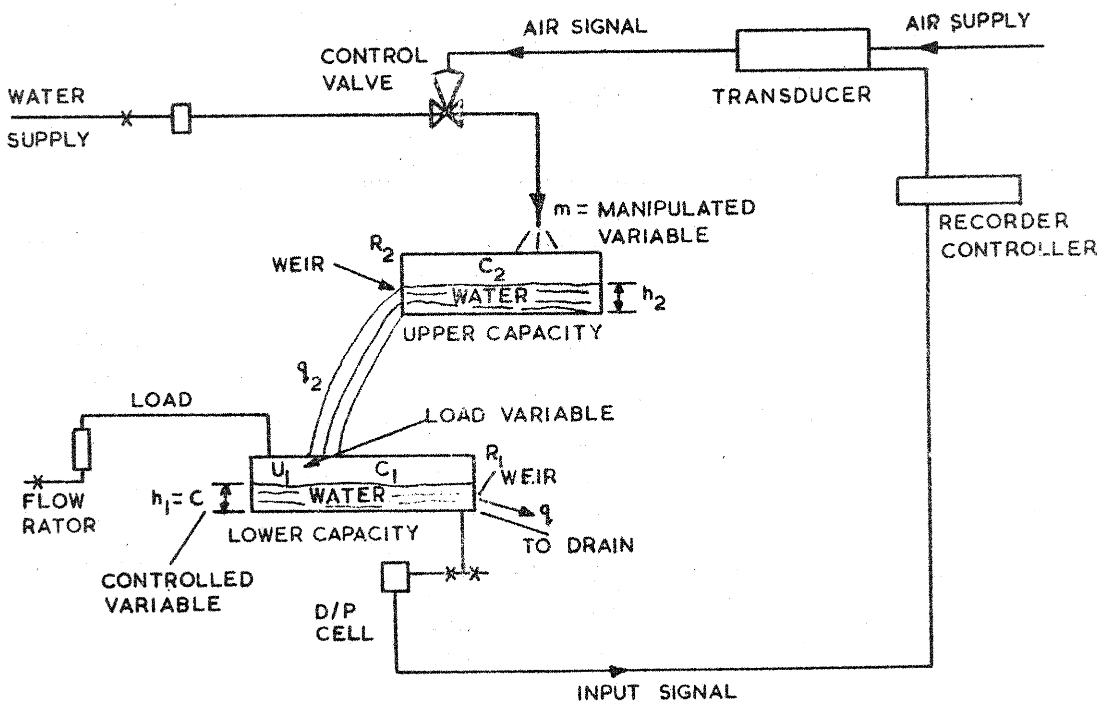
Flow - Flow of air is comparable with electric current and the quantity of air molecules passing a given point is selected as the basis for measurement. Mole units are awkward to work with and by using the ideal gas relationship can be converted to cubic in/min.

$$q = \frac{V}{t} = \frac{NMT}{t.p}$$

N is the number of molecules
M is the gas constant
P is pressure
V is volume
T is absolute temperature

Power - Power is proportional to the product of flow (cu. in/min) and pressure (lb/in^2) which can be related to watts or H.P.

Resistance (See Figure 1) - If constant absolute viscosity is assumed, Ohm's law can be expressed in pneumatic terms as $R = P/q$.



CHARACTERISTIC EQUATION IS GIVEN BY

$$R_1 C_1 R_2 C_2 \frac{d^2C}{dt^2} + \left(T + R_2 C_2\right) \frac{dc}{dt} + C = 0$$

FIG. 2. LINEAR HYDRAULIC ANALOGUE.

Where R = resistance, P = pressure differential, and q = the rate of flow. It is unfortunate that no pneumatic resistance will obey Ohm's law exactly, as actual air viscosity varies with pressure. However, conditions occurring in one part of a circuit will occur elsewhere and overall design conditions will still hold.

Capacitance - Capacitance is dependent upon the circuit volume and is usually extremely large when compared with values typical in electric circuits. The pneumatic unit of capacitance is more equivalent to the megafarad.

Now $C = N/P$, where C is the capacitance. But $V = NMT/P$, where V is the volume. Therefore, $N/P = C = \frac{V}{MT}$

MT is constant for practical purposes, thus the controlling parameter is volume.

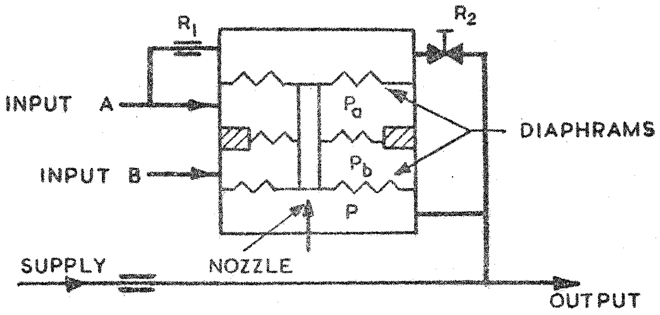
The American effort

American research into fluid computing devices has been in progress for a number of years, and from their publications it is evident that much basic work has been carried out. Most of the American effort has been a co-operative basis and there has been a large degree of collaboration between firms and academic institutions. A few of the interested bodies in this new science are

1. Massachusetts Institute of Technology
2. U.S. Army's Diamond Fuze Ordnance Laboratory
3. The Kearfott Corporation
4. North East Electronics
5. The Bristol Company of America

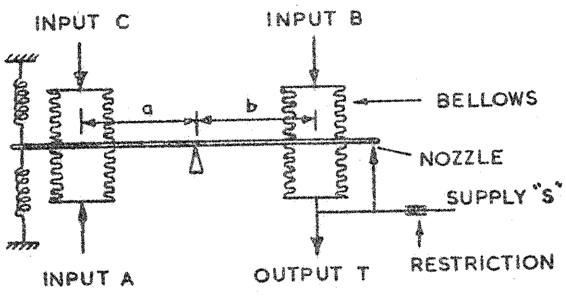
Using the parameters outlined above, engineers are currently engaged in the design of pneumatic elements, such as thyratrons, triodes, amplifiers, and transformers, which have application in the process control field. The uses of fluid analogue computing cover a wide sphere, and are used especially for teaching aids and long cycle time process controllers. The Air Research Company has developed a computer for process control and chemical engineers are considering their uses for the control of large scale chemical plant. In this context, analogue computers are of great value as they are not affected by acids and alkalis, as comparable electrical devices would be.

Research workers at Princeton University(2) have built an analogue computer from conventional pneumatic controllers, pressure regulators, and a series of tanks and capillary tubing, in which the errors were less than ±10% on amplitude and ±7.5% on phase angle for the lower frequencies of operation. However, for high frequencies, the errors involved increased drastically (up to as much as ±50%). General conclusions from their work



$$P = \frac{(R_1 + R_2)}{2R_2}(P_a - P_b) + P_b$$

FORCE BALANCE TYPE



GENERAL EQUATION $T = A + B - C$

TORQUE BALANCE TYPE

FIG. 3. ADDITION , SUBTRACTION , AND INVERSION.

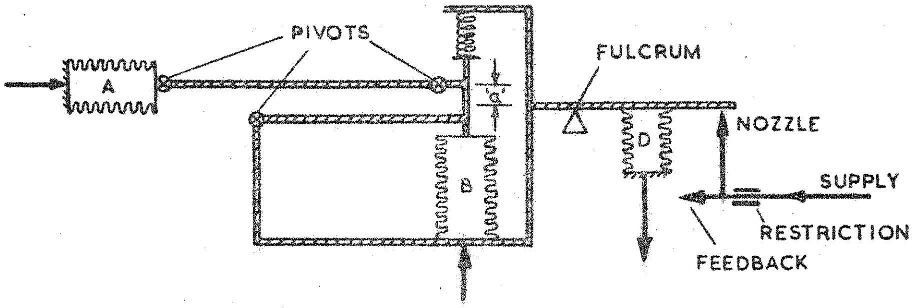


FIG. 4. MULTIPLICATION, DIVISION AND SQUARE ROOT EXTRACTION.

were that the pneumatic analogue is a cheap and useful tool for studying automatic control theory at an elementary level. The working principles are simple and are of great potential usefulness to the process industries.

Yale University Chemical Engineering School(3) is also using the pneumatic analogue for the study of process behaviour. This computer is capable of analysing the effects of load upsets, controlled step changes, transmission lines, and non-linear transmission characteristics. Simulation of process lead time and gain can easily be achieved and the computer is simple to construct. Time constant values range from 9 to 900 secs. For the principles required of it, it is more reliable and cheaper than the equivalent electronic circuit.

The application of fluid analogue computing to teaching is in current use in the U.S.A. and, in fact, several firms market low cost computers especially for this purpose. One of the advantages of fluid computers is their simplicity and flexibility as visual aids. They generally consist of one or more vessels arranged either in series or cascade, through which the fluid flows by means of a valve. By using proportional weirs as flow resistances, linear time constants are achieved and the solving of differential equations is possible, (see Figure 2). Using this system of computing, time constants within the process can be obtained to within 5% of the theoretical values throughout the flow range. One very important aspect of analogue computation is that field specifically consisting of pneumo-mechanical elements. These devices are in wide use in the U.S.A., again mainly in the process industries, and are sold to users either as a complete facility to control a process, or as separate units for specialist applications. The separate units are usually the basic elements which perform addition, subtraction, multiplication, differentiation, integration, inversion, multiple addition, square root extraction, and function generation. It is though worthwhile to describe briefly the design and mode of operation of some of these, to enable the reader to clarify the difference between this well tried type of computation and modern logic devices.

a) Addition, subtraction, and inversion

These functions are usually performed by force balance or torque balance units, as shown in Figure 3. Provision can also be made for multiple input signals.

b) Multiplication, division, and square root extraction

These functions may be performed by a torque balance unit, as shown in Figure 4. To multiply 2 input signals together they would be applied to bellows A and B with the output taken from bellows D. The input at A provides a moment about the fulcrum, while the input at B alters the moment arm 'a'. The beam is balanced by a feedback pressure from the detecting nozzle to the bellows D. Therefore, output pressure from $D \alpha A \times B$.

In order to divide, the two signals would be applied to bellows A and D with the nozzle acting on top of the beam and feedback to bellows B.

Therefore, output pressure from B α A/D.

To obtain a square root, the input signal would be taken to bellows D with nozzle reversed and feedback taken to bellows A and B with a common output.

Therefore, output pressure from AB $\alpha \sqrt{D}$

The main disadvantages of analogue computers are that the speed of operation is low and the accuracy poor, while the governing parameters become non-linear at high pressures. These factors alone restrict their use to the process control field, and thus they can have no application in aircraft, machine tools, or for guidance systems, where high accuracies and speeds are required.

It was felt, however, that no compromise existed between the multi-second analogue computer and the nano-second electronic computer, and therefore much basic work has been carried out on fluid computers with higher accuracies and operating speeds. It is for this reason that research into analogue computing has been largely superseded by basic work into fluid logic devices of the digital type.

Digital computing

The term digital computing is perhaps not as rigid as is necessary for the purposes of this survey, as any device which performs logic actions with signals of a constant magnitude can be termed digital. However, it is intended in this section to deal with two aspects of digital computing, namely, specific applications in sequence control, and also the basic research into the behaviour and potential applications of small module size logic units.

Sequence control units have been in widespread use all over the world for a number of years and, as with the analogue units, are usually of the pneumo-mechanical type. It is not intended to discuss these units in great detail but to indicate how wide the sphere of digital computing really is, and why, in this particular instance, pneumatics are used. The basic research has been into elements of ball valve type as produced by Kearfott, and pure fluid logic devices as produced by the U.S. Army's Diamond Fuze Ordnance Laboratory.

Sequence control units

The basic mode of operation of these units is, as already stated, mechanical, for it is by suitable arrangement of shuttle valves that logic functions can be performed. Many firms in the U.S.A. (and also

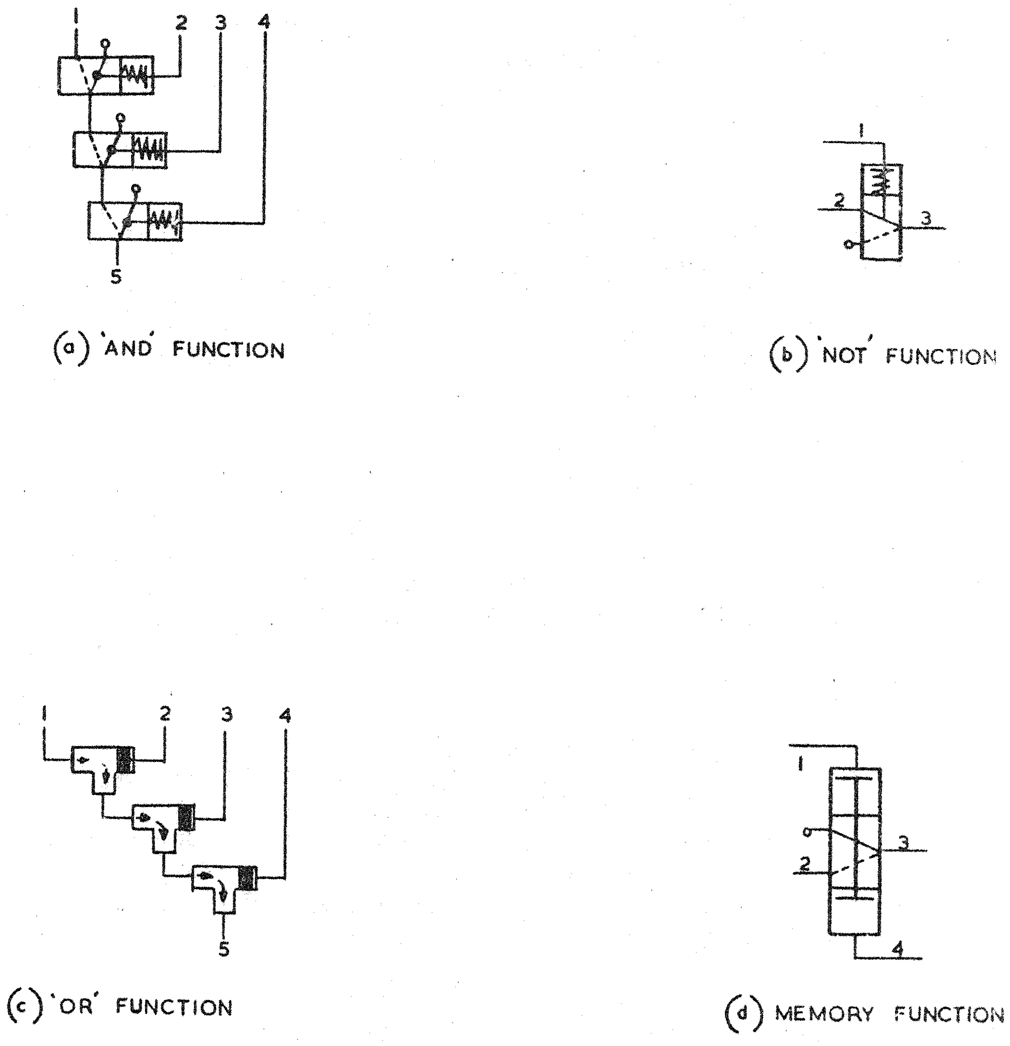


FIG. 5. 3 WAY VALVES CONNECTED TO PERFORM LOGIC OPERATIONS.

in the U.K.) manufacture this type of device, i.e. three way valves, non-return valves, check valves etc. Recently circuit logic and Boolean algebra have been applied to sequence control problems, with encouraging (and profitable) results in the form of simpler and cheaper circuits.

The general impression gained by reading literature on this topic is that pneumatic sequence control has, until recently, been applied only where all other methods are unsatisfactory. However, with the new logic approach to the subject, and the realisation that pneumatic methods are extremely reliable, a large market is opening up for the sale of these devices. At present some of the applications are

a) Machinery control
b) Materials handling
c) Pressure control
d) Special purpose valves

The following are some typical logic functions, and how they are performed with some relevant applications.

AND function Fig. 5(a). Air operated, three-way valves can be connected to provide the AND function. Lines 2, 3, and 4 must all be pressurised before pressure from line 1 can feed to line 5. This function is sometimes used for protective circuits on machines.

NOT function Fig. 5(b). This function uses a three-way, spring return valve. As long as line 1 is NOT pressurised, line 2 is connected to line 3.

OR function Fig. 5(c). The shuttle valves make simple OR gates. Pressure in any of lines 2 or 3 or 4 seals off the pressure at the remaining inputs. In this manner valves could actuate one cylinder.

MEMORY function Fig. 5(d). This relies upon friction to hold a double piloted spool valve in either extreme position. A momentary signal in line 1 moves the piston downward, connecting line 2 to line 3. This remains until a signal at 4 resets the valve.

The advantages of pneumatic sequence units are that

a) they are simple in design and easy to maintain.
b) prices are low and valves are dimensionally small.
c) air compressor plant is installed in most factories.
d) they have great flexibility, as standard parts can be used.
e) the safety factor is high.
f) the initial outlay involved when pneumatic units are installed is usually rapidly regained.

It has been said that pneumatic equipment cannot perform certain control operations which are obtainable with electrical equipment.

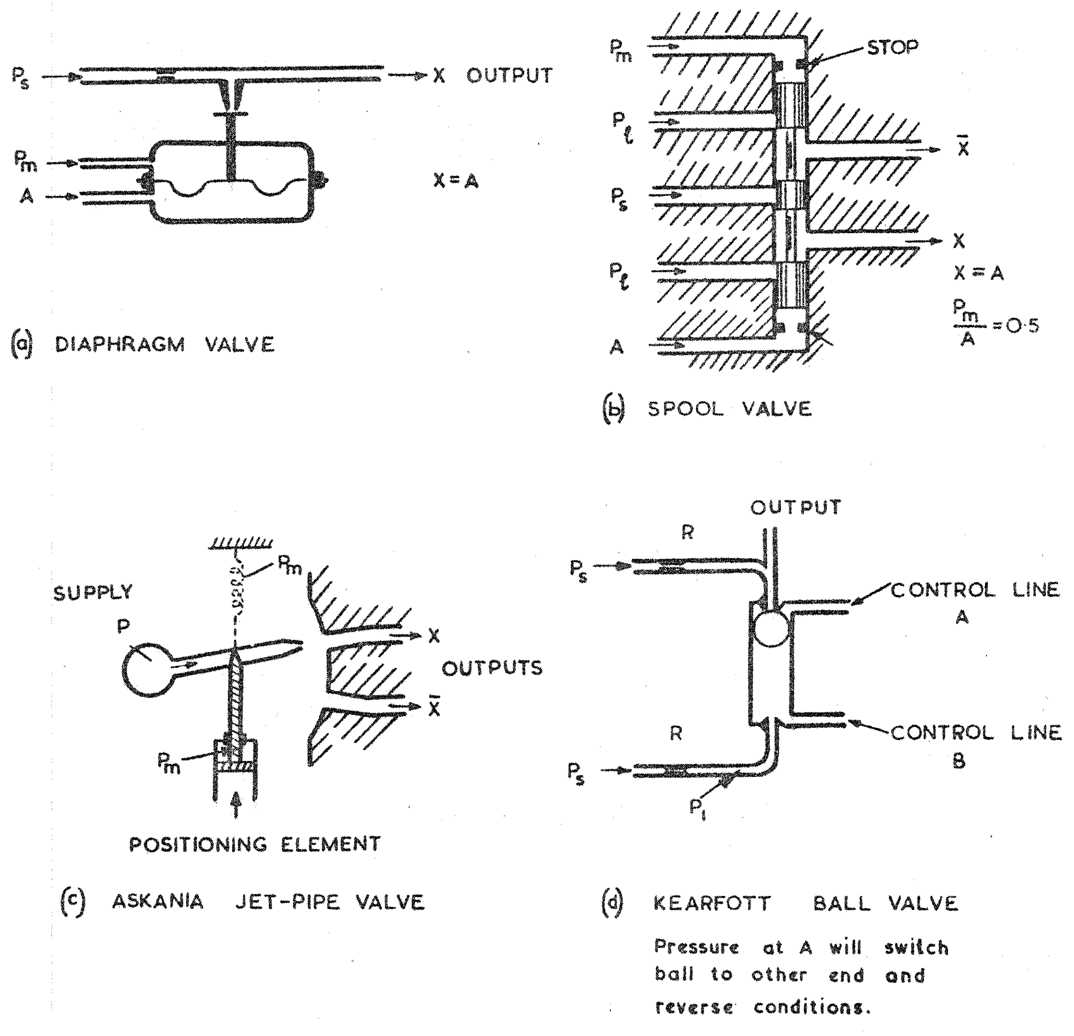


FIG. 6. DEVICES WITH MOVABLE MECHANICAL COMPONENTS

This is true with complicated circuits. However, the more simple electrical functions, such as circuit switching, signal storage, lock in and lock out operations, are obtainable with pneumatic circuits and methods.

Fluid switching elements

The initial idea that a fluid could perform a logic operation was conceived as long ago as 1940 by K.W. Todd, who patented a mechanical relay of the fluid jet type, but since then interest in this field has waned until comparatively recently. This is mainly due to the development of analogue computing techniques which have already been described. Much recent development of logic devices has taken place since 1959, for example, I.B.M. Zurich has had a team of five working on the problem for the past two years.

The best way to describe these fluid logic elements is to subdivide into two parts.

A) Those devices with movable mechanical components ('Pneumech' elements)
B) Those devices without moving parts (pure fluid elements)

A) Devices with movable mechanical components

The basic mode of operation of all digital devices depends upon the presence or absence of a signal, say Ps. Now any controlling of this signal must be performed by the presence, or absence, of any signal, Pi. Thus if reference is taken as Pr, then for operation of any logic device the minimum number of pressure levels required for amplification is three. If amplification is not required, the minimum number of signals required is two, in this case Pi = Ps.

The diaphragm valve shown in Fig. 6(a) is used in digital systems, and is similar to the units described for analogue process control. Fig. 6(b) shows a simple amplifier of the spool valve type; this type of valve has undergone considerable research and development at I.B.M. Laboratories Zurich,[4,5] and hydraulic networks such as shift registers matrices, binary counters, and the more conventional logic devices have been developed and tested.

The basic conclusions arrived at, concerning the spool valve devices, were that

a) the response of hydraulic units depends directly on fluid inertia. Thus the channels must be kept short for fast response.

b) transmission propagation velocity depends on the velocity of sound in the fluid.

c) the difficulties arising from impedance matching problems are large, and proper functioning of units is largely gained by trial and error methods.

d) miniaturisation of the devices shows that initially response time reduces proportionally with linear size. However, this effect does not continue indefinitely for, at the smaller sizes, secondary effects, such as viscosity and manufacturing tolerance, make themselves felt. It has been experienced that the minimum size of bore for maximum speed of operation is .05″ to .08″ (1.5 to 2.0 mm).

e) cavitation is a source of annoyance to the designer for although in some cases it can reduce the response time, in most instances its effects are to cause instability and erosion of the hardware.

f) the governing parameters of a spool valve type of valve operating at 10 atmospheres were

Response time = 1 ms
Volume, including control channels = .06 in (1 cm^3)
Piston diam. = .08 in (2mm)
Power required for a repetition rate of 1 ms = 25 W
Leak power loss = 200 mW

It is felt by I.B.M. that arithmetic units for computation may be relatively distant but there are more immediate applications. One would be to control the intake and exhaust ports of an I.C. engine, using a binary counter to replace the step down gears and timing cams.

Fig. 6(c) shows the jet pipe valve of the Askania type, as used for the construction of a pneumatic keyboard patented in America in 1961.

Fig. 6(d) shows the Kearfott ball valve.[13, 17, 18 and 19] This device has been claimed to have particular application where conversion between pneumatic and electrical signals is required. The Kearfott Company also claims that this unit is extremely reliable and can be manufactured with extremely high packaging densities of the order of 2000 elements/in^3 (120/cm^3). They also claim operating frequencies of 10 - 100 Kc/s for the basic bi-stable unit. Limitations to this frequency are, however, the speed of propagation of the pressure disturbances within the circuit, the power density per unit cross section of passage, and the minimum size available with present fabrication techniques. Kearfott are working on sizes of .020 in (5 mm) for ball tube diameter resistance orifices of between ,010 in. (.025 mm) and .0004 in. (.001 mm) diameter; they claim that a medium size general purpose computer would occupy $5\frac{1}{2}'' \times 5\frac{1}{2}'' \times 1''$. (140 x 140 x 25 mm).

It is not intended to discuss these particular devices in detail, as most of the technical aspects of this report concern the Kearfott ball valve. There is a variety of uses for these units, for with speed of operation claimed, they could be used for controlling cryogenic units, rocket motors, and guidance platforms. The small size and reliability offered by pneumatic computers allows for the possibility of extensive portable computing facilities for military uses, such as ballistic,

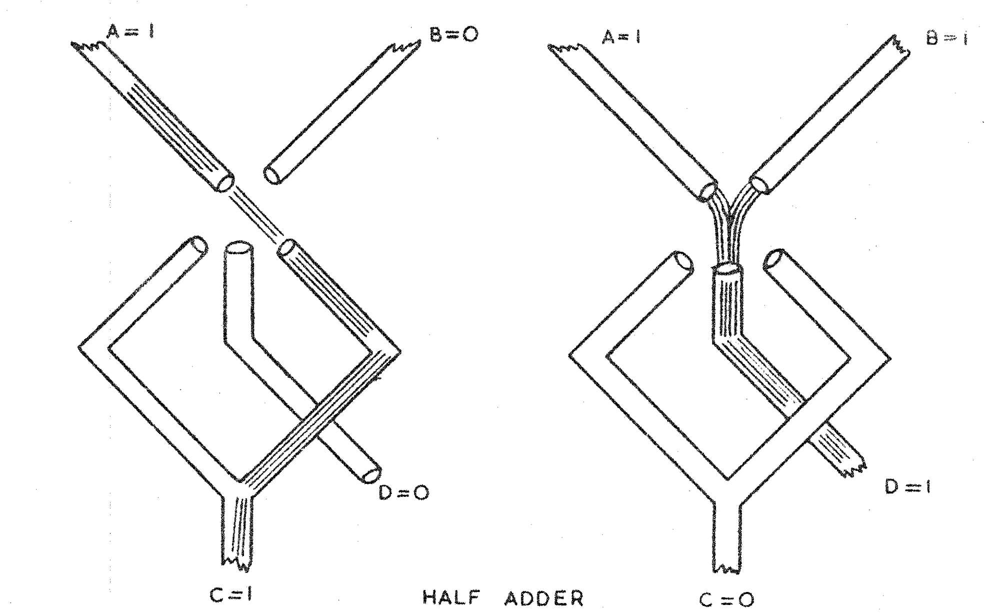


FIG.7. GREENWOOD'S DEVICE.

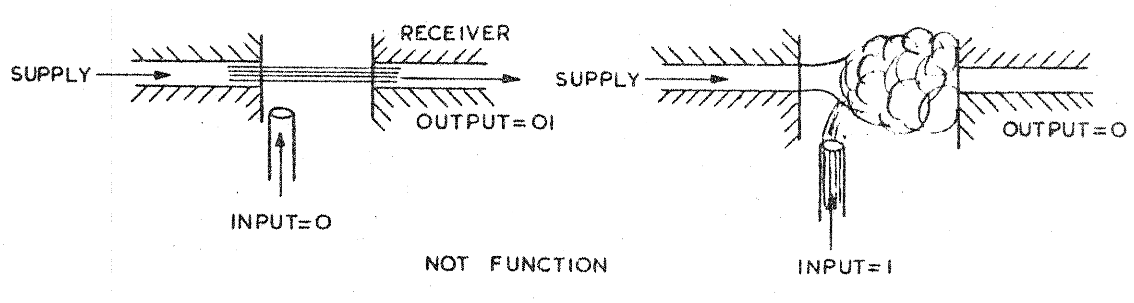


FIG.8. THE TURBULENCE AMPLIFIER.

tactical, and logistic. Other immediate uses are for desk calculators, machine control, readers for the blind, and telemetry equipment.

The advantages of these logic units are as follows.

a) Broad operating temperature range limited only by material used.
b) Immunity to radiation.
c) Ease of information insertion by means of punched tape, cards, or direct mechanical transducers.
d) Capable of extremely high shock loading; 50,000g would be required to disturb a bi-stable element operating on 100 p.s.i. differential pressure.

The disadvantages are as follows.

a) Tolerances on port diameters as little as ±.0005 in. (±1.25 μ) and on ball and cylinder diameters ±.0002 in. (.5 μ) tend to make the cost high.
b) The working fluid passing through the units must be filtered to ensure no blockage exists. This entails filtering down to three microns.

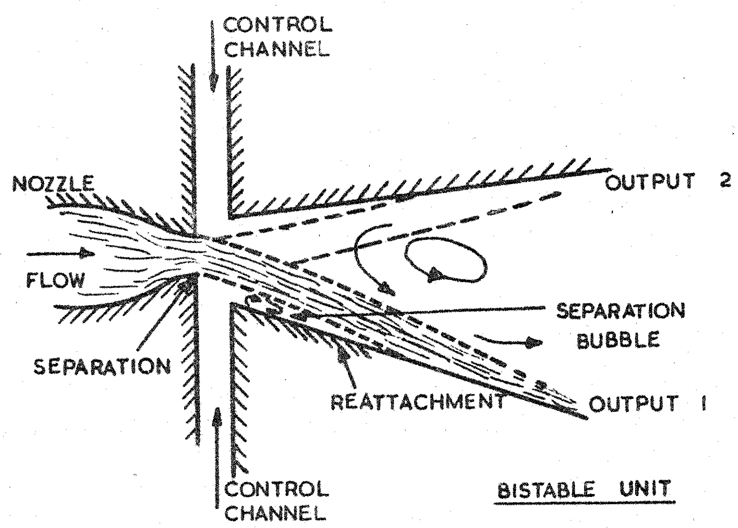
B) Pure fluid devices

The pure fluid logic device is a relatively new development, although the basis of performing logical operations with a fluid is an old concept. These devices are characterised by three major groups.

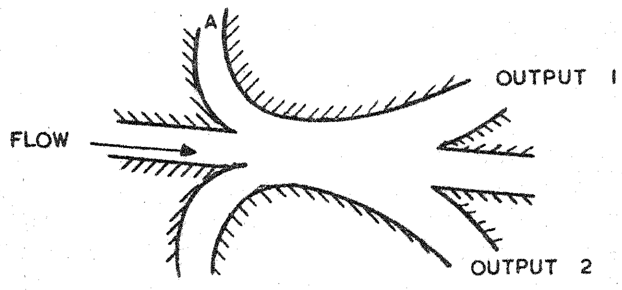
1. The unbounded or free jet elements.
2. Bounded jet elements.
3. Rotational flow effect elements.

1) Unbounded jet elements are those elements which rely upon the interference of one jet with another to produce a deflection of flow. The momentum controlled type of unit was first developed by Greenwood, at Massachusetts Institute of Technology, who developed the half adder. The amplification of this device is not usually greater than 4, but this is more than adequate for most logic operations. Fig. 7 shows the operation of Greenwood's device clearly; if inputs A and B are present, the two jets impinge and the resultant flow is from the CARRY; if either A or B are present alone, then the SUM output C, results. The element is a passive element, that is to say, both streams lose energy within the unit and amplification of the CARRY output is often necessary if this is to be connected to similar devices.

A further type of unit is the pressure controlled type, where deflection of the power stream is possible by raising or lowering the static pressure at one side of the stream. This type behaves exactly as the air curtain used in multiple stores at entrances; when there is a pressure difference between the inside of the stores and the exterior



a.) TURBULENCE REATTACHMENT DEVICE



b) VISCOUS ADHESION DEVICE.

FIG. 9. BOUNDED JET ELEMENTS.

the curtain is deflected. This type of device has been used to detect pressure pulses in pneumatic transmission lines.

The turbulence amplifier operates on the principle of forcing turbulence into a laminar stream and thus preventing a large proportion of the flow from entering a receiver (Fig. 8). Pressure gains of from 5 to 500 are possible with this device, the higher gains being achieved by increasing the distance between the supply and output tubes. This device is responsive to high frequency sounds; for instance, one such unit was forced into the turbulent condition by a dog whistle at 300 ft. distance.

The advantage of these units is, however, the amplification factor, which enables a large number of units to be coupled directly without further amplification.

Although the unbounded jet elements have been investigated thoroughly, there is no specific application for them, as yet, other than those demonstrations to indicate their logic performing capabilities. It is felt that the turbulence amplifier, although an ingenious device, is lacking in practical application. Its high sensitivity to ultrasonic vibration makes it a very doubtful starter for industry, where it would be in an environment of large vibration. As for the momentum controlled and pressure controlled amplifiers, these have largely been superseded by the following bounded jet elements.

2) Bounded jet elements (as shown in Fig. 9) use boundary walls to provide the mechanics of switching the power stream; this is done by two methods, (a) a turbulent reattachment effect, (b) a viscous adhesion effect.

a) The turbulent reattachment effect is the effect produced by a turbulent shear layer at the edge of the jet, and the subsequent reattachment of this shear layer to the adjacent boundary wall. A detailed account of this mechanism can be found in refs. (4) and (6). The reattachment of the shear layer is dependent upon Reynolds number and the geometric shape of the device. This separation region can be increased in length by the injection of a fluid into the control channel, increased to such an extent that the flow separates from the wall and attaches to the opposite side. When the control flow is removed, the flow, now firmly attached to the opposite wall, stays in position, giving a bi-stable switching action. All the basic logic functions can be obtained using this technique. Limitations of the turbulence amplifier are that

i) the maximum jet velocity is limited by the pressure difference across the jet required to maintain the curvature of the stream against the adjoining wall. A critical cavitation number for fluids can be defined by the supply pressure Pv, in the form

$$\sigma = \frac{Pb - Pv}{Ps - Pb}$$

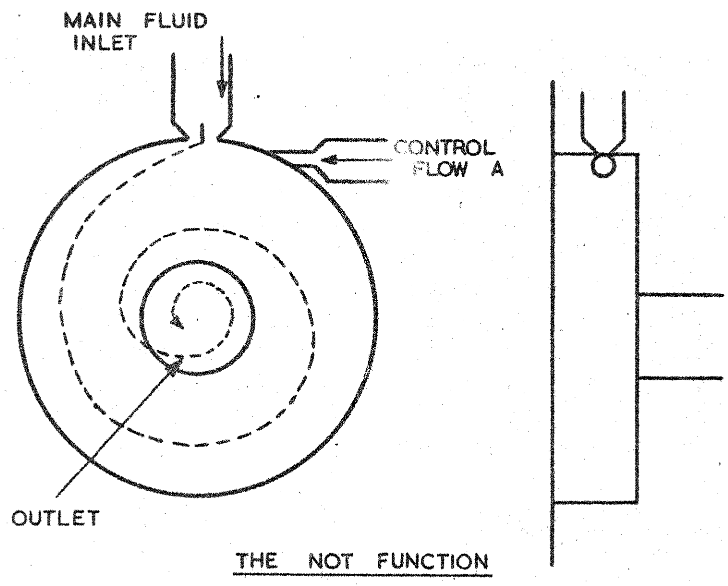


FIG. 10, ROTATIONAL FLOW ELEMENT

This value depends on the shape of the device, and is in the order of 0.2. For gases, the limitation is the sonic velocity.

The switch time is the time from the initiation of an input to the output being in the new position. This time is proportional to the transport time of a molecule through the device. The constant of proportionality is the Strouhal number S, i.e. the ratio of response time to transport time.

Response time $t = SL/U$, where S is a function of the control pressure and element shape, U = mean velocity of flow at nozzle exit.

Typical operating values for an element are

Nozzle width = 0.006 in. (0.15 mm); length 0.06 in. (1.5 mm)
Strouhal number = 15 Reynolds number = 1000
Cavitation number = 0.2
Max. nozzle velocity = sonic for gas
= 4.5 ft/sec (15 metres/sec) for water.

Response times 22 μs Hydrogen
75 μs Air
750 μs Water

Power required for flow =

4.8W Hydrogen
0.7W Air
0.1W Water

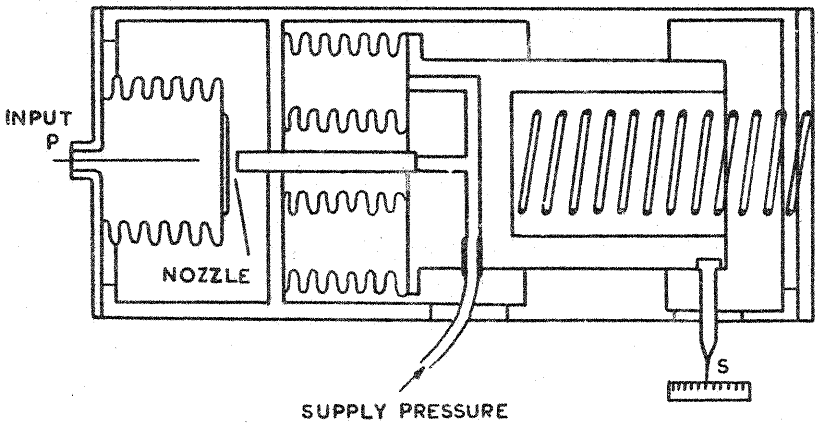
b) Viscous adhesion devices rely upon the adhesion of one fluid with another. Fig. 9(b) shows a schematic layout of this device.

If an input is fed into the control line, A, this will adhere to the solid wall to output 1. The power stream will, in turn, follow the control stream and proceed to output 1. The cessation of the control stream, however, allows the power stream to revert to its original position. By connecting feedback paths to this device, it will act as an oscillator. Very little is known about this device and no papers or performance data are available at present, to the author's knowledge.

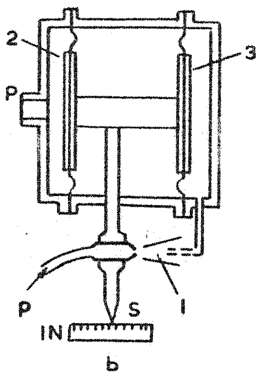
3. Rotational flow effect elements. The basic action of these devices is to induce rotational flow into the power stream and hence decrease the static pressure. Thus, in the device shown, (see Fig. 10) if a control pulse is fed into A, the output pressure immediately drops, giving a NOT logic operation.

Application and manufacture

The applications and manufacturing techniques of some of the elements



a NOZZLE VANE UNIT



b NOZZLE PIPE UNIT

FIG.11. PNEUMATIC SENSING ELEMENTS

are worth considering, as it is apparent that many revolutionary fabrication methods have evolved with the development of these devices. Both the Diamond Fuze Ordnance Laboratory and I.B.M. Zurich have used photo-etching techniques for the mass production of fluid amplifiers. Some research into this method was done by the Corning Glass Works, and involves exposing ultraviolet light onto glass and then heat treating to allow a fast etch. By this method, shapes of the accuracy and size required have been achieved with no great difficulty. Similar processes have been developed by the Bowles Engineering Corp., using an ultraviolet sensitive plastic. Some attempts to manufacture the moving part elements by the lost wax process have proved satisfactory and, also, success has resulted from the use of engraving techniques.

The ability to manufacture any of the already described devices to a repeatable pre-determined tolerance is essential if the performance of the units is to be consistent and predictable.

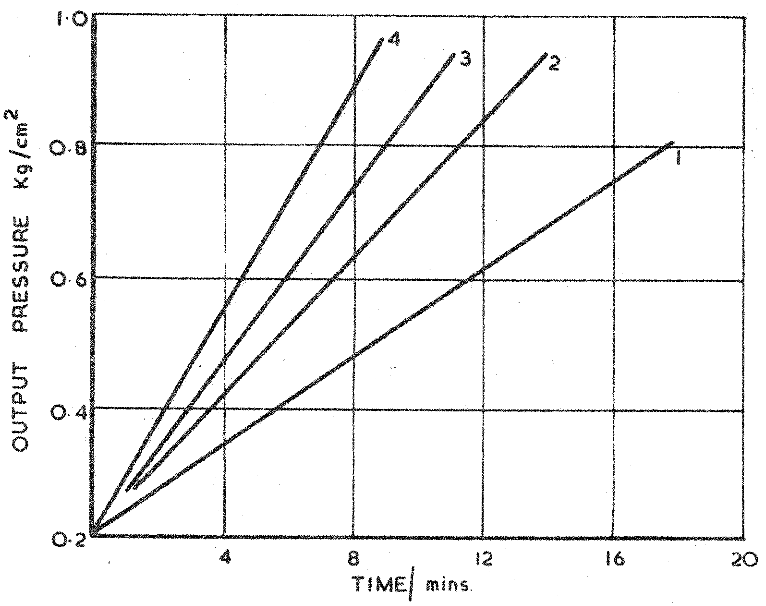
The application of the turbulence amplifier is wide, and several firms have demonstrated its potential by producing working models for show at conventions and lectures. D.F.O.L., for example, have built a three-wheeled car steered by the vector thrust of a small gas turbine mounted at the rear. The direction of the turbine is controlled by a five stage proportional amplifier, which actually deflects the jet from the turbine. This device has a power gain of 100,000. This is an indication of how a turbulence amplifier could be used for vectoring rocket thrust on missiles. The U.S. Army has also used the turbulence amplifier to simulate the pumping action of the heart, and this device has been run continuously for 5 months in a reliability test.

I.B.M. considers that the best use of fluid logic devices would be to combine the various types of unit to optimise their performance; for instance, a half-adder could be made using a momentum controlled unit and a turbulence amplifier. It is judged that this method of applying fluid logic is by far the most promising means of developing complex computers.

THE RUSSIAN EFFORT

It is unfortunate that little information of real value is obtainable from Russia, as it is evident from their publications that much work has been done on fluid logic devices. The general picture obtained from reading Russian literature is that the science is viewed with the same degree of importance as in the U.S.A., but the sphere of application is slightly different. Here there is a large stress on the application to the process control and machine tool industries, but no indication is given as to the possible uses in the military field.

Much of the Russian work has been based on analogue methods, and some very accurate and complex systems have been developed in this context. This, perhaps, is an indication that their efforts are some way behind the American achievements. A large proportion of the analogue work has



CURVE No.	INPUT PRESSURE	TIME CONST.
1	0·045 atm	83·4 secs
2	0·070	83·5
3	0·098	83·4
4	0·116	84·8

FIG. 12. INITIAL RESPONSE CHARACTERISTICS.

been the construction of computers to solve mathematical problems. With regard to the digital topics of this science, some useful papers have been published concerning relays of the pneumo-mechanical type. Again, however, the size and response of these elements do not compare favourably with the American devices. A large proportion of the Russian work has originated at the Institute of Hydraulics and Telemechanics in Moscow, where most of the basic research in fluid and gaseous systems is dealt with.

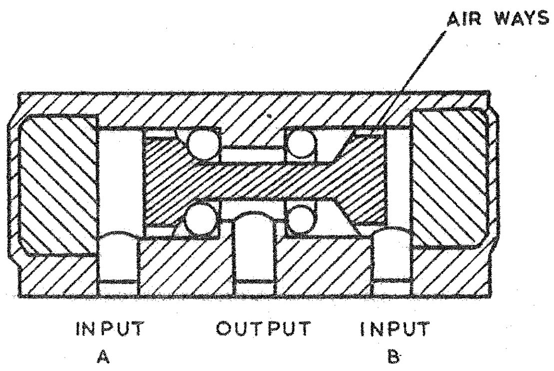
Analogue computation

A considerable amount of published information is available on pure research into analogue devices, whereas no practical applications are cited. An excellent paper has been produced by Zalmanzon and Semikova[25] on the characteristics of pneumatic jet elements. This work has been of great value in the evaluation of controlling parameters in subsonic jets, and uses are suggested for position sensing mechanisms. Fig. 11(a) shows the normal position sensing equipment of the nozzle vane type, while Fig. 11(b) shows the jet-pipe arrangement. This device uses the pipe as a feed-back arrangement from which position can be sensed to a high order of accuracy.

It has also been suggested that the principles of jet-pipe elements be applied to addition, multiplication, and division. This is done on the premise that for every given position of the pipe, the ratio of the pressure on the pipe to the pressure in the front of the nozzle is independent of supply pressure. These devices perform functional transformations of the type required to produce and finish cam mechanisms, lever mechanisms, etc. The development of low pressure computing elements appears to be of extreme interest, and investigation has revealed that these are used for high accuracy but low frequency operations, as would be required in the process industry. For example, an aperiodic integrator has been constructed that produces time constants with a widest variation of .5 - 1.0% up to frequencies of 6 rads/sec. This, however, has been achieved only by using pressures as low as .07 - .116 atmospheres. Fig. 12 shows the output pressure response to a step input pressure and gives some idea of the long time constants involved.

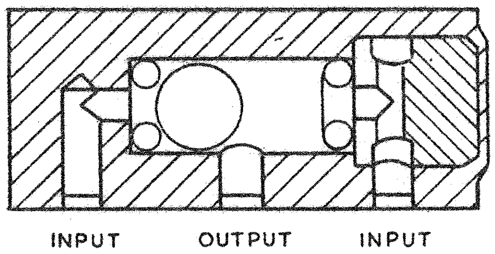
The best method of obtaining linear characteristics for the analogue type of computer is to design all the elements in a circuit on the basis of a single standard unit, as is done in the case of electronic computers. Another method is, as already stated, to use very low pressures, which also reduces the consumption of air considerably. These methods, which have been adopted in certain cases for pneumatic summation and pneumatic relay technology usually of the flapper nozzle type, and are said to be extremely reliable.

One use of the pneumatic analogue has been to utilise the pneumatic behaviour to predict the performance of dynamic systems, that is, the use of the computer for solving high order differential equations.



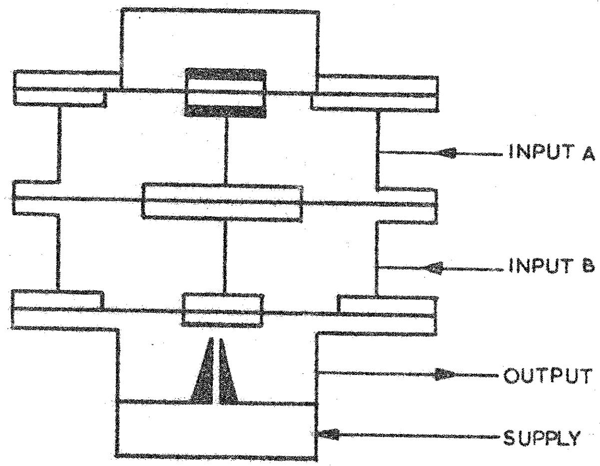
'AND' VALVE

With both inputs A and B shuttle takes up central position and air passes to output through the airways



'OR' VALVE

FIG. 13. SHUTTLE AND BALL TYPE UNITS.



With input 'A' relay functions as a 'NOT' unit
With input 'B' relay functions as an ON-OFF switch.

FIG. 14. PNEUMATIC RELAY.

Surprisingly accurate results have been achieved by these methods, with .5% difference between theoretical and practical solutions. These results are found to be independent of fluctuations in temperature less than ±3°C.

Investigation into the theory and design of the basic elements has, as in America, been very useful in aiding the designer to improve pneumatic circuitry considerably. One point to be considered from this work is that, to achieve repeatable results from pneumatic resistances, it is desirable to use capillary tubing rather than sharp edged orifices.

Russian industry is at present undergoing a change from automation of individual processes to the integrated automation of complete production. In this context, much experimental work has been done to use the pneumatic analogue. One method of solving problems such as this is to write down all the transmission functions of the controlling parameters of the system and arrange them in a matrix form. From this matrix, the transmission function of the dynamic element can be found, and hence the ideal system controller can be designed.

Digital Computing

Sequence control systems

The sequence control of machine tools by pneumatic relay devices appears to be as widely used in Russia as elsewhere. This is most probably because the pneumatic systems have proved easier to develop and produce than comparable electric devices. The use of shuttle and spool type valves to perform logic operations is quite standard, as is the logical approach to circuit design.

It is thought worthwhile to describe one type of logic device which does not appear to be manufactured elsewhere. This type is basically mechanical, but it is of interest to note that the OR function uses a ball valve, as does the American Kearfott device. Fig. 13 shows the design and mode of operation of two of these devices. They are used for automating small machine tools, such as drills and capstan lathes for application to transfer lines, for process sequence control, and as safety interlocks.

Rotary distribution circuits designed to act as memory storage are also in use. These circuits use a pneumatic motor to drive a cam shaft which, in turn, operates shuttle valves to control the sequence operations. The device is basically crude but simple to manufacture, and programme sequence can be changed merely by rotating the cams on the shaft.

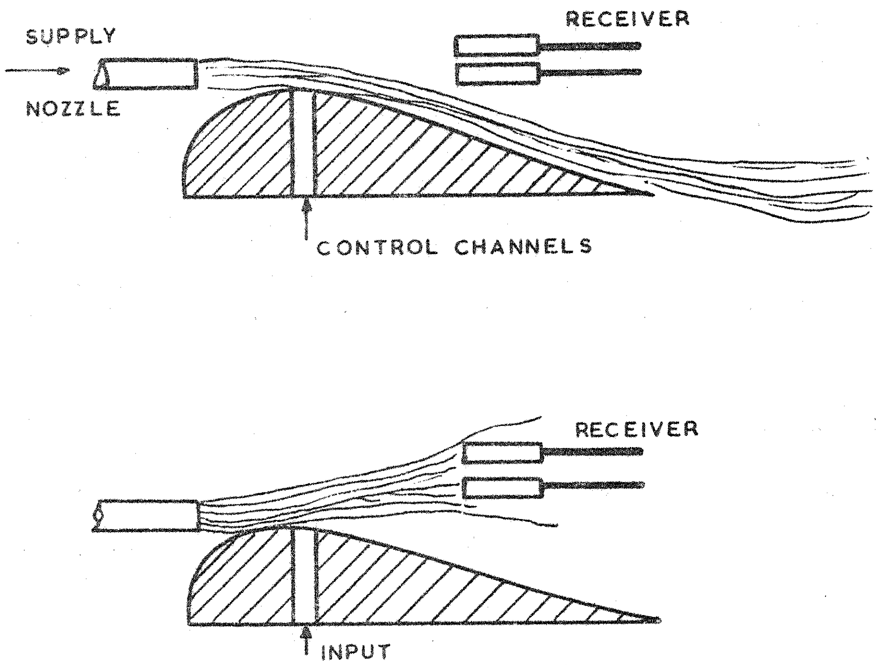


FIG.15. AEROFOIL SECTION ELEMENTS.

Fluid switching elements

A) Devices with movable mechanical components

The basis of the mechanical devices seems to be a straight adaptation of the electrical contact relay, and on first sight one would assume that the same reliability would be achieved. Fig. 14 shows a schematic arrangement of a relay layout. This consists of an actuator and a contact; the contact creates a local resistance and acts as a flapper valve to control the supply pressure. By arrangement for more than one input to the system, limit switches and all the usual logic functions can be made. The size of this type of unit is approximately 2 × 2 in. (5 × 5 mm), built up in sandwich form from ½" (12.7 mm) thick slices. The speed of operation is not known, but it is claimed that they are sufficiently fast for most automatic production circuits. The reliability is also not given, but it has been stated that these devices are not yet reliable enough for mass production. Their application is to the sequence control industry and there is no intention of using them in pure digital computers.

B) Pure fluid devices

The use of pure fluid devices appears to be an exceptionally new art, and no useful applications are suggested other than that they are expected eventually to supersede the mechanical type.

The aerofoil section. This device uses the principle that a jet will follow the surface of an aerofoil, as shown in Fig. 15. If, however, a control pulse is applied, the boundary breaks away and the flow is diverted. When the pulse is discontinued, the device returns to the initial state, acting as a monostable device. This device is identical to the turbulent re-attachment type as described by D.F.O.L. and I.B.M. in America.

One interesting use of the aerofoil is its application to the analogue field for function generation. Functions such as pure sine waves, step, ramp, and triangular functions have been produced by this method. This is achieved by passing the supply pressure into a reservoir, and controlling the output from the reservoir by a feedback to the aerofoil.

The 'Pneulog' system. (see Fig. 16). This has been developed by M. Balda, in Prague. Little technical information is given as to the mode of operation. This element appears either to work on the same principles as the turbulence amplifier or by jet interaction. The element shown is the NEITHER type. (Fig. 16(a)). The schematic layout of the functions shown in Figs. 16(b) and (c) are the OR and AND functions. The OR function is the logical sum, i.e. an input at A or B can produce an output C. The AND function is the logical product, i.e. both inputs A and B are required for an output C.

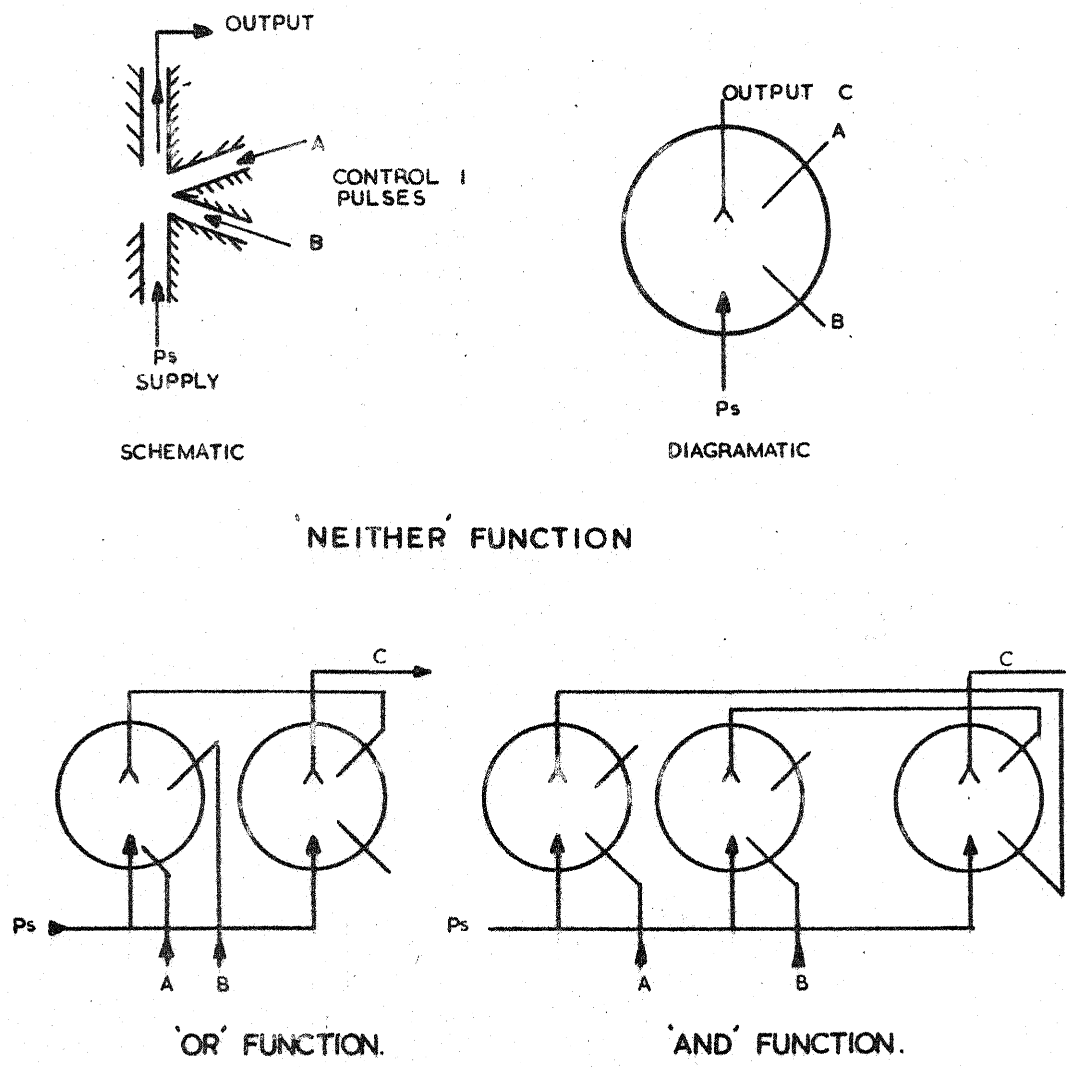


FIG. 16. THE 'PNEULOG' DEVICE

These elements are claimed to withstand shock, acceleration, and temperature change, but the usual difficulties regarding low gain and miniaturisation have been encountered. It is also claimed that these devices may vary the supply pressure from tens of mm of water to many atmospheres, and the most complicated circuits are not affected by pressure fluctuations.

DISCUSSION

It is intended in this section to discuss various topics of fluid computing under the same headings as before, and to compare the work being done in this country.

The review has shown that analogue computation has potential for application to the process industries, and for use as teaching aids at universities and technical colleges. It has no application, however, where fast response times are required, and thus it is not practicable for machine tools, aircraft, or guidance systems. In this country equipment of the mechanical type is being manufactured by firms such as Elliot, Foxboro Yoxall, A.E.I. (Sunvic), Honeywell, Kent and Hagan Controls, etc. These are similar in conception and design to the American devices. Also the applications appear to be basically the same, but there is no evidence to show that computers have been built to optimise industrial processes with these units. With regard to analogue computation for teaching aids, and for solving differential equations, the only work done in this context is, to the author's knowledge, at the British Hydromechanics Research Association, where a computer has been built based on Russian work by I. Ivlichen and E.N. Nadshafor. Demand for this type of computer is likely to be small and those institutions interested in using them will most probably import from the United States, or be capable of building their own, as is done at the College of Aeronautics.

Widespread use of sequence control units both in Russia and America is now coming into vogue in this country. Many firms manufacture spool type valves for automation purposes, but it is evident that the latest logic performing techniques could possibly replace these.

For simple sequence operations, problems of impedance matching of individual units do not arise, and almost immediate application of the Kearfott ball valve is possible.

Research into the new fluid logic techniques has shown that two types have great potential, i.e. the Kearfott ball valve and the pure fluid amplifier. Of these, the pure fluid amplifier appears to have aroused the most interest and more basic work has been done on this type. Most of the work, however, is of a pure research nature and considerably more research and development is necessary before complex units can be applied. The Kearfott ball valve, on the other hand, can be used for practical purposes while under development. It is thought ideal to develop this device in stages by designing and testing for simple purposes initially,

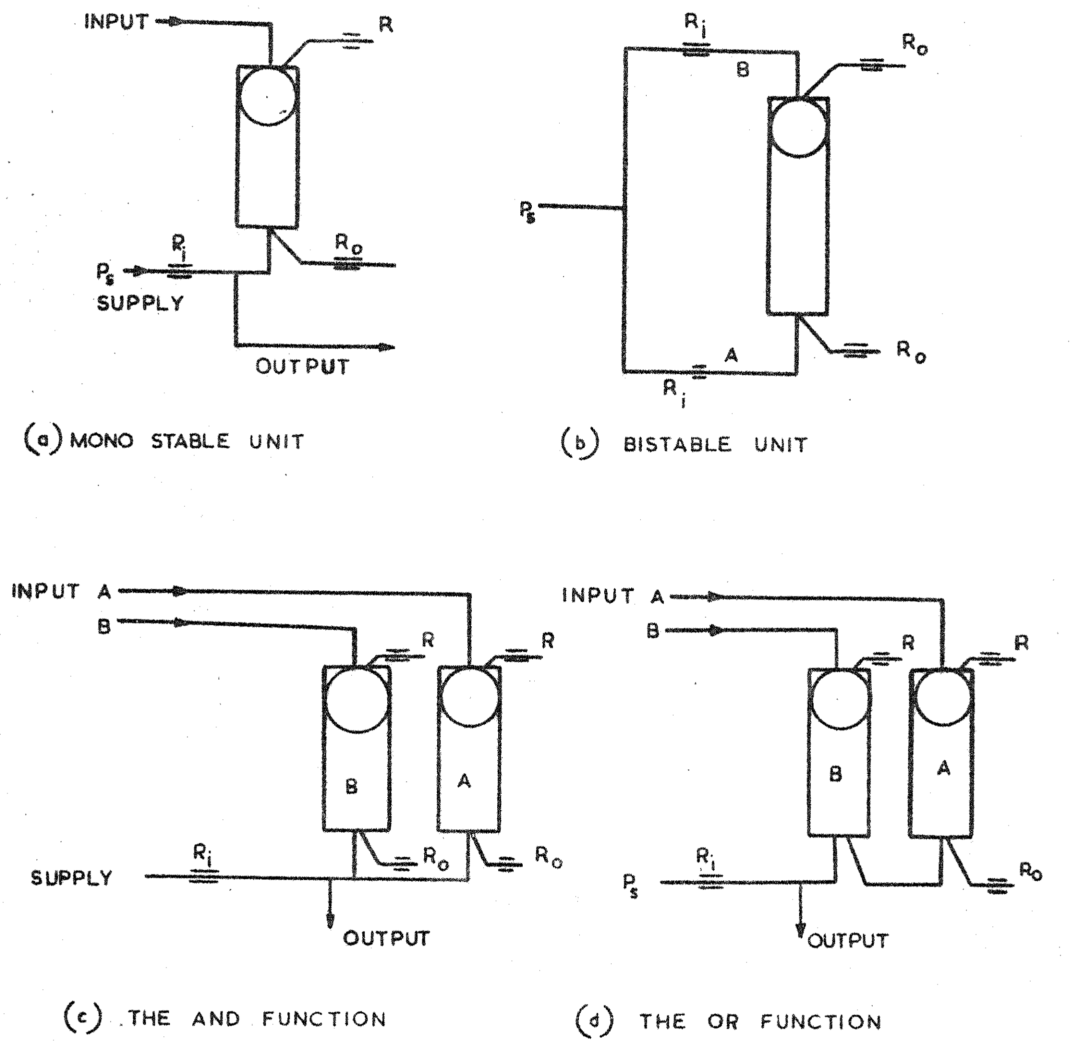


FIG. 17. BALL VALVE CONFIGURATIONS.

leading on to the more complicated circuits later. The pure fluid amplifier may at a later date supersede the ball valve by virtue of its simplicity, although the two systems appear to be complementary in many respects, but it is not intended to investigate this latter device at the College of Aeronautics for at least another 12 months.

DESCRIPTION OF CRANFIELD WORK

From the findings of the review it was decided to carry out research into the Kearfott ball valve (see Fig. 6(d) and page). Plate 1 shows a laboratory model of the basic valve unit. Several of these devices were constructed at the College of Aeronautics, and tests have been conducted to find the parameters governing their operation. Much initial work has been carried out to find the optimum switch frequencies, and, for the size of ball given, this appears to be less than 2.5 milliseconds. This value has been obtained with supply guage pressures from 5 - 20 lb/in^2.

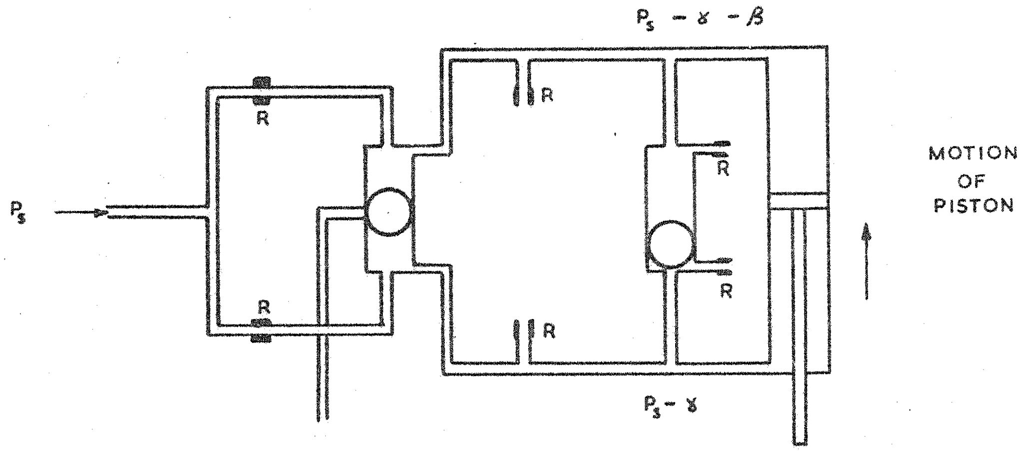
The laboratory models constructed were made using 3/32" (2.3 mm) diameter ball bearings. The switch path lengths were made variable, and resistance values were altered externally by means of sharp edged orifices.

Plate 2 shows the layout of the laboratory rig used to determine optimum switch frequencies.

The mono-stable unit (on-off switch)

Fig. 17 shows a schematic layout of the mono-stable device; this unit is used for performing primitive logic functions, such as AND, NOR and OR, as shown in Figs. 17(c) and (d). Experiments have also been carried out on this device to determine switch frequencies, and exceedingly promising results have been obtained. Graph I shows some results of tests using this device. It may be noticed from the graphs that both the mono-stable and bi-stable devices cease to work at frequencies above 180 c.p.s. This is due to second order effects becoming large and factors, such as ball inertia, becoming sensible. However, the means by which switch frequency was obtained was to measure the output pressure from the devices, and thus the circuit response time was recorded. In every case the ball switch time was a negligible proportion of the circuit time constant . Recent results have shown that reduction in circuit resistance and capacitance reduces the response time drastically.

Limitations to the device are, as one would expect, the speed of sound within the circuit and the power output available. It is felt, however, that for most applications, only small power outputs will be necessary, as the signals will be fed into some type of amplifier.



INPUT PULSE REVERSES PRESSURE CONDITIONS AND CAUSES PISTON TO TRAVEL IN OPPOSITE DIRECTIONS.

FIG.18. SCHEMATIC LAYOUT OF TRISTABLE DEVICE

The bi-stable unit (memory function)

Figure 17(b) shows a diagram of the design and mode of operation of a basic bi-stable unit. Initial tests were conducted to find switch time by physically closing the exhaust ports as shown. Conclusions from this are that the behaviour of the ball is somewhat erratic when used in this manner, and poor response times result. (Graph II shows some typical results).

Second stage tests were made to find the governing parameters of switching when using a forced pulsed input to the system. As a result of this, response times were much improved and became mathematically predictable (see Graph III).

Examination of Graphs I, II and III will show that the output signal amplitude is rather low compared with the supply pressure into the devices. This is largely due to the poor sealing of the ball onto the valve seats, and it is considered that this will be one of the most difficult development problems to overcome.

Preliminary calculations as to the effect of tolerance on the manufactured article point to the fact that normal workshop tolerances of ±.001 in. (.025 mm) on most dimensions will be sufficient. This leaves only the problem of obtaining a tight gas seal between the ball and its seating.

Some attempts have been made to apply the device to some practical usage for demonstration purposes. Fig. 18 shows how a tri-stable device can be used for sequence control. In this context it is felt that the ball valve has particular application, although some means of signal amplification will be necessary before use can be made of it.

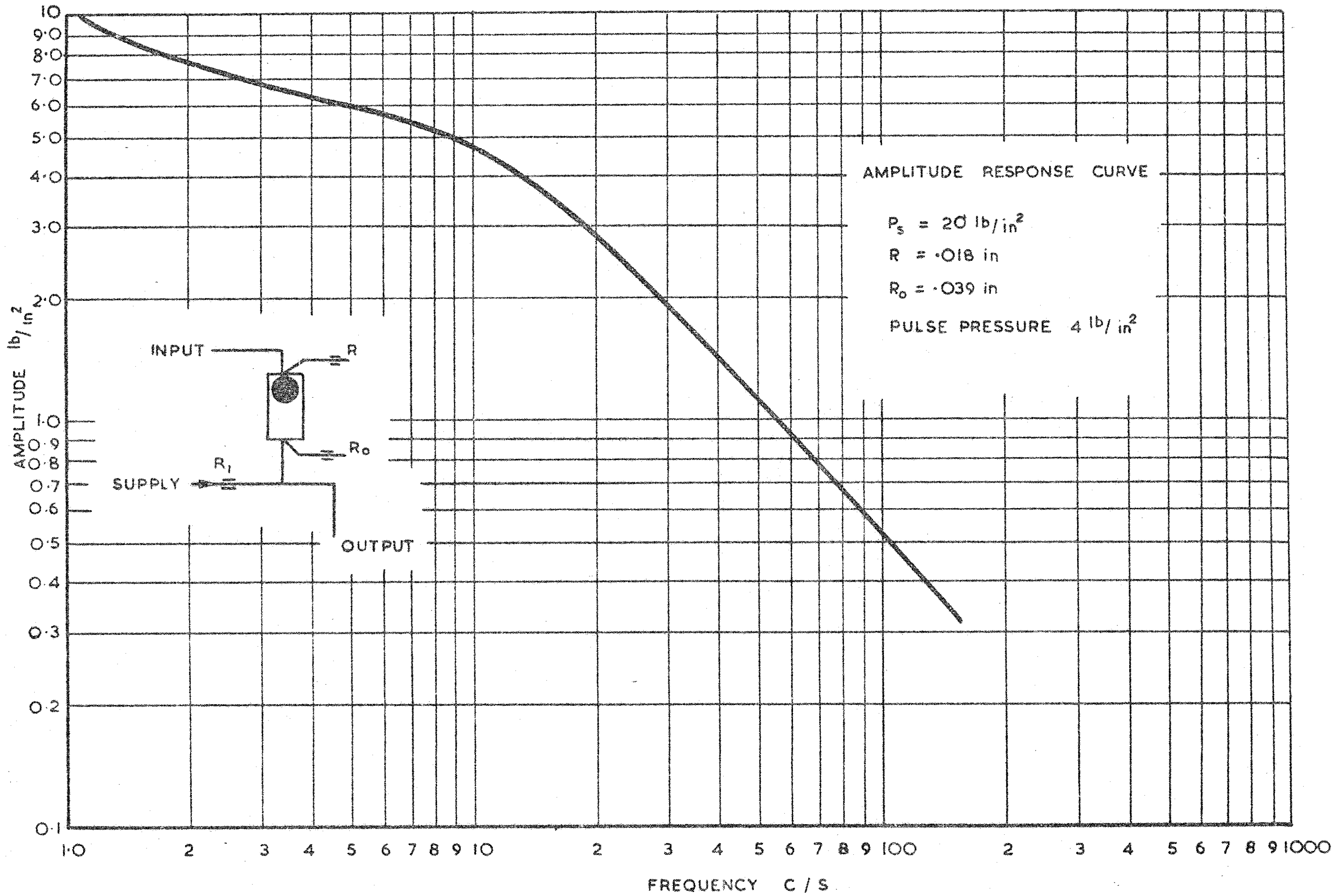
Other work being undertaken at the present is the construction of more complicated logic functions, such as half- and full-adders, and the basic groundwork has also been covered for a decimal to binary encoder, using a pneumatic keyboard.

Recommendations for further work

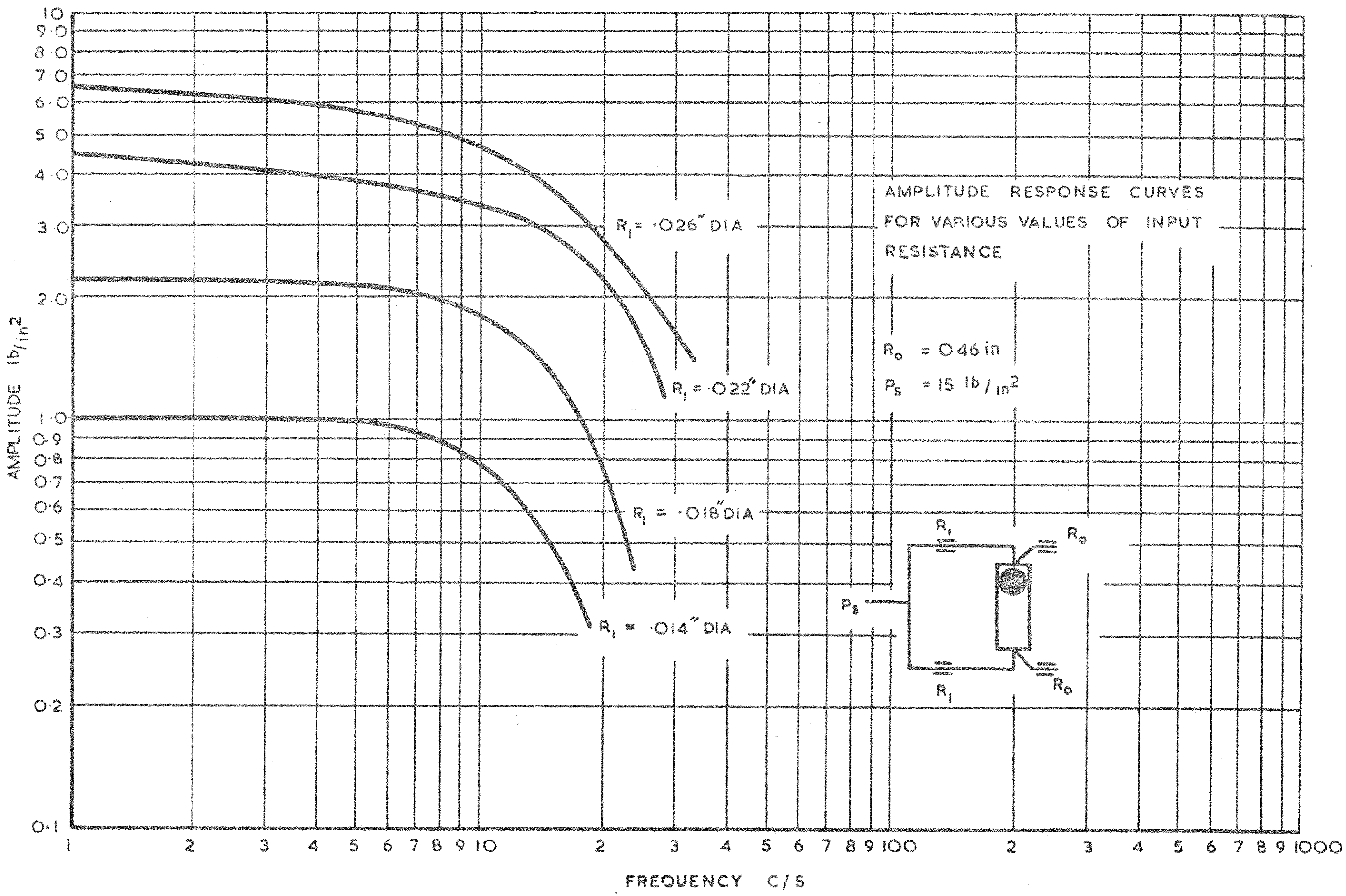
The basic investigation into the more simple logic devices will be complete by July, 1963. It is then intended to develop more fully the application to sequence control of machine tools in the following stages.

1. Research into methods of amplifying the output signals from the devices from pneumatic to pneumatic, pneumatic to hydraulic, pneumatic to electrical.

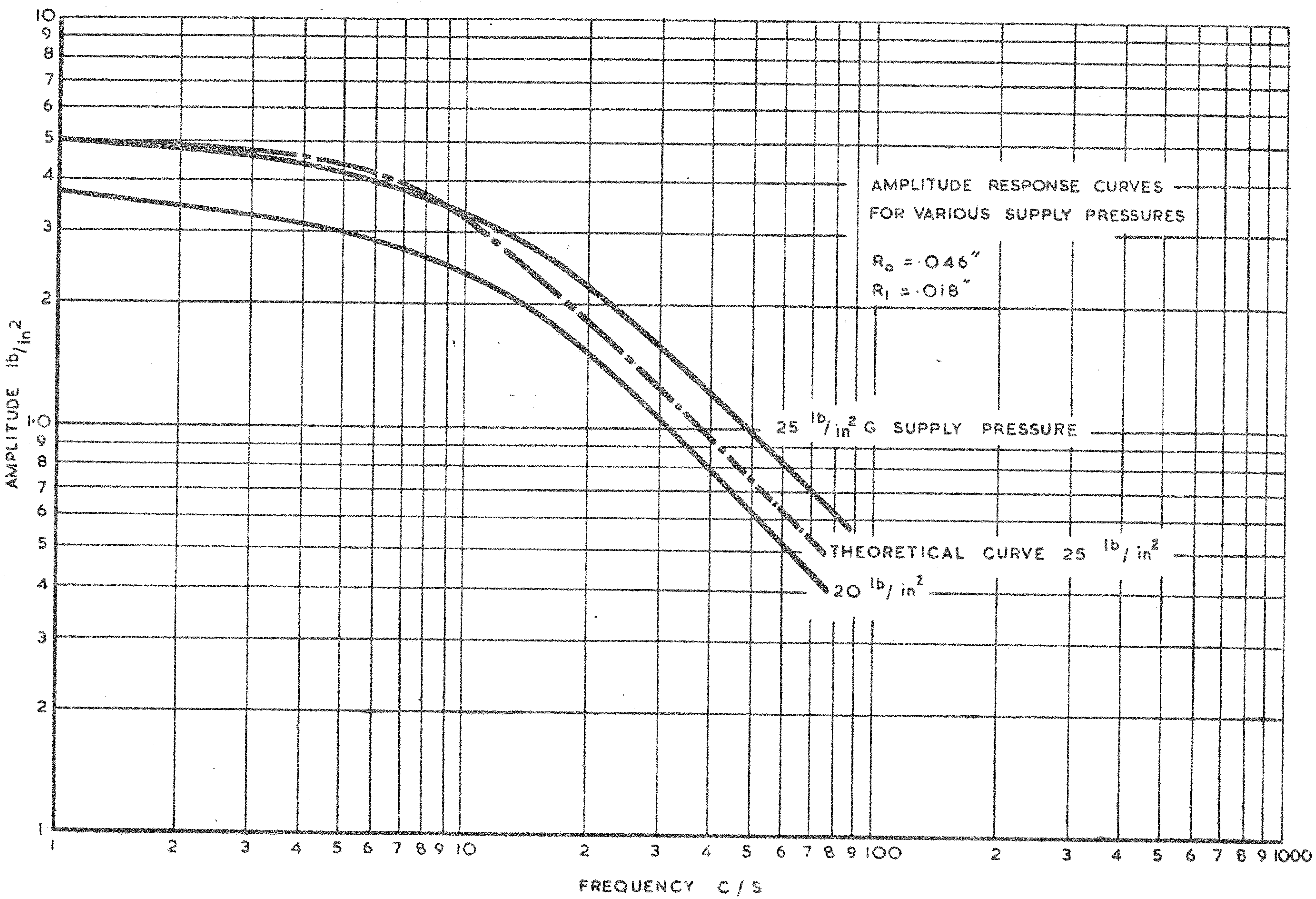
2. Replacement of present methods of electro-pneumatic step control by completely pneumatic circuits.



GRAPH I. FORCED SWITCHING MONOSTABLE UNIT



GRAPH II. PHYSICAL SWITCHING BI-STABLE UNIT.



GRAPH III. FORCED SWITCHING BI-STABLE UNIT.

3. Universal sequence control including the design of pneumatic limit switches, and an investigation of the problem of impedance matching complex circuits.

4. Investigation of tape input systems with pneumatic reading heads, for application to sequence controlled machine tools, and the development of continuously controlled systems.

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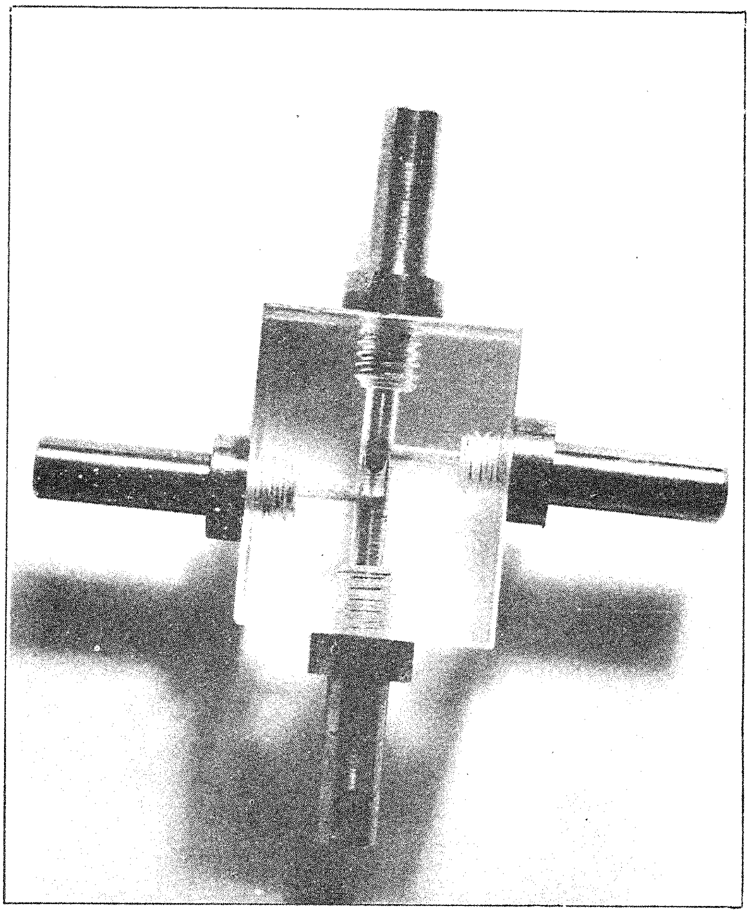

PLATE 1 BI-STABLE UNIT

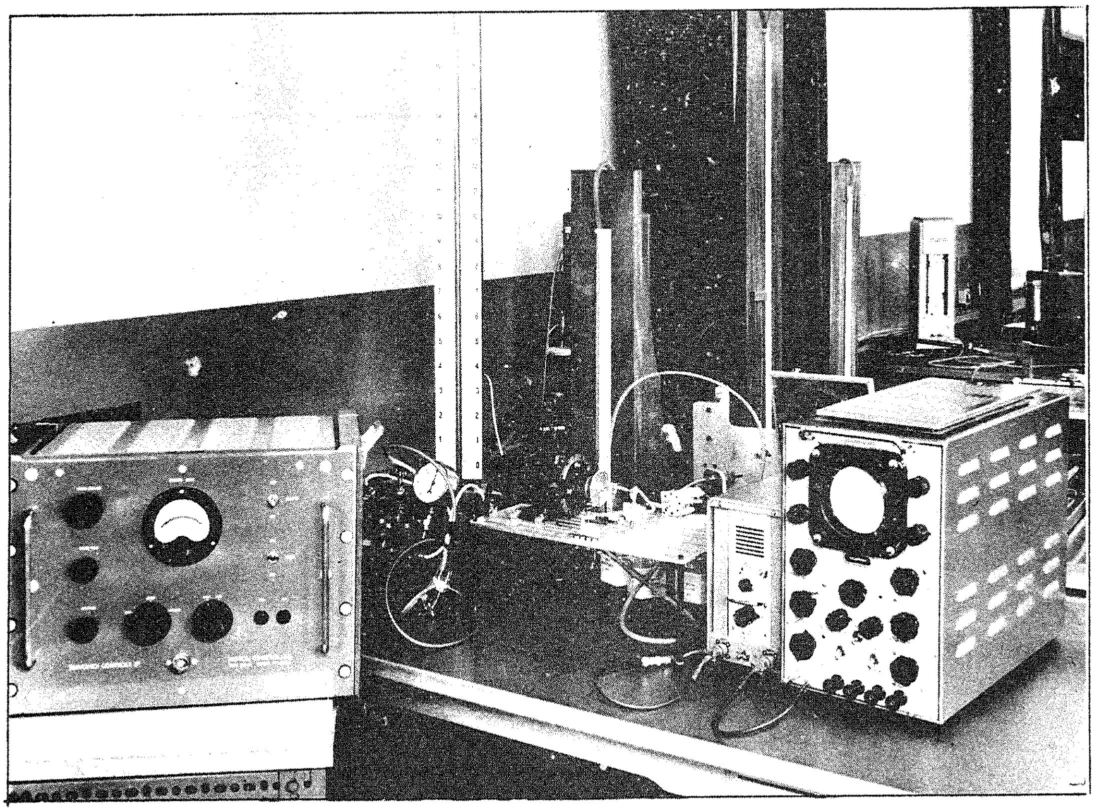

PLATE 2   GENERAL LAYOUT OF LABORATORY APPARATUS

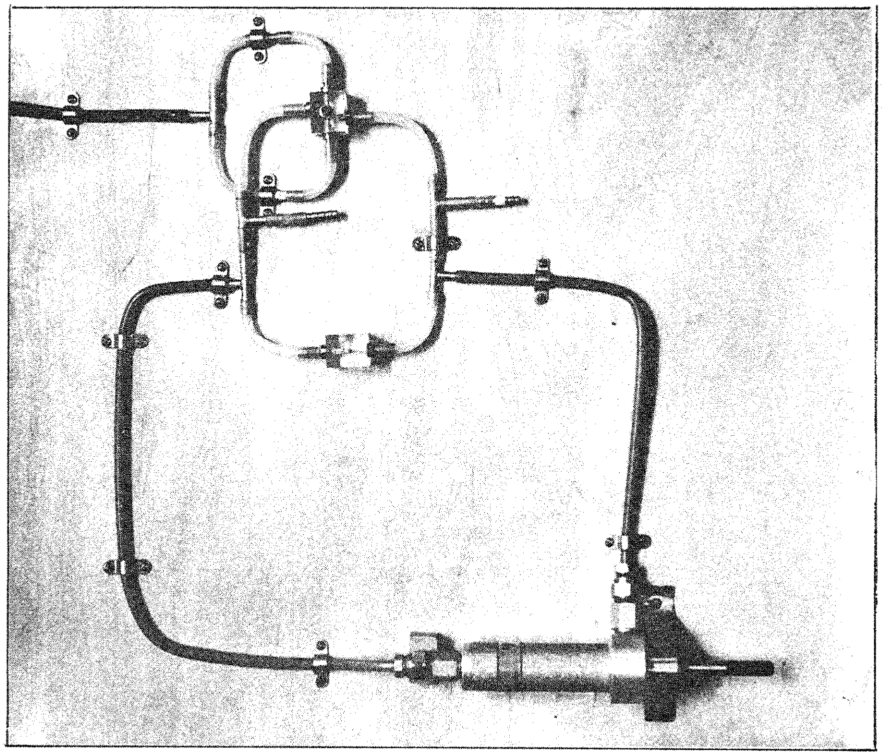

PLATE 3 SHOWS HOW A TRI-STABLE UNIT CAN BE USED FOR SEQUENCE CONTROL