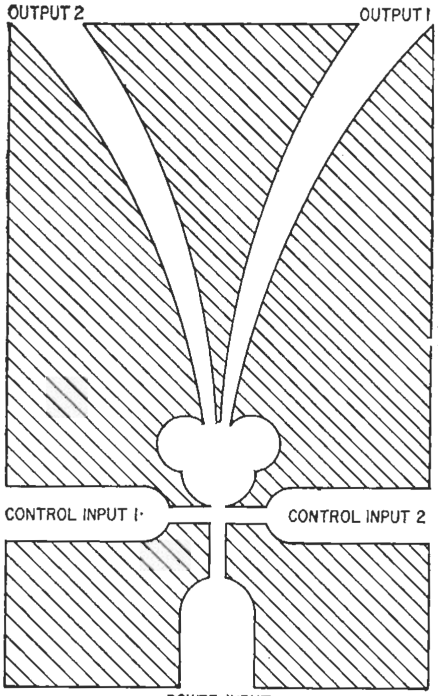

Fig. 1—Schematic drawing of a proportional fluid amplifier. Deflection of input stream, and hence of output, is proportional to input signals.

The Fluid Amplifier

Why in an electronics magazine? Because these etched devices of channels and portholes may replace many control and computer circuits

By T. F. SINCLAIR

Every electronics student, at one time or another, has been shown how the flow of electricity can be compared to the flow of fluids. Water-filled tanks, punctured at various heights, are traditionally used to represent voltages. Fluids flowing through pipes of different sizes show the effect of resistance on current flow. Now the tables have been turned and an all-fluid device, the fluid amplifier, handles liquids and gases much the same as an electronic amplifier handles voltages and currents. Even more startling, the fluid amplifier can be used to replace electronic circuits in certain applications.

The concept of the fluid amplifier was first announced by the Army more than 4 years ago (RADIO-ELECTRONICS, August 1960). Since that time, the device has been improved and developed. Right now, at least two companies are offering off-the-shelf delivery of fluid amplification components and prototype systems. The basic device has been scaled up large enough to control the stream of hot gases from a rocket motor, and miniaturized to match the size of its electronic counterparts in computer circuits.

What is it?

Unlike electronic amplifiers that require voltage for their operation, the no-moving-parts fluid amplifier uses liquids or gases under pressure as a source of power. The basic principle of the fluid amplifier is surprisingly simple, and is shown in Fig. 1.

A stream of fluid squirting from a nozzle can be deflected or moved by a much smaller control stream directed at the side of the main stream. The ability to change the path of a large stream of fluid with a small control stream is the basis of all the fluid-amplifier devices. If an output pipe is positioned in front of the main, or power, stream, the force of the control can be used to aim the fluid into the pipe. The amount of fluid collected by the pipe will depend on the strength of the control stream. Since the power-stream output is then proportional to the much smaller control-stream input, the device behaves as an amplifier.

In Fig. 1, the power input stream passes through a nozzle and is split evenly between the two outputs when there is no fluid signal at the control inputs. If a fluid signal is applied at control input 1, the power stream is diverted toward output 1. Activating control input 2 pushes the power stream toward output 2. When the strength of the signal to both control inputs is equal, the power stream again splits evenly.

The strength of the fluid signal at the control inputs can be varied, and the difference in pressure or flow between the two outputs will be proportional to this variation. In this way, a small difference between the two control inputs is amplified to a large difference at the outputs. Very-high-power gains can be obtained with the proportional fluid amplifier.

In the bistable fluid amplifier, an interesting result of the interaction between the fluid stream and a nearby wall is put to good use. A jet of fluid

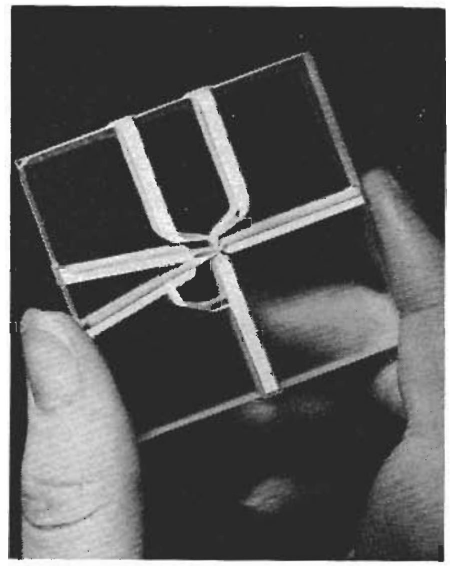

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Fig. 3—Experimental fluid amplifier with three control inputs. Channel connecting one control input with power channel is feedback loop!

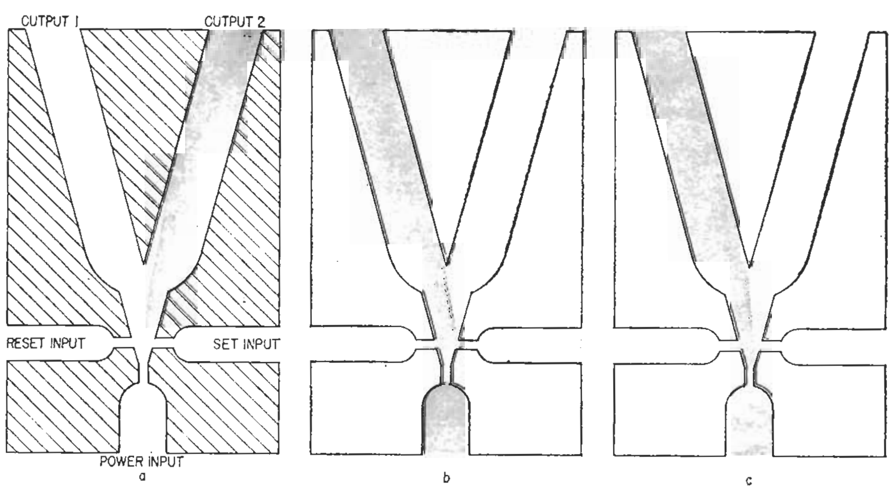

Fig. 2—How a fluid flip-flop works. In (a), power input stream is "attached" to right walls and fluid flow is stable from output 2. In (b), fluid control signal is applied to SET *input, forcing power stream to switch to output 1. In (c), fluid stream is now attached to left wall and will remain there until signal is received at* RESET *input.*

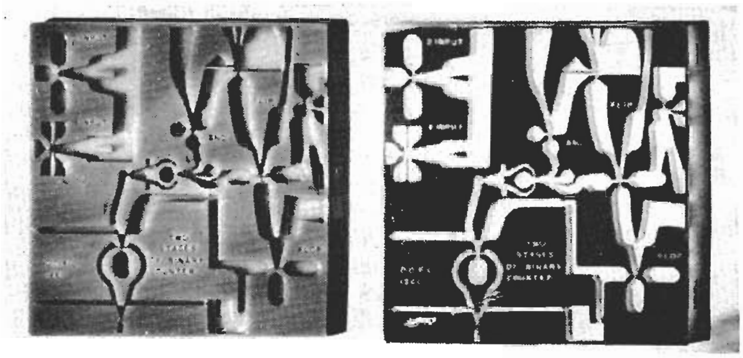

Fig. 4—Standard fluid-amplifier test pattern. "Circuit" is formed in glass by photo etching.

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will attach or stick to an adjacent sidewall if the wall is offset or inclined in a specific manner. Once the stream has attached to the wall it will remain stable in that position. Fig. 2 illustrates how the bistable fluid amplifier, or fluid flip-flop, operates by using that effect.

When there is no control signal, the power stream attaches to one wall and all the fluid flows from one output. The amplifier remains stable in this position until a signal is applied to the *set* input. Fluid flowing through the *set* input forces the power stream to break away from the wall and switch quickly to the other output. The power stream will remain stable in this position until a signal is applied at the *reset* input. Thus, the small control streams can force the power stream to switch rapidly from one output to the other.

The fluid flip-flop is bistable; it has only two states, and can be used as an element of a digital computer. The presence or absence of an output signal can indicate a 1 or a 0, the only two numbers required in binary computations. It also serves as a memory element, since it remains locked in either state until a control signal is received. This is similar to the electronic flip-flop, where a tube or transistor is either conducting or cut off to provide the two stable conditions.

Switching speeds of fluid flip-flops are much lower than those possible with electronic circuits. Even so, speeds of several hundred cycles per second are now possible with ultimate operating frequencies greater than 10 kc predicted.

Other useful computer elements can be produced by modification of the basic flip-flop. NOR and AND gates are two common computer circuits which are easily handled with fluid devices. Fig. 3 shows an experimental fluid amplifier that has three control inputs, and a feedback loop added for stability.

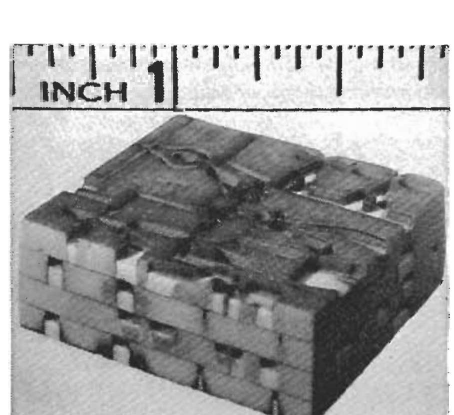

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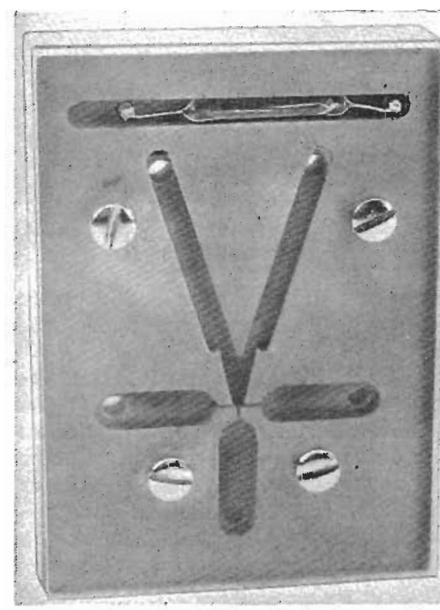
Fig. 5—Three-dimensional fluid-amplifier systems can be built by stacking and laminating several photoetched glass component plates.

Fluid-amplifier systems can be produced in metals and plastics by common machining methods. However, the difficulty and expense of forming very small channels and nozzles has prompted a search for better production techniques. At the present time, photo-etched glass and plastic components are receiving considerable attention.

Etched-glass amplifiers are made by first exposing a specially sensitized glass plate to ultraviolet light passed through a photographic negative of the desired circuit pattern. The glass is then heated to "develop" the exposed areas. When treated with an acid, the exposed material dissolves much faster than the unexposed glass and the circuit pattern is reproduced in depth. The etched-glass panel can be sealed to other glass plates to form a single, durable unit. Fig. 4 shows a standard fluid-amplifier test pattern etched in glass. The miniature unit shown in Fig. 5 is produced by stacking and laminating several glass plates to form a three-dimensional component array.



Bowles Engineering Corp.

Fig. 6—Fluid flip-flop amplifier with electrical readout—reed relay in glass tube.

A similar photoetching process has been developed using a light-sensitive plastic material instead of glass. If plastics prove suitable for fluid amplification systems, precision injection molding may be the ultimate answer to mass-produced elements.

Why fluid amplifiers?

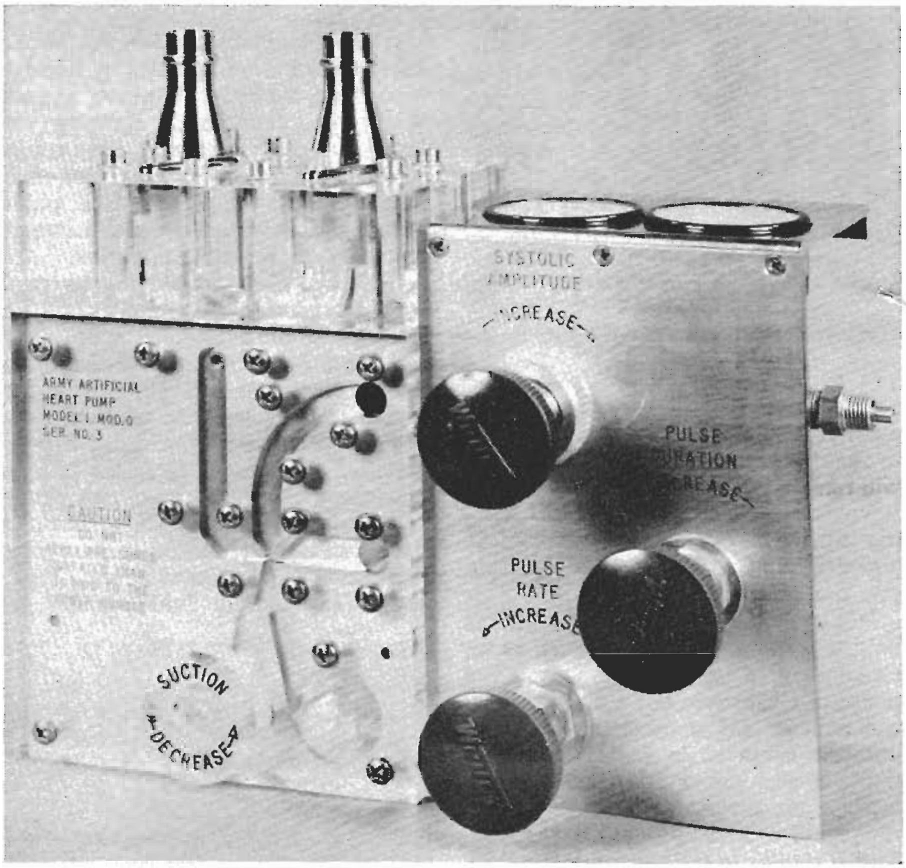
The eventual mass production of fluid amplifiers will result in a cost per element considerably less than for similar electronic circuits. Even now, off-the-shelf fluid flip-flops and proportional

In answer to a few editorial queries about fluid-amplifier details, Mr. Sinclair replied:

"Water and air are the most common fluids [for use in fluid amplifiers]. Air is probably preferred. In the case of liquid computers, water would be used. The less viscous the fluid, the better for high-speed switching. That's why gases are preferred. I have not seen any reference to the use of low-viscosity organic liquids [alcohols, nonflammable petroleum derivatives, etc.]. They would present many problems—special pumps and lines of resistant material (wouldn't want the computer to spring a leak because the fluid dissolved a seal), health and fire hazards, and evaporation. The system would be sealed if necessary to recycle the fluid in use. If the system can be attached directly to an infinite source (a water main or an air compressor), the sealed system would not be needed.

"The unit for fluid resistors [analogous to the ohm] is pounds-seconds/ft^5! Yes, that **is** feet raised to the fifth power. Actually, that is a resistance-to-flow term. Some fluid amplifiers work on a pressure basis and in that case **pressure drop** would be used as a measure of resistance—pounds/in^2 or some other force-per-unit area term.

"Capacitance and inductance, primarily electric field effects, have no direct fluid analogs. There is, however, a fluid diode: a simple check-valve. And a no-moving-parts fluid diode has been developed."



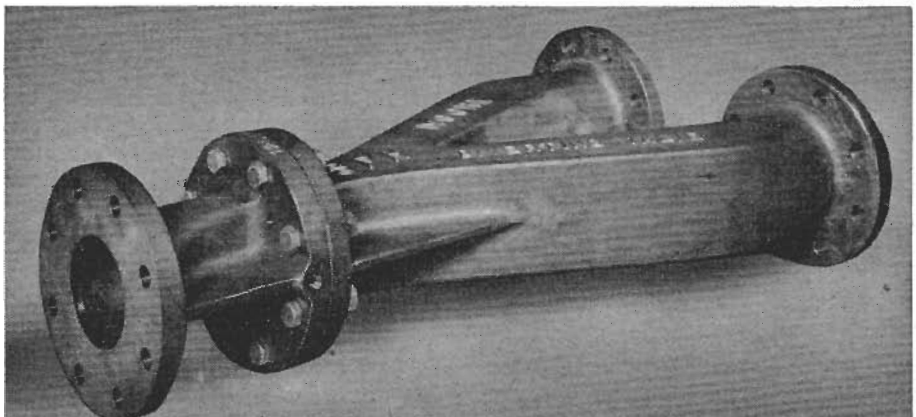
The Army's Artificial Heart Pump. Some of the fluid channels can be seen just above the knob marked SUCTION DECREASE.

amplifiers are being offered at prices competitive with their electronic relatives.

Reliability tests have shown that fluid amplification devices have lower failure rates than electronic circuits under certain conditions. Greater reliability is vital under extremes of temperature, vibration and radiation. Each fluid amplifier stage is a single component. The fluid flip-flop, for example, is a single element replacing the two transistors, several resistors and connections in a typical electronic flip-flop. [Molecular and thin-film circuitry are resulting in similar single, integrated electronic function blocks.—*Editor*]

Fluid circuits can have their inputs and outputs coupled directly to certain systems. Hydraulic or pneumatic inputs from various sensing elements can feed directly into the fluid circuit. The output may be used to power machines, valves, automatic typewriters or other pressure-operated devices. To transmit signals over long distances, or to match electrical equipment, pressure transducers can be used to convert the fluid output to an electrical signal. The fluid flip-flop amplifier shown in Fig. 6 incorporates an electrical readout. The fluid output drives a magnetic piston to operate the glass-enclosed reed relay shown at the top of the unit.

Diverting valve made by Moore Products Co. will switch 750-gallon-per-minute stream of water from one outlet to other in 1/10 second without shock or water hammer. It has no moving parts.



Some uses for fluid amplifiers

The Army, developer of the original fluid amplifier, has shown considerable imagination in applying these devices. It has built a full-size car powered by the jet blast from a gas turbine engine and steered by deflecting the jet with a multiple-stage fluid-amplifier system. While this application may not be practical, the same technique applied to rocket engines could provide a new and efficient method of steering large rocket boosters.

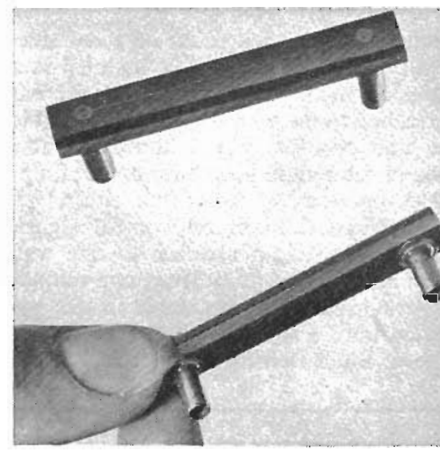


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Fig. 7—Pneumatic resistors for fluid-amplifier circuits. Like electrical resistors, these can be "wired" in parallel or in series for nonstandard values.

The Army has also developed an artificial heart pump controlled by fluid amplification techniques. Compressed gas, controlled by a bistable fluid amplifier, is used to squeeze a thin rubber bag, causing it alternately to fill and empty with blood. This pulsing action propels the blood through a circulatory system in a manner very similar to that of a beating heart. Blood pressure and pulse rate can be varied over fairly broad limits by adjusting the fluid amplifier control and power input streams.

The most exciting use for fluid amplifier elements will be the all-fluid computer. Completely fluid-operated computers using elements based on the fluid flip-flop are a real possibility. New components, such as the pneumatic resistors shown in Fig. 7, are helping to speed the development of pure fluid systems. In the near future we may see fluid desk calculators or small fluid computers that plug into a compressed air or water line instead of the usual electrical outlet. (R-E, Dec. 1964, page 10.)

Other possible applications for fluid amplification systems can be found almost anywhere. Sound, for instance, can be produced by the movement of a fluid—air. (Gases are fluids, too, by definition). A pneumatic phono cartridge shouldn't be too hard to make. Who knows? You might be the first on your block to have an all-fluid stereo system!

END