Title
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## Ernest O. Lawrence Radiation Laboratory

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## ABSTRACT

The electromagnetic flowmeter is an instrument which measures the velocity of a fluid moving in a tube or pipe. By constraining the vessel in a sleeve, flow may be measured directly. A magnetic field crosses the tube at 90 deg to the axis of the tube and to the plane of the electrodes. As the ions in the fluid pass the magnetic field, a voltage is induced in the electrode.

This flowmeter is different from existing flowmeters because of the unique trapezoidal wave form that energizes the magnet. In this Laboratory we have found that there are serious difficulties with electromagnetic flowmeters using sine waves or square waves. This report describes the trapezoidal-wave electromagnetic blood flowmeter. This new flowmeter is compared with other types of electromagnetic flowmeters. The construction of the transducer element is also discussed.

# A TRAPEZOIDAL-WAVE ELECTROMAGNETIC BLOOD FLOWMETER*

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## INTRODUCTION

The instantaneous measurement of the flow of blood through the arteries and veins of animals and man is both interesting and important in physiological biophysics. Many methods have been devised to measure the flow of liquids through tubes, and most of these have now been applied to the measurement of blood flow. The recent exponential growth of the electronics industry has made possible modifications and improvements of early techniques. The electromagnetic flowmeter is an example. The principle of the electromagnetic flowmeter was first described in 1832 by Faraday.[1] The first measurements were made by Young et al. in 1920.[2] The first successful attempt to measure the velocity of flow in tubes was made by Williams in 1930.[3] Williams also succeeded in measuring the distribution of velocities across the diameter of the tube. Fabre, in 1932, first suggested the use of the electromagnetic flowmeter for use with blood.[4] The first application of the electromagnetic flowmeter to blood flow was reported independently by Kolin[5] and Wetterer[6] in 1936 and 1937, respectively.

The ideal blood flowmeter can be placed around an intact vessel in the animal and the cables brought through the skin. The blood flow can then be measured with the animal unanesthesized and free to move about without restriction. A small, light-weight transducer has been described by Kolin.[7] The amplifier must be capable of amplifying signals of from 1 to 50/μv with a noise level of less than 0.5 μv referred to the input. The frequency response of the instrument should be flat to at least 200 cps. The instrument must also faithfully record flow signals in spite of annoying potentials present in the surrounding tissues, such as those arising from the heart (EKG).

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†Predoctoral Fellow of the National Institutes of Health.

It was our purpose to build a flowmeter to meet the above requirements. Two modern electromagnetic flowmeters were considered: one uses a sinusoidal wave, the other, a square wave to energize the magnet. The differences in the two varieties of flowmeters are discussed later. A sinusoidal flowmeter like one described by Kolin was built in this Laboratory.[7] Certain design modifications were found necessary. These modifications are described elsewhere in this report. It soon became clear that neither the sinusoidal nor the square-wave flowmeters were ideal. Shirer et al. suggested that a clipped triangular wave would solve many problems encountered with previous designs of flowmeters.[8] He also discussed the relative merits of almost all known electromagnetic flowmeters. The authors agree with Shirer and have designed a flowmeter that uses a clipped triangular or trapezoidal wave.

## THEORY OF OPERATION

In the operation of the electromagnetic flowmeter, a current energizes the magnet coils, as shown in Fig. 1. A magnetic field perpendicular to the vessel results.

The energizing current may be a sine wave, a square wave, a trapezoidal wave, or some other time-variable shape. The importance of the shape of the wave is discussed later. The flow of fluid through the vessel induces a voltage across the electrodes, which are perpendicular to the field and to the vessel. This voltage is a measure of the velocity of the fluid in the vessel. Since the vessel is held to a specific diameter, the flow measured in units of volume per unit time can be recorded directly.

The electromotive force E induced in the electrode circuit may be explained as follows:

$$E = \frac{dW}{dq} , \text{ where W is work, and q is charge,} \tag{1}$$

hence

$$dW = E\,dq , \tag{2}$$

and

$$dW = F\,ds , \text{ where F is force, and s is distance,} \tag{3}$$

But

$$ds = vdt , \text{ where v is velocity, and t is time,} \tag{4}$$

therefore

$$E\,dq = Bli\,v\,dt , \text{ where, i is current,} \tag{5}$$

$$E \frac{dq}{dt} = Blv\,i , \tag{6}$$

$$E\,i = Blv\,i ,$$

and

$$E = Blv . \tag{7}$$

It may be seen from Eq. (7) that the signal voltage E is proportional to the magnetic field, B, the diameter of the vessel, l, and the velocity of the fluid, v.

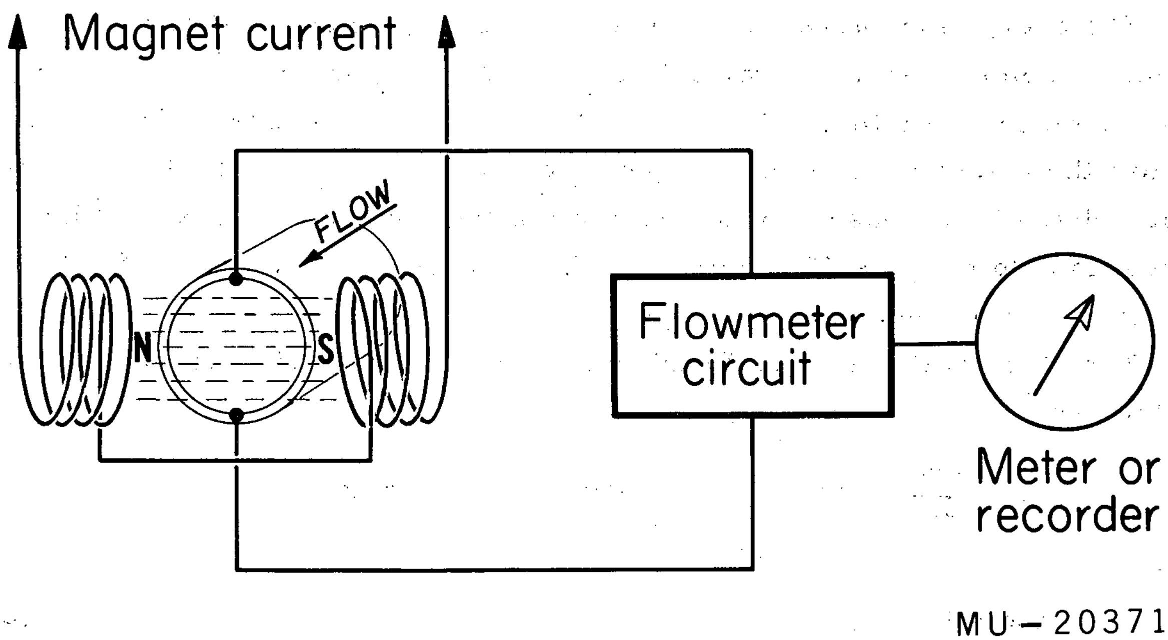


Fig. 1. Principle of electromagnetic induction.

If the magnet current varies with time, the signal voltage also varies with time. For a sinusoidal magnet current, the signal voltage may be expressed

$$E = B\,l\,v\,\sin\omega t = l\,v\,(B_{peak}\,\sin\omega\,t). \tag{8}$$

It follows that when the magnetic field B varies with respect to time, the resultant signal voltage at any one instant is proportional to the velocity of the flow and to the magnetic field at that instant. The output of the probe has been expressed by Kolin[9] as

$$V = (\mu H_0\,\sin\omega t)dv - (A_0\cos\omega t) \times 10^{-8}\ v,$$

where $\mu\,H_0\,\sin\omega t$ is the instantaneous magnetic flux density, d is the diameter of the flowing stream (in cm), v is the mean (cross-sectional) velocity (in cm/sec), and $A_0\,\cos\omega t$ is the instantaneous transformer component. The component ($A_0\,\cos\omega t$) is an induced voltage due to a coil of wire enclosing a time-variable magnetic flux. This induced voltage is proportional to the rate of change of the flux (dB/dt). It may be noted that (at least in theory) this transformer component could be eliminated by carefully positioning the leads of the probe so that they enclose zero net flux. However, other methods seemed more practical.

One method--that used by Kolin and others--was to discriminate against the transformer component by using a phase-sensitive detector or a similar gating scheme. The gate opens for transmission of signal when the magnet current, and therefore the magnetic field, is at a maximum.

Because of the 90-deg displacement of the transformer component of the signal with respect to the magnet current, the transformer component is zero when the gate is open for transmission (providing the gate time is extremely short). If, as is usual, the gating-time duration is approximately 10% of the total period of a cycle, the transformer voltage will be crossing the zero axis and the net average voltage due to the transformer action will be zero.

Another way to eliminate the transformer component is to use a square-wave magnet current. During the rise and again at the fall of the square wave there will be a transformer component that tends to be extremely large for a short time. If the gate is opened only during that part of the square wave which has zero slope, there is no transformer component, and a pure flow signal is sampled. There is a tendency for the infinite, instantaneous transformer component to overload the amplifier, and the authors considers this a serious obstacle to the use of the square wave. Shirer et al. discuss the square-wave electromagnetic flowmeter at length.[7]

A third approach is to use a sinusoidal magnet current and to add a voltage to the output of the probe. This added voltage should be equal in magnitude but 180 deg out of phase with the transformer component. A complete discussion of this method was published by Hogg, Mittelmann, and Schover.[10]

We propose that a trapezoidal magnet current be used. The trapezoidal wave gives rise to a finite transformer component during the rise and fall of the trapezoidal wave, but there is no transformer component signal during the zero-slope portion of the curve. The development of this system of measuring flow is the main subject of this report.

## THE TRAPEZOIDAL-WAVE FLOWMETER

Figure 2 is a block diagram of the flowmeter. It consists of a wave-form generator, a magnet-current amplifier, and a flow-signal amplifier and demodulator.

The function of the wave-form generator is to provide a trapezoidal wave form to the magnet-current power amplifier and to supply the rectangular pulses that open the gate in the output amplifier of the flow-signal amplifier and demodulator. The schematic diagram of the wave-form generator is shown in Fig. 3.

The output of a cathode-coupled multivibrator operating at 1000 cps is amplified and then clipped with zener diodes to provide a square wave. This square wave is then integrated, yielding a triangular wave. The triangular wave is clipped and a trapezoidal wave results. The triangular wave is also used as an input to a Schmitt circuit. The Schmitt circuit (cathode-coupled binary circuit) provides a negative and a positive-going gate drive pulse. The Schmitt circuit is triggered at a level above the limiting voltage of the zener diodes. This is necessary so as to open the gate during the time when the trapezoidal wave form has a zero slope. We found it necessary to delay the gate drive pulses somewhat, to compensate for a finite time delay of the flow signal in the input amplifier of the flow-signal amplifier and demodulator. Figure 4 shows wave forms produced at significant points in the wave-form generator.

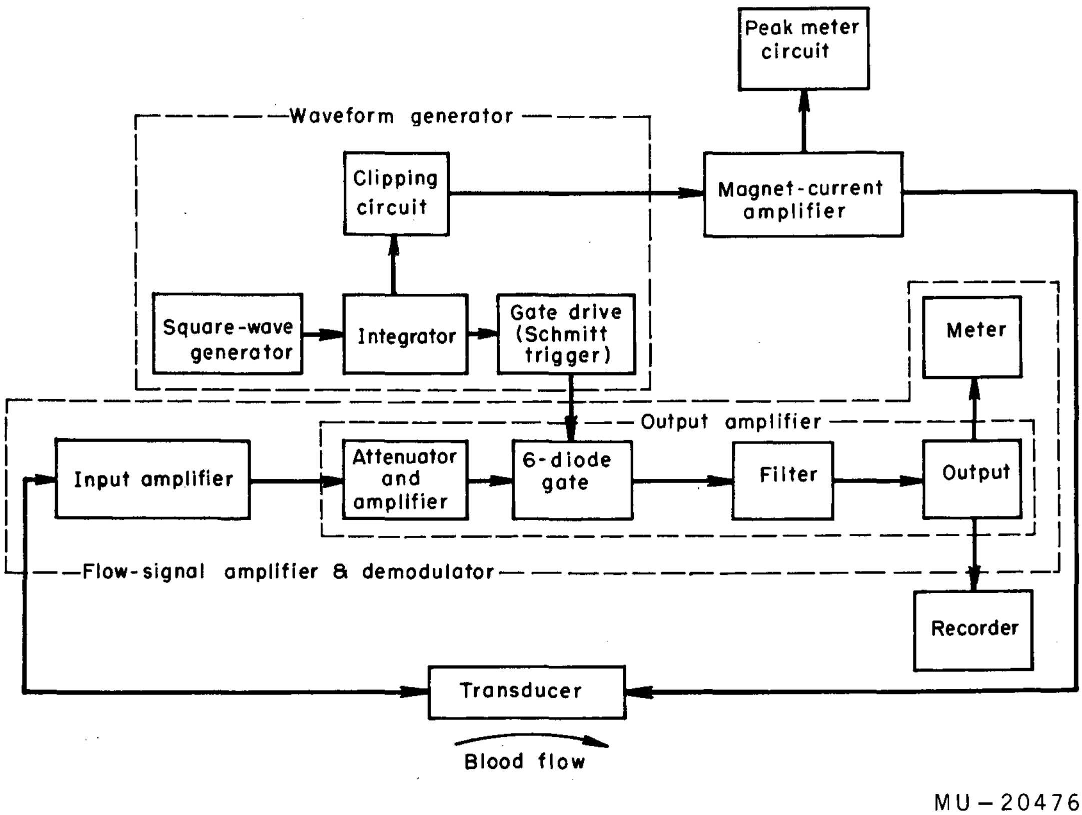


Fig. 2. Functional block diagram of the trapezoidal-wave flowmeter.

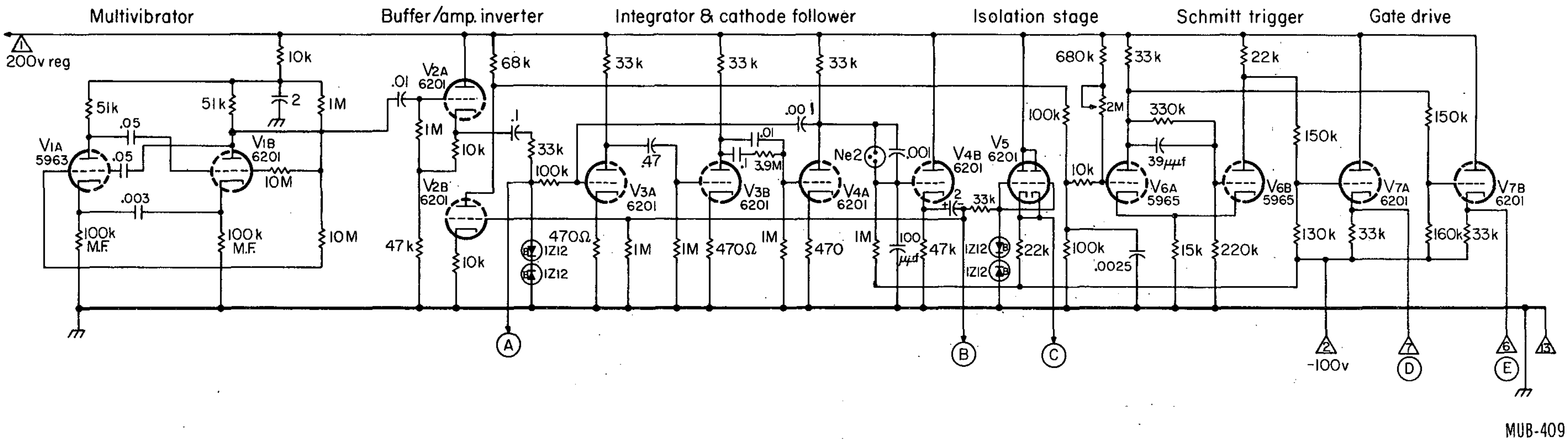


Fig. 3. Wave-form generator circuit.
Here A, B, C, D, and E refer to wave forms in Fig. 4.

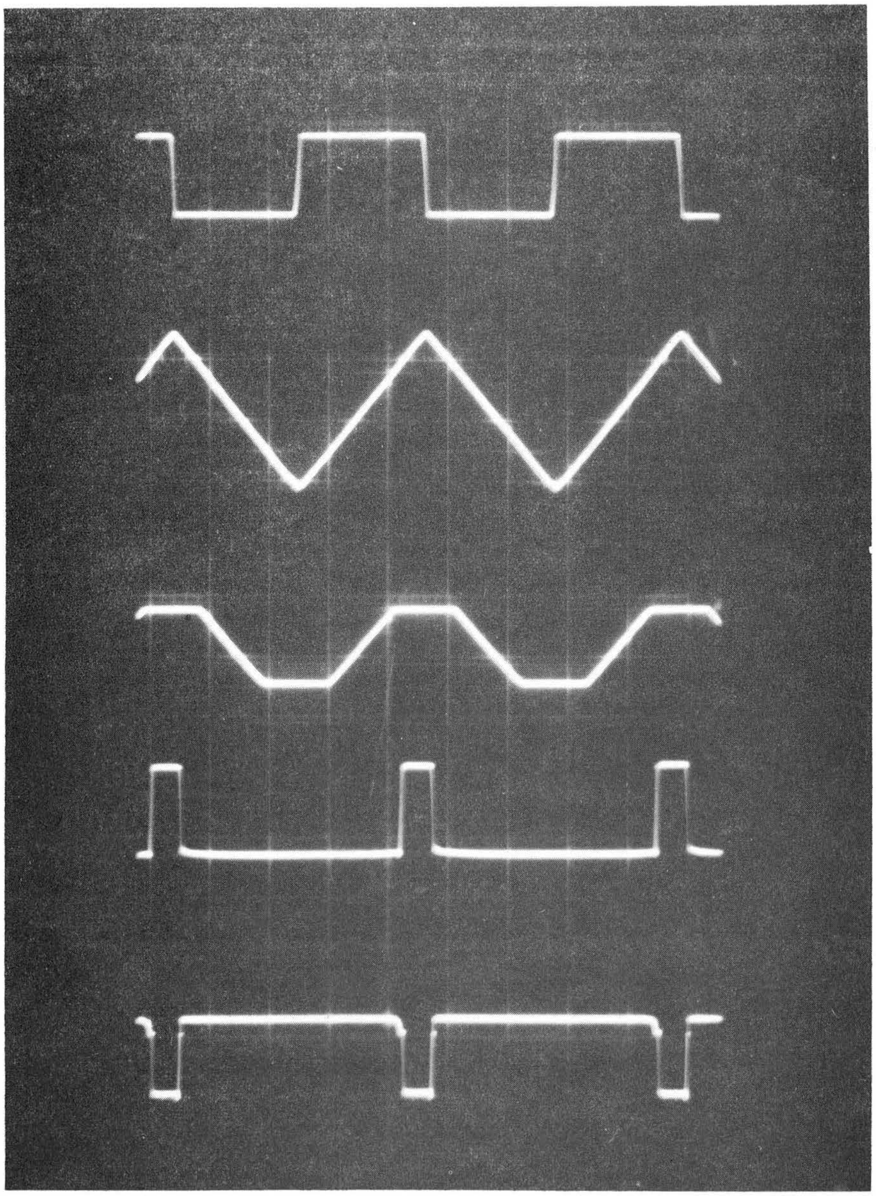

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**Fig. 4.** Wave forms of functional components in the waveform generator. Here A is the output of the square-wave generator, B is the integrated square wave, C is the clipped integrated square wave or the trapezoidal wave, D is the positive-going gate drive pulse, and E is the negative-going gate drive pulse.

Figure 5 is a photograph of the printed-circuit-board layout of the wave-form generator.

The magnet-current amplifier is a transistorized power amplifier, shown schematically in Fig. 6. Power transistors are especially well-suited for this application, as they are basically low-voltage high-current devices. The amplifier was originally designed as an audio amplifier for the 72-in. bubble chamber at the Lawrence Radiation Laboratory by Mr. Robert Sorensen, Electronics Engineer.

The amplifier is coupled to the cathode-follower trapezoidal-wave output of the wave-form generator. Feedback is utilized for current stabilization of all stages. The feedback system also stabilizes the voltage division across the power output of the two 2N277 transistors, which operate in a class-B, push-pull arrangement. The pair of 2N158 transistors and the preceding 2N34 and 2N35 transistors also operate as class B. The two 2N277 transistors have a small forward bias, set by the voltage drop across the 100-ohm resistors, to minimize crossover distortion. This is also accomplished in the preceding stages with the 300-ohm resistors and with the 1N91 diode. The 1N91 germanium diode is used for biasing instead of a resistor to compensate for the temperature variation in the emitter-base resistance. The input amplifier, a 2N34, operates class A. It should be noted that the 2N277 power transistors must be mounted on an adequate heat sink.

The output of the power amplifier is measured as "peak"* magnet current by using the circuit shown in Fig. 6. A reversing switch is provided to insure that a positive-flow signal will cause an upward deflection on the recorder. The output of the amplifier is transformer-coupled to the magnet of the transducer. This is done so that the center tap of the magnet coil will be at ground potential, and to facilitate impedance matching.

This power amplifier and the output transformer faithfully provide a 1-amp trapezoidal current to the magnet coil of the transducer. If the transducer is properly made, during the zero-slope portion of the trapezoidal wave there will be no transformer component induced by the electrodes and connecting leads supplying the flow signal to the input amplifier. Figure 7 is a photograph of the printed-circuit layout of the magnet-current amplifier.

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*Peak is defined here as the maximum positive magnitude of a wave measured from the average value of that wave (i.e. the dc component).

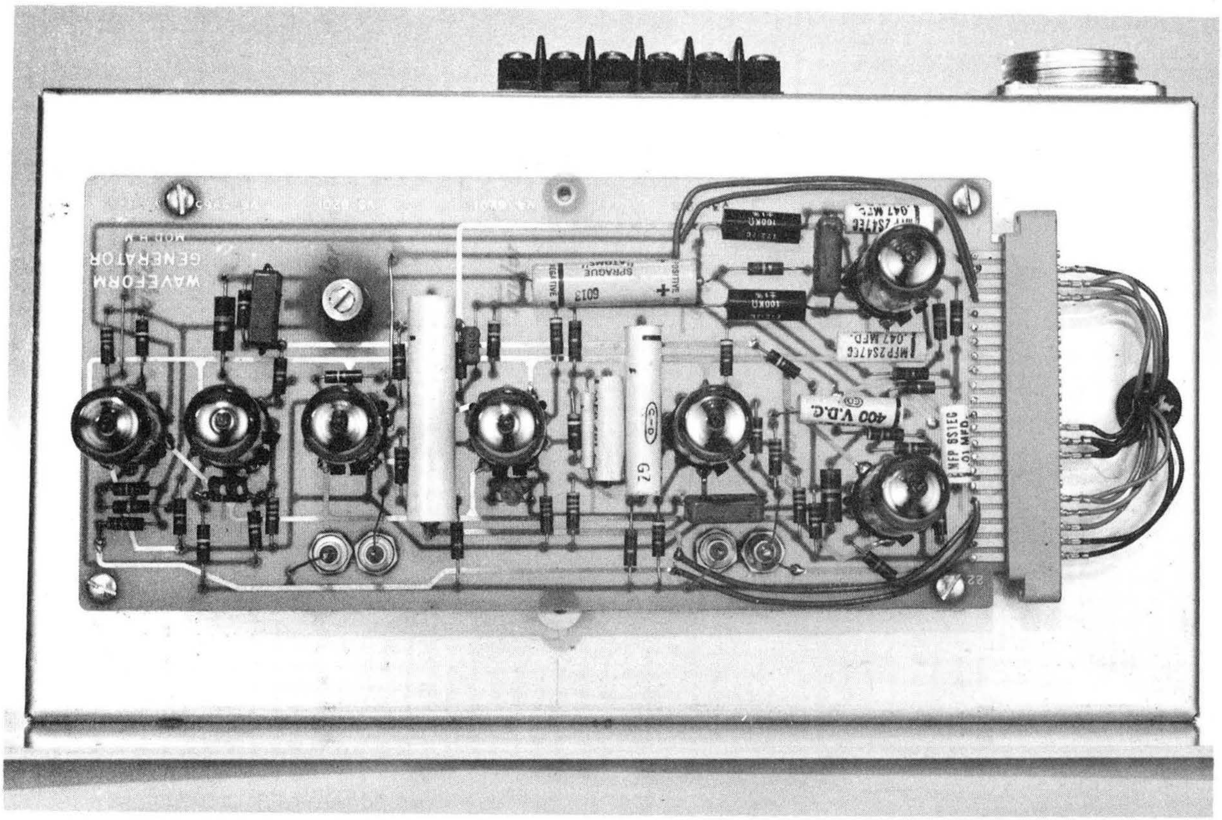

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Fig. 5. Waveform-generator printed circuit.

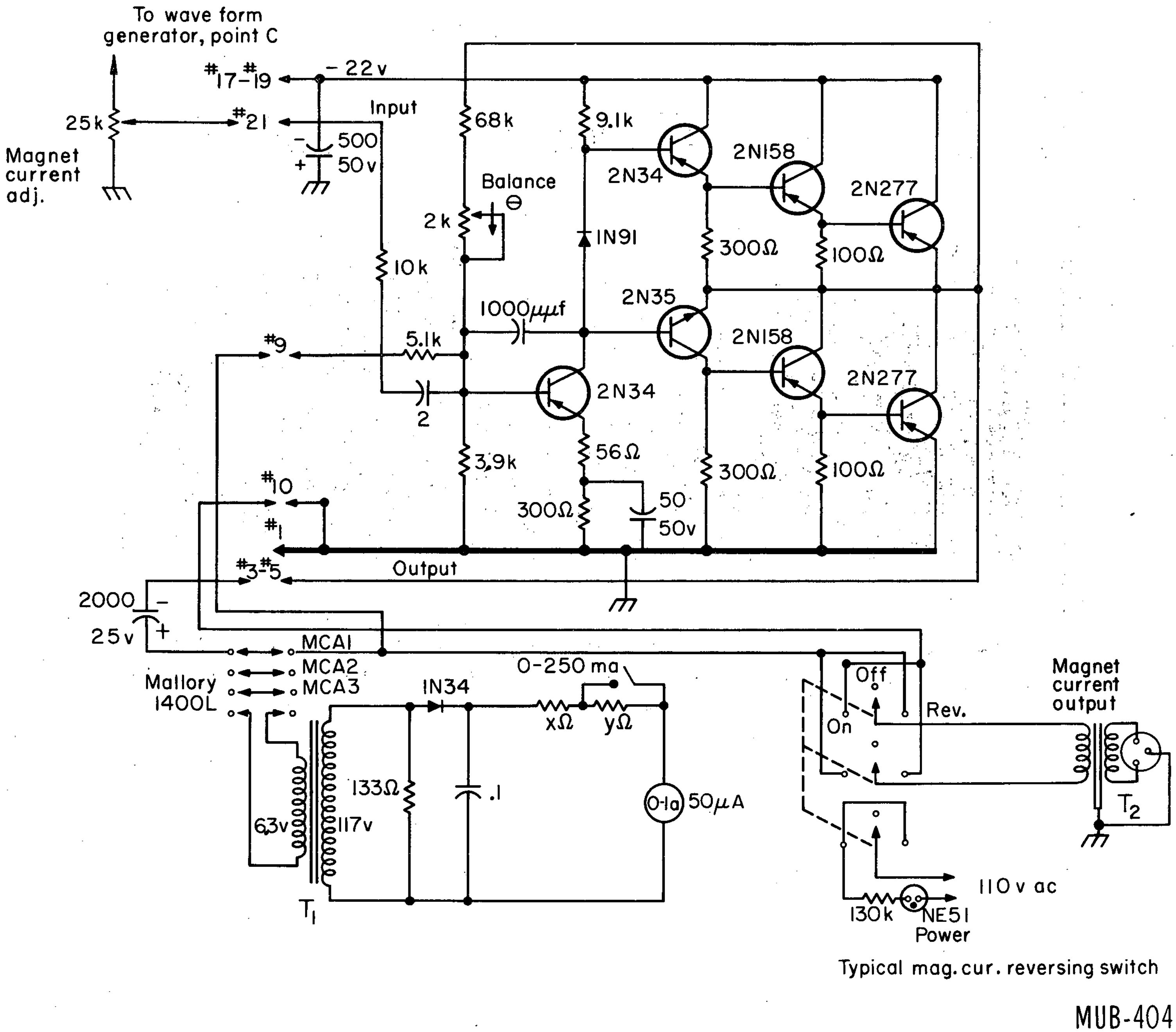


Fig. 6. Magnet-current amplifier circuit. Here $T_2$ is a UCRL P6134 transformer, and $T_3$ is a Triad TY67A transformer.

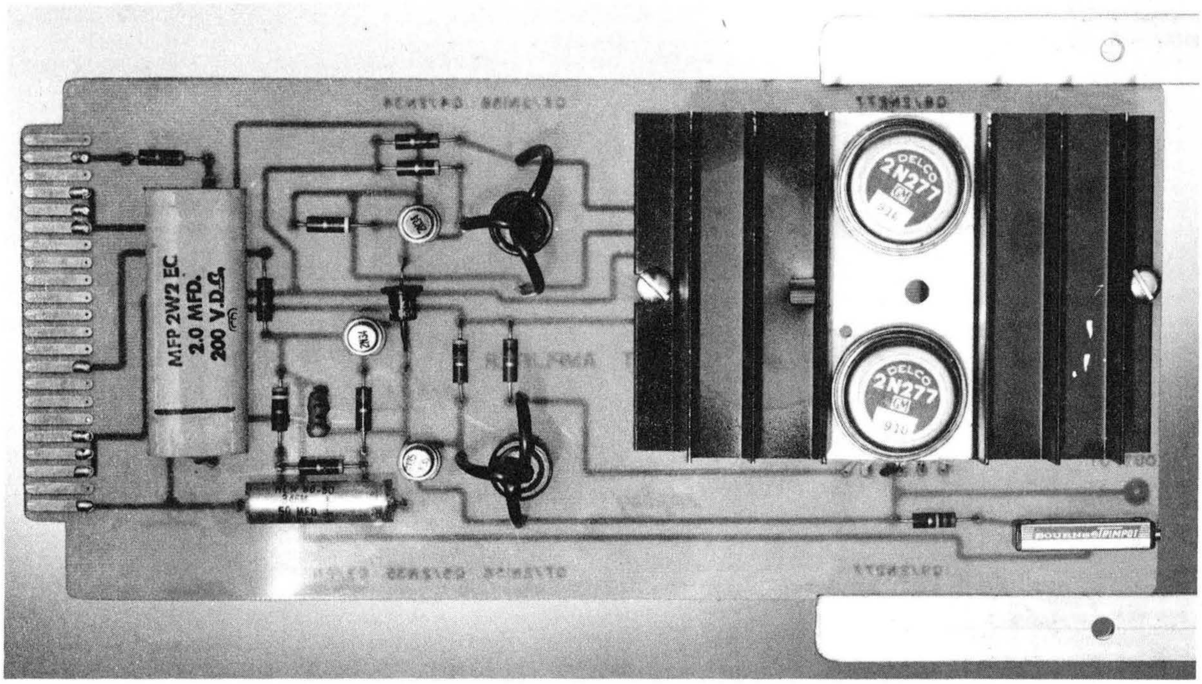


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Fig. 7. Magnet-current amplifier.

For this discussion, the flow signal amplifier and demodulator has been arbitrarily divided into two parts: the input amplifier and the output amplifier. This entire unit amplifies the flow signal, which is of the order of magnitude of 1 to 50 μv peak. It then demodulates the signal and provides a low-impedance output signal adequate in magnitude to drive a recorder directly.

Many circuits were considered for the input amplifier. The ideal input amplifier must have a noise level (shorted input, referred to the input) of less than 0.1 μv. The authors chose to use a modified Tektronix, type-122, low-noise preamplifier as the input amplifier. In 1955 Brophy, suggested several improvements in the circuitry of the Tektronix 122 which lower the equivalent noise at the input to 0.5μv.[11] Brophy replaced all plate and cathode resistors in the first two stages with noninductive wire-wound resistors. The second-stage 12AU7 was changed to a 12AX7, necessitating that its cathode resistor be changed from 100 to 200 K ohms. Brophy also connected the heaters of the first two stages in series, so as to halve the heater current. Brophy reported that with these changes the over-all gain of the amplifier is increased from 1000 to 2800, the high-frequency cutoff is reduced from 40 to 20 Kc/sec, and the maximum undistorted input signal is 10 mv peak-to-peak.

The authors replaced all plate and cathode resistors with metal film resistors, changed the second stage to a 12AX7, lowered the heater potential as described above, and in addition used a Triad G 10 Geoformer as an input transformer. The use of the Geoformer provides an additional gain of about 40 before the first stage. The circuit was then built on an etched board as shown in Fig. 8. The amplifier has an input impedance of approximately 600 Ω, a gain of over 100,000, and an equivalent input noise of 0.008 μv with the input terminals shorted. It is shown, schematically, in Fig. 9.

The zero-slope portion of the trapezoidal waveform remains flat at the output of the input amplifier.[12] There is, however, a finite delay in the flow signal. For this reason, the gate drive pulses were delayed in the waveform generator. Note that a large common-mode signal will swamp the amplifier, and therefore, two halves of the magnet coil must be balanced. This will be discussed further in the next section entitled Transducers.

The signal is coupled to the output amplifier through a variable attenuator. It is then amplified by a conventional pentode amplifier. The flow signal is then demodulated with a six-diode gate. The gated signal is then filtered with

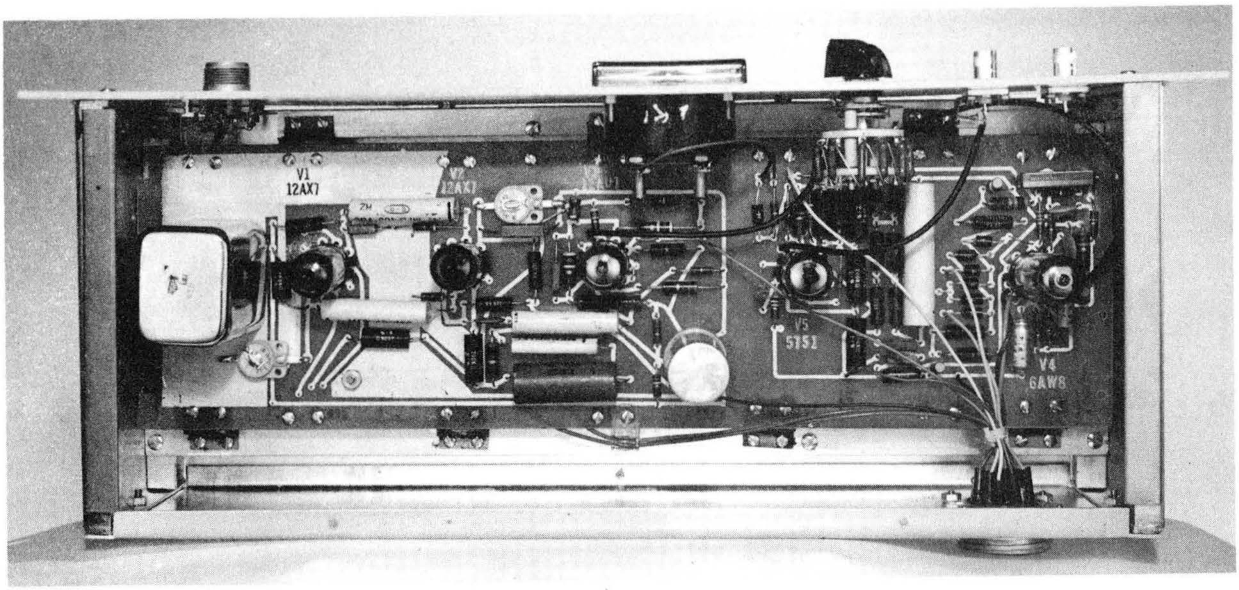


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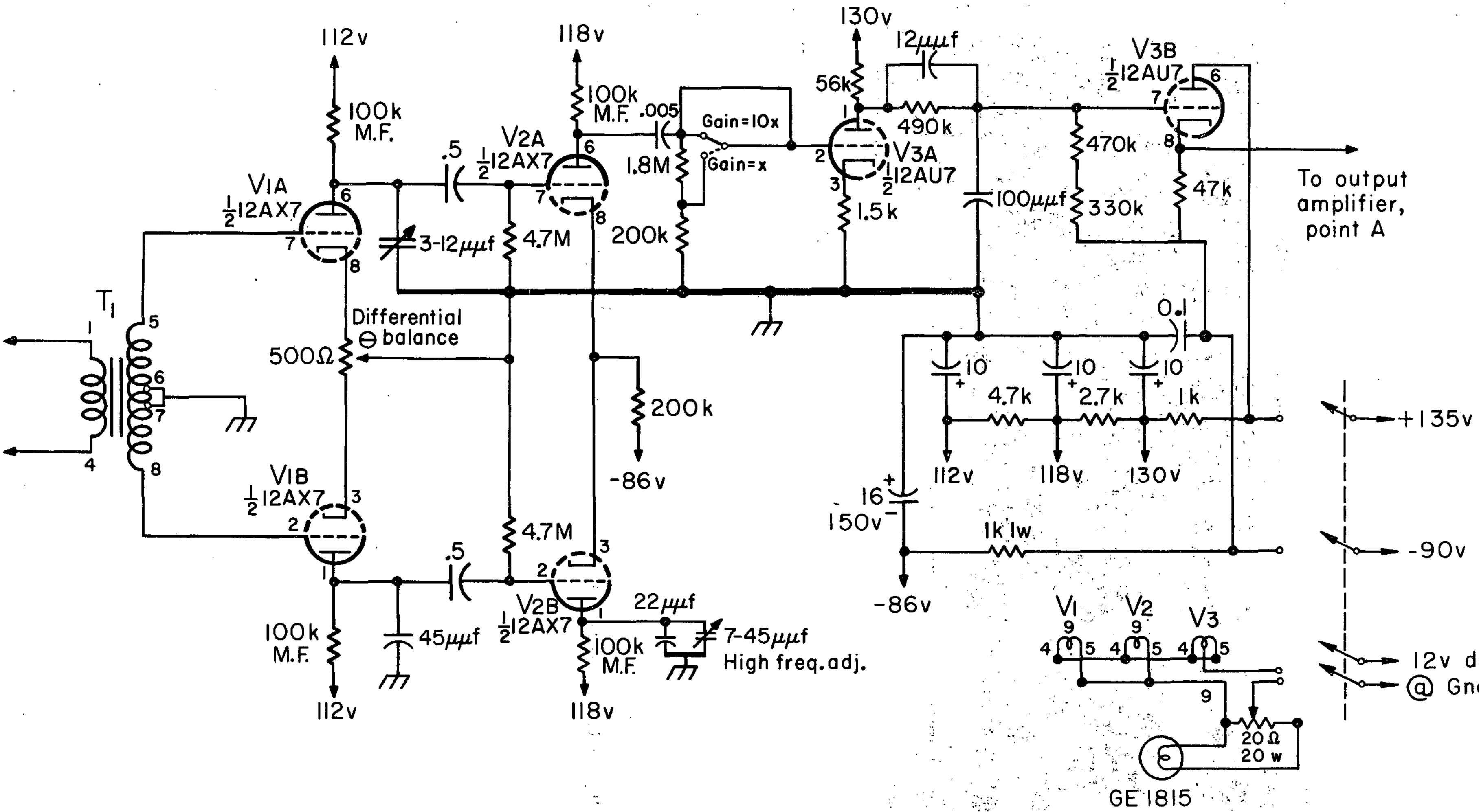
Fig. 8. Flow signal amplifier and demodulator printed circuit.




MUB-403

Fig. 9. Input amplifier circuit. Here $T_1$ is a Triad G-10 Geoformer.

a twin tee to eliminate most of the 1000-cycle component. The signal is coupled to a negative-feedback-stabilized, dc-coupled amplifier. The first half of the tube is used as an amplifier. The other half of the tube is a cathode follower which provides a low-impedance output. The output-signal magnitude is monitored on a panel meter. The schematic of the output amplifier is shown in Fig. 10. The printed circuit layout of the flow signal amplifier and demodulator is shown in Fig. 8. The completed unit is shown in Fig. 11.

The six-diode gate was chosen because it would allow linear, bilateral transmission with a gain of almost unity. It is, therefore, possible to charge as well as discharge the storage capacitor connected to the output of the gate. This storage capacitor holds the signal between sampling cycles of the gate. The operation of the gate is discussed by Millman and Taub.[11]

The flow signal amplifier and demodulator has an over-all gain of about 200,000. It is possible to use very small transducer elements. The smaller the transducer element, the easier it becomes to implant it in the animal and maintain the animal's physiological status.

The power supply for the flowmeter is a modified U.S. Navy preferred circuit, number 8.[13] It supplies voltages of +200, -100, -90, and +135, all regulated to better than 1%. The power supply shown schematically in Fig. 12 supplies power for the entire flowmeter with the exception of the magnet current amplifier and the heaters of the input amplifier. A transistorized power supply (Lawrence Radiation Laboratory No. 7V 2853) supplies -22 v to the magnet current amplifier and +12 v to the input amplifier. The schematic diagram for the transisitorized power supply is shown in Fig. 13 and its printed-circuit layout is shown in Fig. 14.

## THE TRANSDUCER

The flowmeter transducer generates a voltage analog of the blood velocity in an unopened artery. Because the artery is constrained to a constant diameter by a hard plastic sleeve, the voltage signal recorded is, upon calibration, a direct measure of flow (volume per unit time). The transducer element is one of the most important parts of the flowmeter and is the most difficult to construct. In theory one would expect that placing a magnet coil around an artery along with electrodes that are aligned at right angles to the magnetic field and to the artery would not be a difficult task. This, however, is not the case.

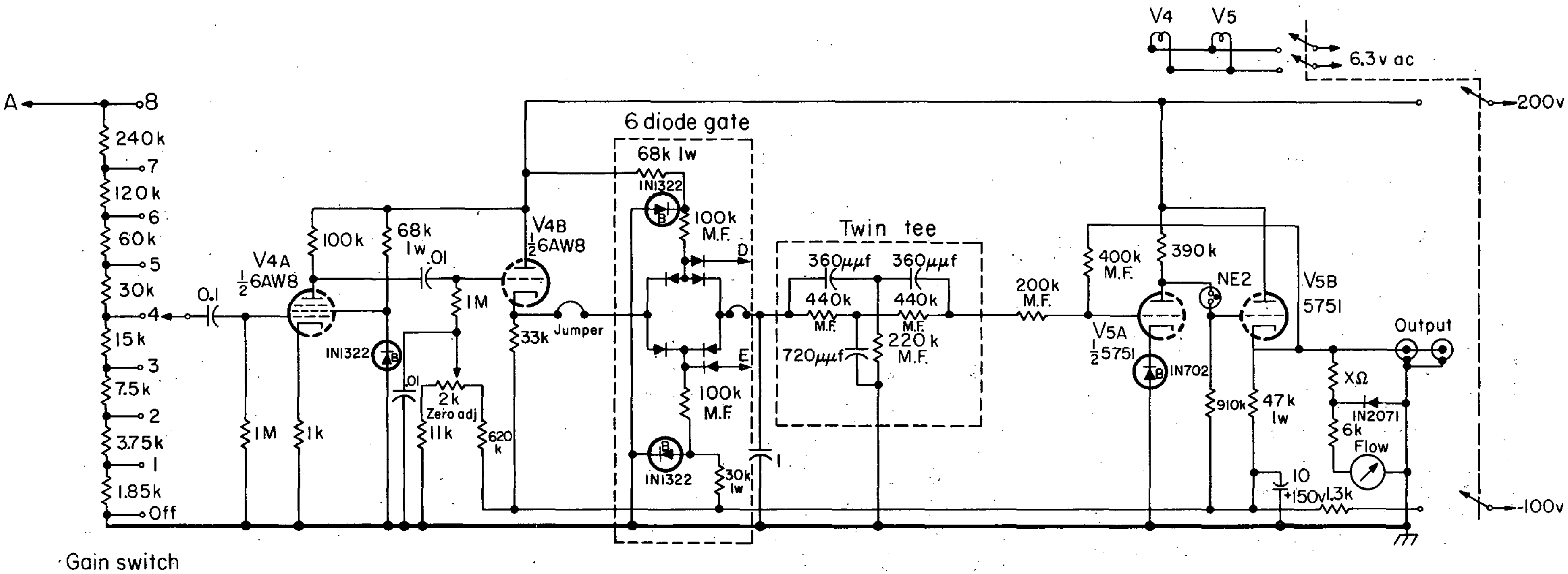



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Fig. 10. Output-amplifier circuit.

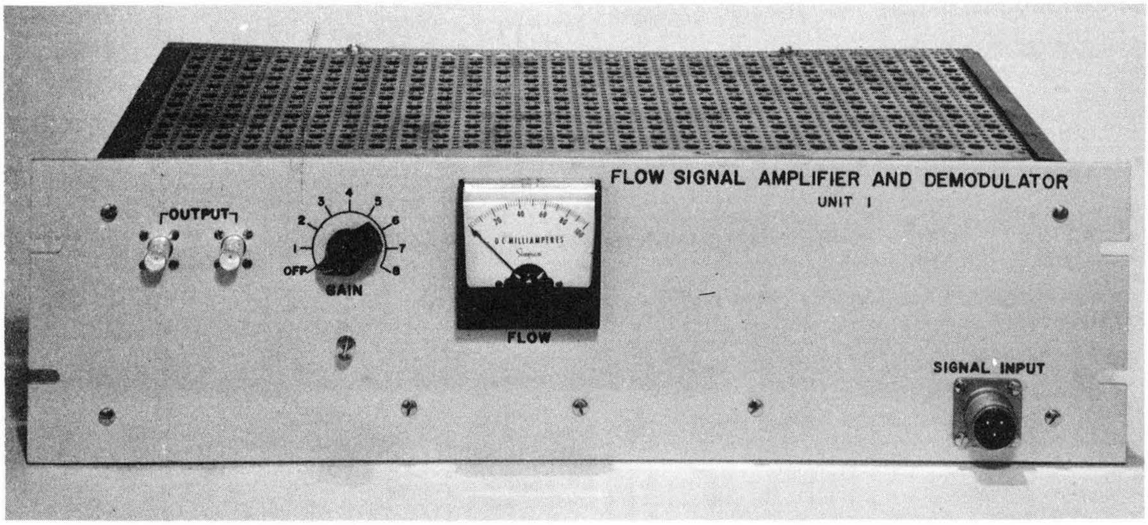


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Fig. 11. Flow-signal amplifier and demodulator.

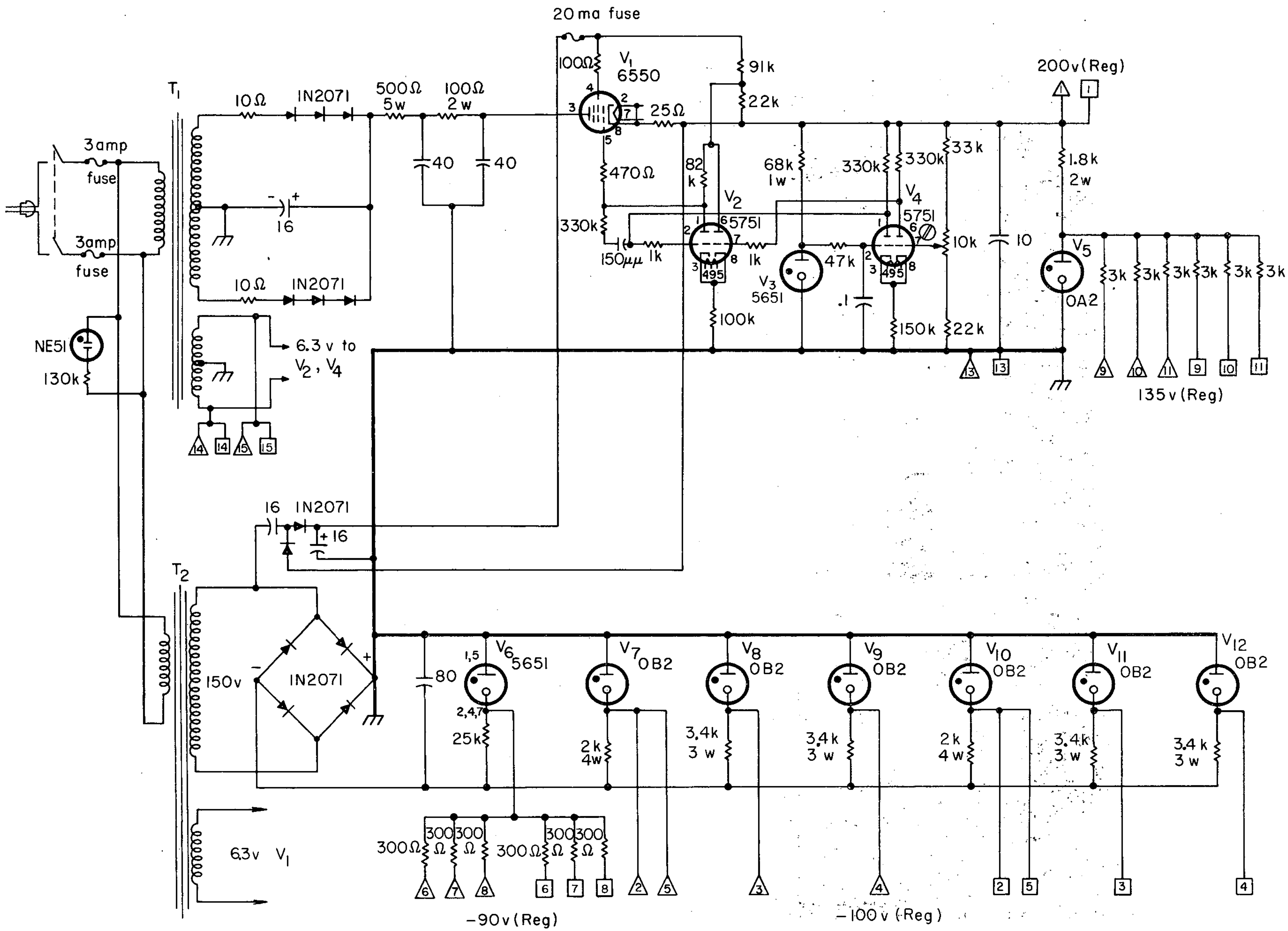


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Fig. 12. Main power-supply circuit. Here $T_1$ is a Thorardson 22R06 transformer and $T_2$ is a UCRL 1167 transformer.

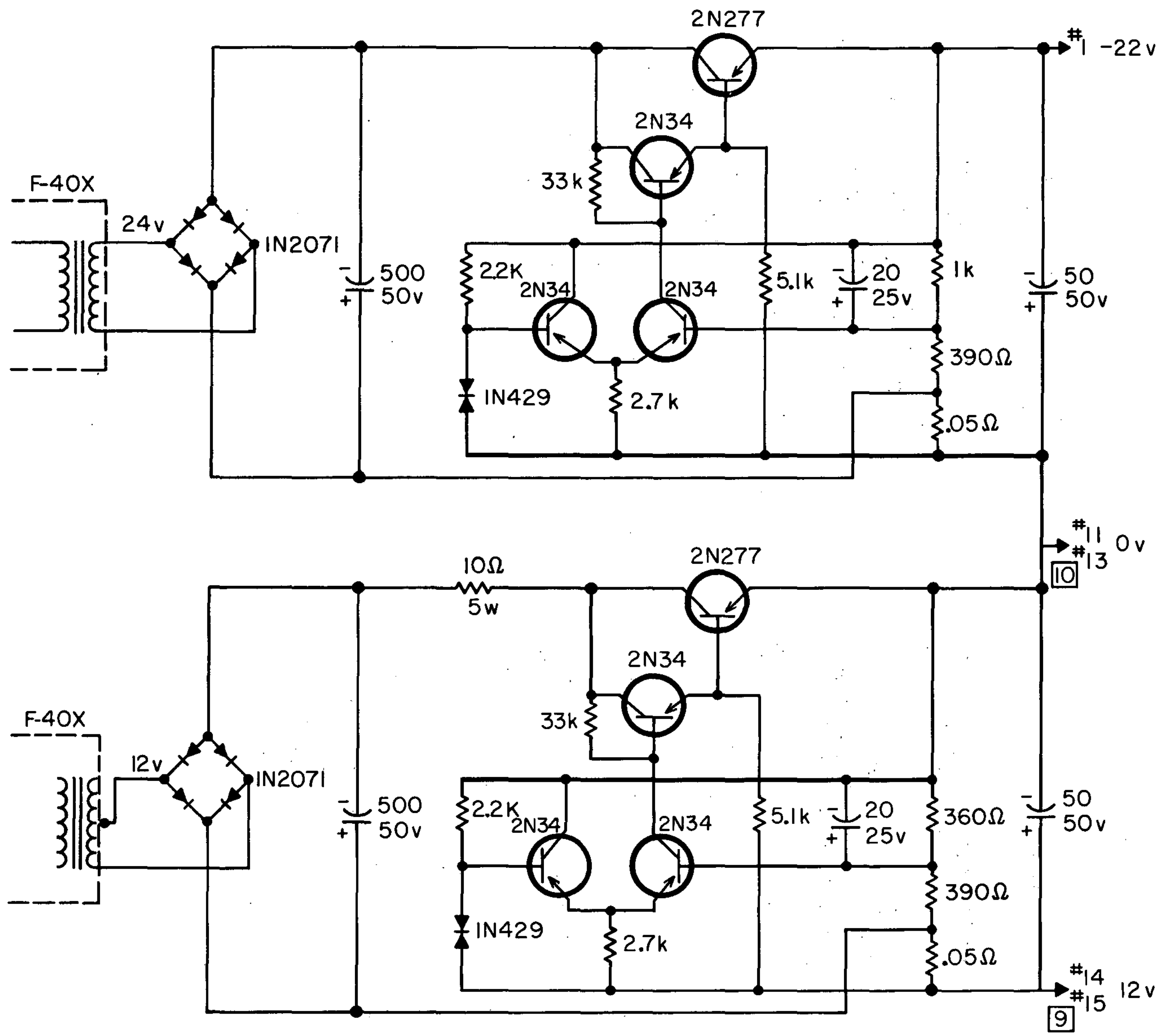


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Fig. 13. Transistorized power-supply circuit.

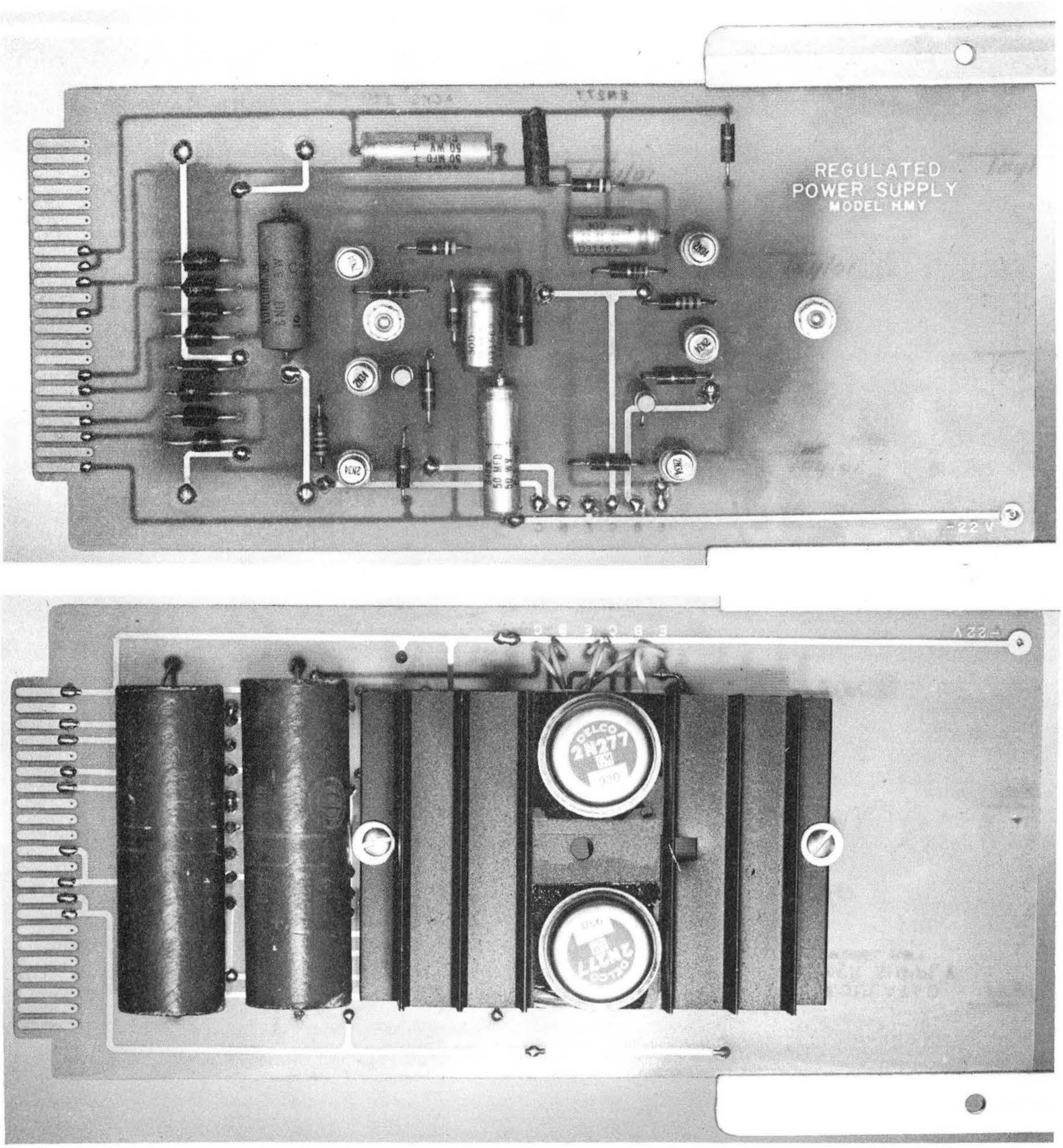


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Fig. 14. Transistorized power supply, top and bottom view.

A variety of designs for transducers have been used in the history of electromagnetic flowmeters. The authors have limited this discussion to include only some of the minature transducers.

The problems that one expects to encounter in the design of a transducer are especially critical when the magnet is energized with a sine-wave voltage. Figure 15 illustrates diagramatically one of the basic problems of the sine-wave flowmeter. If we consider the blood in the artery as the source impedance, we can represent the input signal as having originated from two generators--a true flow signal and a transformer component generator. The capacitors represent stray capacitance which exists between the coil halves and between each half of the coil and ground. If the source impedance changes, even slightly, the phase of the transformer component changes. In this case, the phase-discriminating gating circuit, which is adjusted for a prior condition, now allows some transformer component as well as flow signal to appear in the output as flow signal. This effect appears to be more obvious when blood is flowing through the tranducer than when saline solution is used.

Figure 16 shows two transducers designed for the sine-wave flowmeter.[14] These are the smallest transducers that have been described to date. The electrode leads must lie entirely in a plane that is 90 deg to the magnetic field in order to minimize the transformer component. This appears to be extremely difficult to achieve, since the electrode leads and magnet coils are secured simultaneously, and testing is not possible until assembly is complete. The two halves of the magnet coil must also be balanced so that the area adjacent to the electrodes (center tap) is, essentially, at ground potential. Otherwise, a large common-mode signal will result which will overload the input amplifier.

Figure 17 shows three other transducers designed for the square-wave flowmeter.[15] The authors have had no practical experience with these designs. Two observations are in order however. The ferrite cores used in these transducers may cause more distortion of the field than an air core. In addition these transducers are too large to be chronically implanted. (The authors note, however, that these transducers are not being used for chronic implantation.)

If the gating circuit samples the flow signal during the zero-slope portion of either the square wave or the trapezoidal wave, there should be no transformer component in the output. Since the transformer component is the first

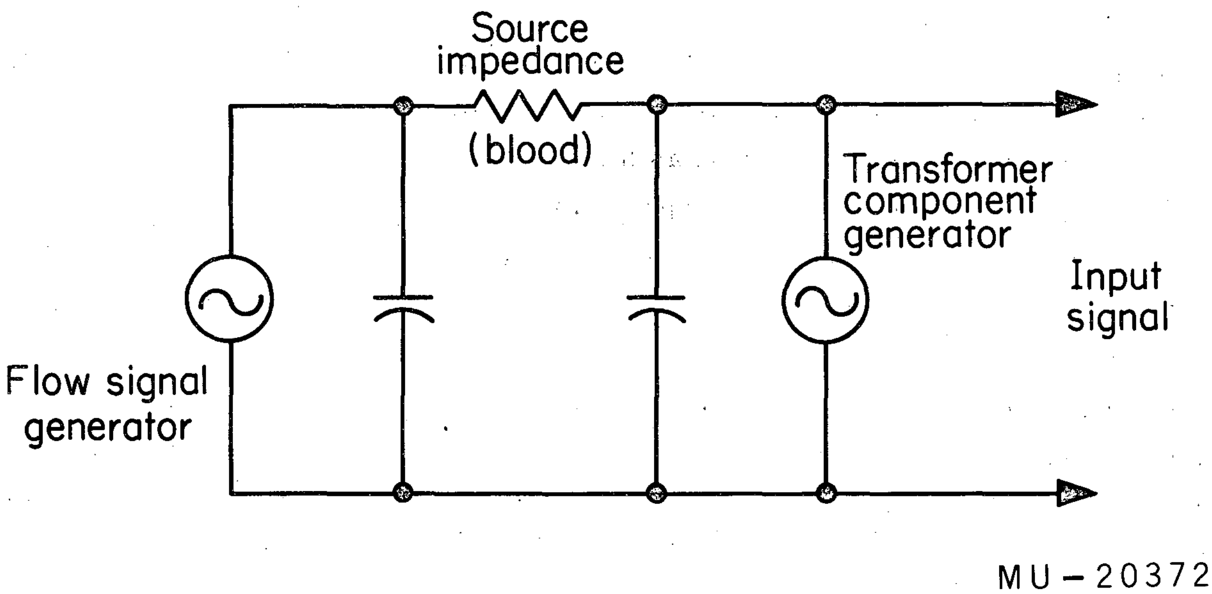



Fig. 15. Analog of sine-wave transducer.

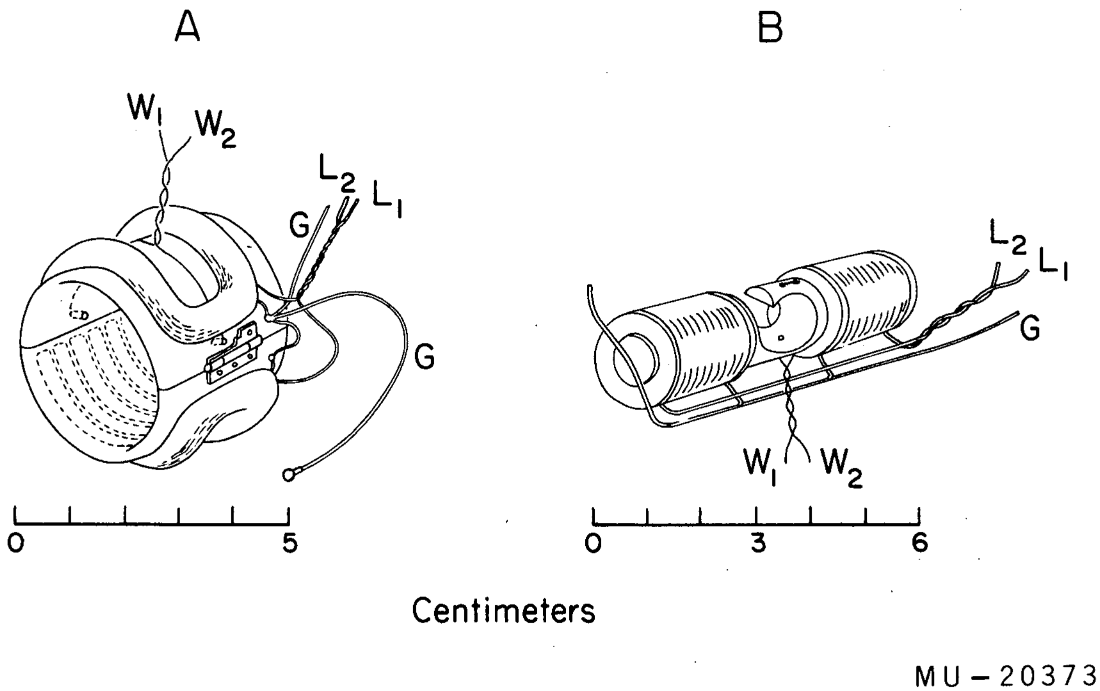



Fig. 16. Transducers designed for the sine-wave flowmeter.

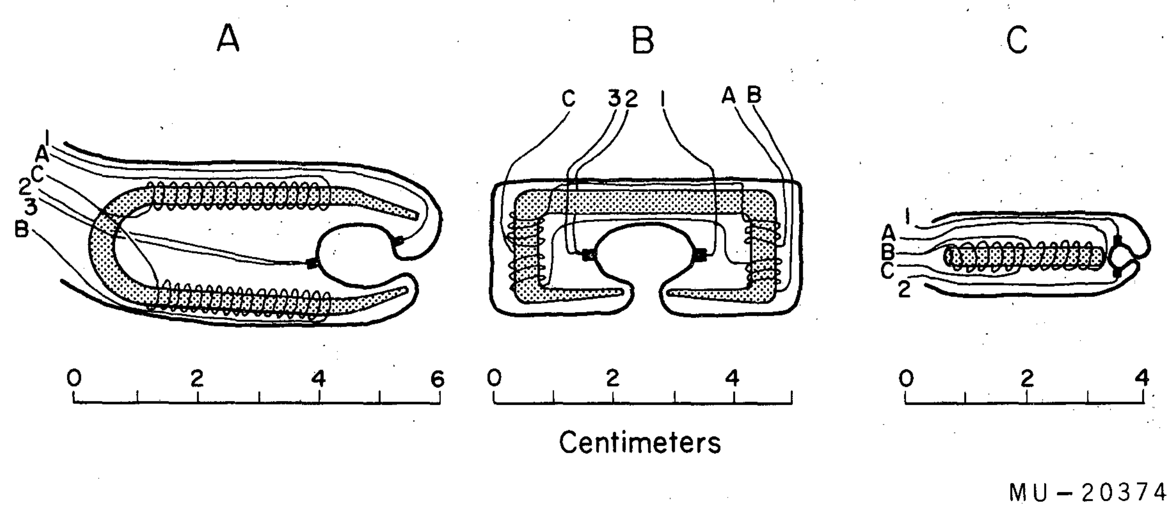



Fig. 17. Transducers designed for the square-wave flowmeter.

derivative of the current in the magnet coil, it follows that the transformer component for the trapezoidal wave is as shown in Fig. 18. Theoretically, it is a positive-and a negative-going square pulse occuring each cycle. In practice, however, the electronic circuitry that must be used causes the rise and fall of the transformer component to be exponential. In the trapezoidal-wave flowmeter, the transformer component is actually zero by the time the gate is open.

A similar analysis would also apply to the sine-wave and square-wave flowmeters. The transformer component for the sine wave is another sine wave displaced, theoretically, 90 deg from the magnet current. Disadvantages of the sine-wave flowmeter have been discussed. The transformer component for the square wave is an extremely large spike. Although this spike may be limited or eliminated by the blanking circuitry, in practice there will also be an exponential rise and decay for this transformer component. Since the transformer component associated with the square wave is very large and since the blanking circuitry follows the input amplifier, considerable difficulty would be expected in trying to eliminate all traces of that component. One would expect that the gate could only be open a small fraction of a cycle in this case. One advantage of the trapezoidal-wave flowmeter is that the gate can be open between 10 and 15% of each cycle.

One of the authors has made several transducers of the design shown in Fig. 16. A large common-mode signal was evident in the input signal, which appears to be due to the unbalance in the transducer.

The transducer can be balanced externally as follows: A small transformer is wound. The 15-turn primary which is energized by a fraction of the magnet current has a 6-ohm variable resistor in series with one lead. The five-turn secondary is shielded from the primary and is placed in series with one of the electrode leads. By adjusting the variable resistor, the transducer can be externally balanced.

The authors are now constructing a transducer of a new design, which should eliminate the need for the transformer. The magnet coil will be bifilar as shown in Fig. 19. This will eliminate any capacitive imbalance in the transducer. In order to minimize the transformer component, one electrode lead will be externalized and place in final position after the rest of the transducer is completed. It is hoped that in this way the transformer described above can be eliminated. Figure 20 shows the design of the new transducer.

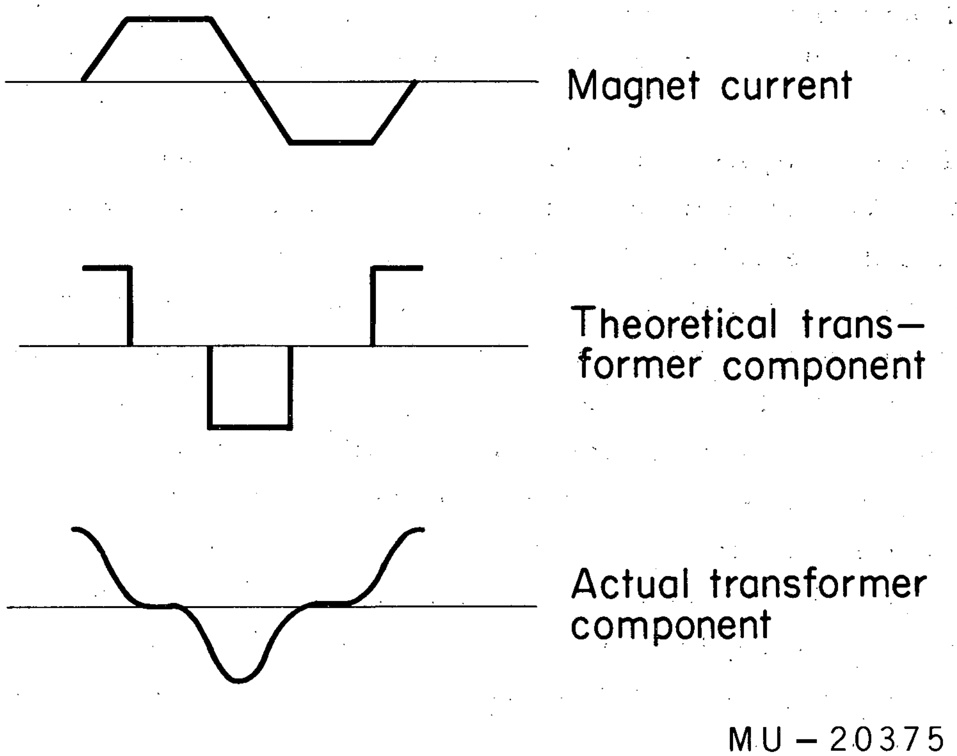



Fig. 18. Transformer component in the trapezoidal-wave flowmeter.

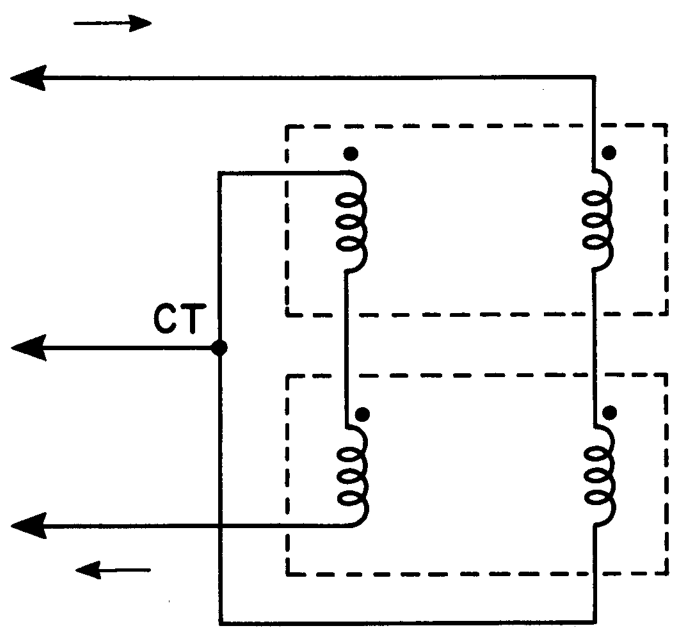



Fig. 19. A center-tapped bifilar-wound coil.

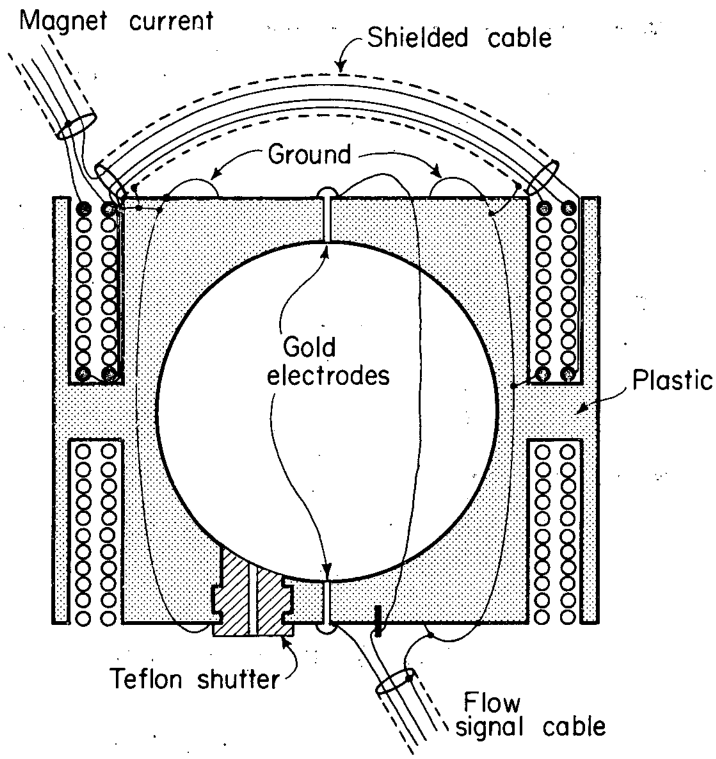
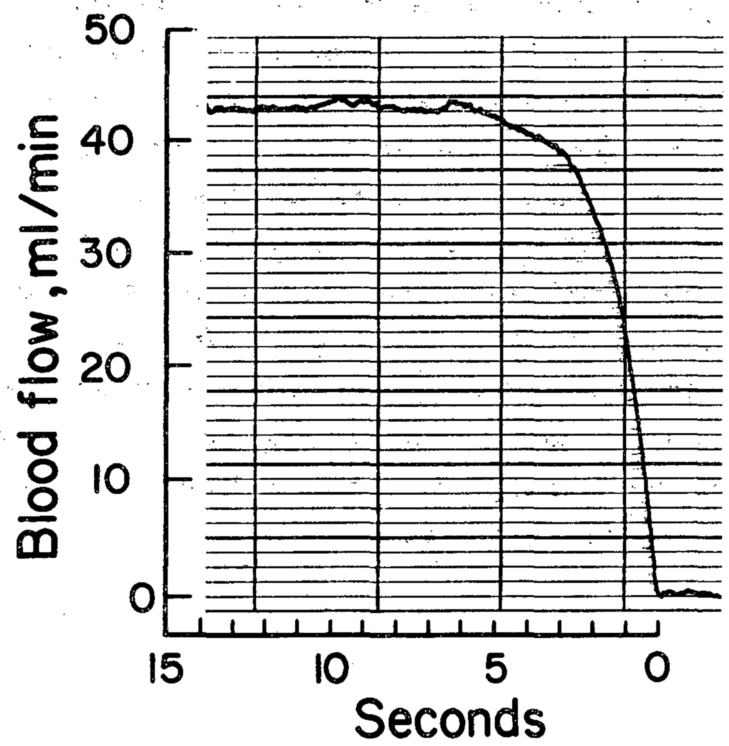



Fig. 20. A new transducer designed for the trapezoidal-wave flowmeter.

## CALIBRATION

Each transducer must be calibrated separately. The transducer responds with a greater signal for saline than for blood for equal flows of each. The flow signal also decreases about 5% for every 10% increase in red-cell concentration, according to Spencer and Dennison.[15] The transducer should be calibrated *in situ* in order to provide true absolute values of flow. The authors recommend the use of a mechanical stromuhr or, when convenient, merely allowing the blood to flow into a graduate for a unit period of time. Figure 21 shows a record of the flow through the iliac vein of a rabbit.

Figure 22 is the circuit for a calibrator. This calibrator supplies a signal of 5, 10, 20, or 50 μv to the input of the *flow-signal amplifier and demodulator*. The output is then recorded as if it were a flow signal. This provides a test signal to insure that the electronics and the recorder are operating satisfactorily. This calibrator does not supply any information about the calibration of the transducer and hence does not measure blood flow. It does, however, allow the experimenter to check the instrument to be sure that it is operating the same before and after the experiment.




MU-20378

Fig. 21. Flow record taken from the illiac vein of a rabbit. The clamped vein was released at T=0. Calibration will tend to be high because the electrodes were in contact with the blood during preliminary calibration.

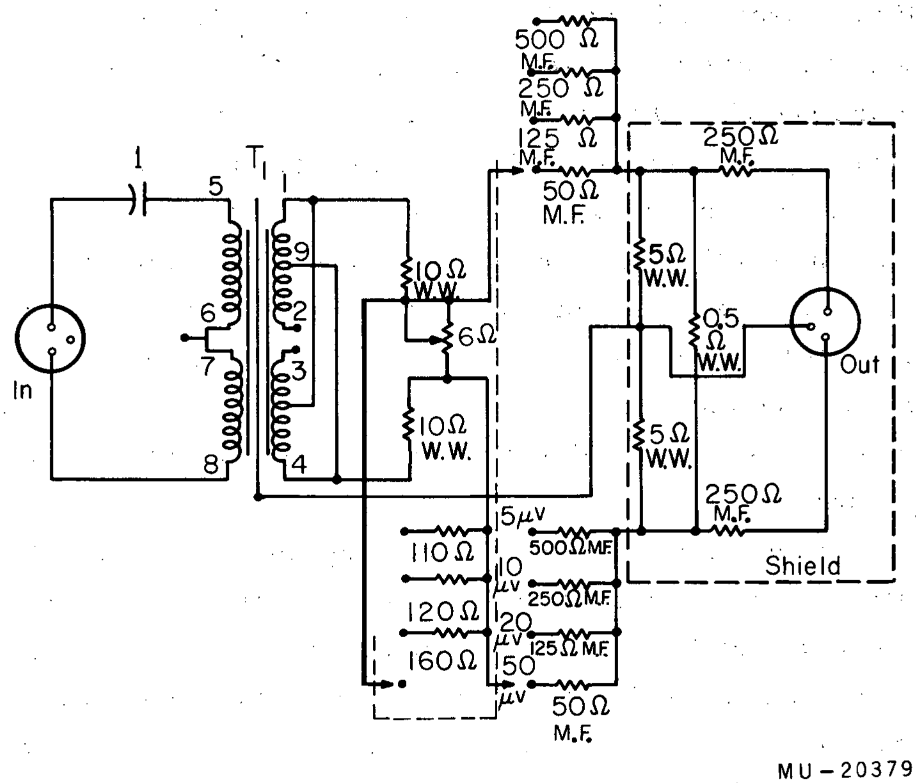



Fig. 22. Calibrator Circuit.

## CONCLUSION

A sensitive electromagnetic blood flowmeter has been designed which will effectively measure blood flow in vessels from 1.5 mm to 10 mm or greater, without breaking the vessel wall (Fig. 23). The instrument is not difficult to use and should require a minimum of maintenance. The use of printed-board circuitry has significantly lowered the cost of the instrument. At present, the transducer is the most difficult part to make. Within the next year it is hoped that good transducers will be commercially available. Transducers are presently being constructed by the authors.

We feel that the day is near when physiologists will be able to measure blood flow in any number of vessels at the same time. Indeed, when this is done the physiologist will be able to more efficiently study problems in circulatory physiology.

This flowmeter is not without clinical application. The authors feel that the flowmeter could become a standard piece of equipment in modern surgery, especially gastrointestinal surgery. When one segment of the gastrointestinal tract is to be removed, it is necessary to cut off the blood supply to that area. If that blood supply happened to supply some other area of the gastrointestinal tract by collateral circulation because of some undetected damage elsewhere, a large portion of the gastrointestinal tract would be depleted of its blood supply. This could result in the loss of the patient due to surgical shock.

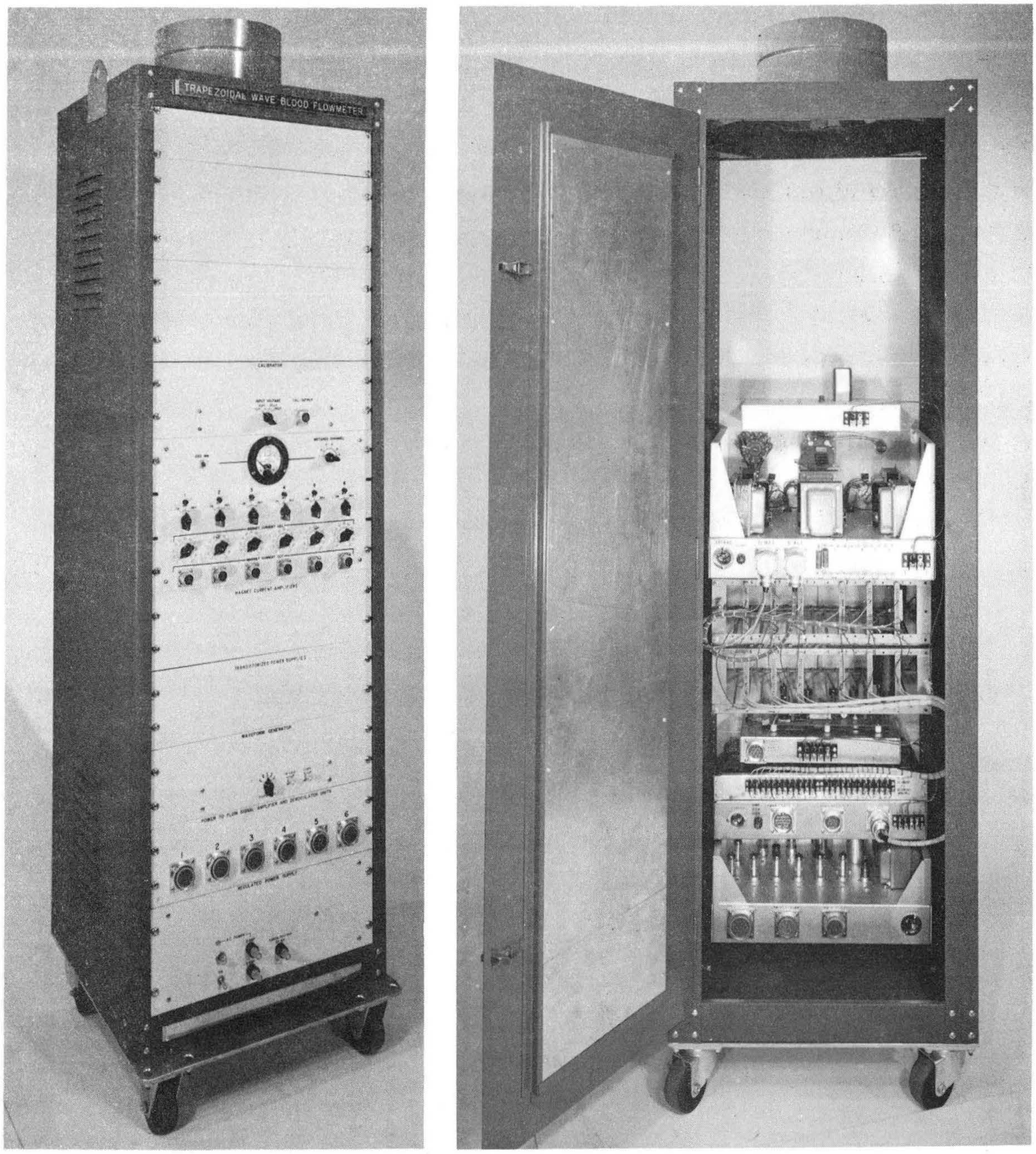



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Fig. 23. Trapezoidal-wave electromagnetic blood flowmeter: (left) front view; (right) rear view.

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The authors wish to acknowledge the support given to them which have helped to make this instrument a reality. This project would not have been possible without the cooperation of Dr. John Lawrence, director of the Donner Laboratory, and his staff. The far-sightedness and patience of Mr. Robert San Souci, Business Manager of the Donner Laboratory has done much to make this project a success. We would also like to thank Dr. Ernest Dobson for his advice. We also wish to acknowledge the advice and cooperation of the Engineering Group and especially Mr. Wesley Rutz and Mr. Charles Dols, electrical engineers. The Electronic Production Shop and its supervisor, Mr. William Blisard, have also helped to make the trapezoidal-wave electromagnetic flowmeter possible.

## CIRCUIT CORRECTIONS

Fig. 3. The cathode resistor in $V_{4A}$ should be 470 ohms. The 33 k resistor coupling the cathode of $V_{4B}$ to $V_5$ should be 10 k ohms. A .01 μf capacitor should go from the plate of $V_{4A}$ to $B^+$.

Fig. 7. The transistors must be selected for optimum performance.

Fig. 9. The 12AX7 tube used in $V_1$ must be selected for equal gain at the plates of $V_2$.

Fig. 10. IN629 diodes were used in the 6 diode gate. The resistor between the zero adjust and -100 volts must be selected. Higher gain may be obtained in two ways, if needed: A 100 μf (6 volts) capacitor may be placed in parallel with the cathode resistor of $V_{4A}$ or the input grid resistor to $V_{5A}$ may be decreased to 100 k ohms. The 360 μμf capacitors in the Twin Tee were changed to .01 μf. The 720 μμf capacitor was changed to .02 μf. The 440 k ohm resistors were changed to 15 k ohms. The 220 k ohm resistor was changed to 8.2 k ohms. Metal film resistors are the resistors of choice in the Twin Tee.

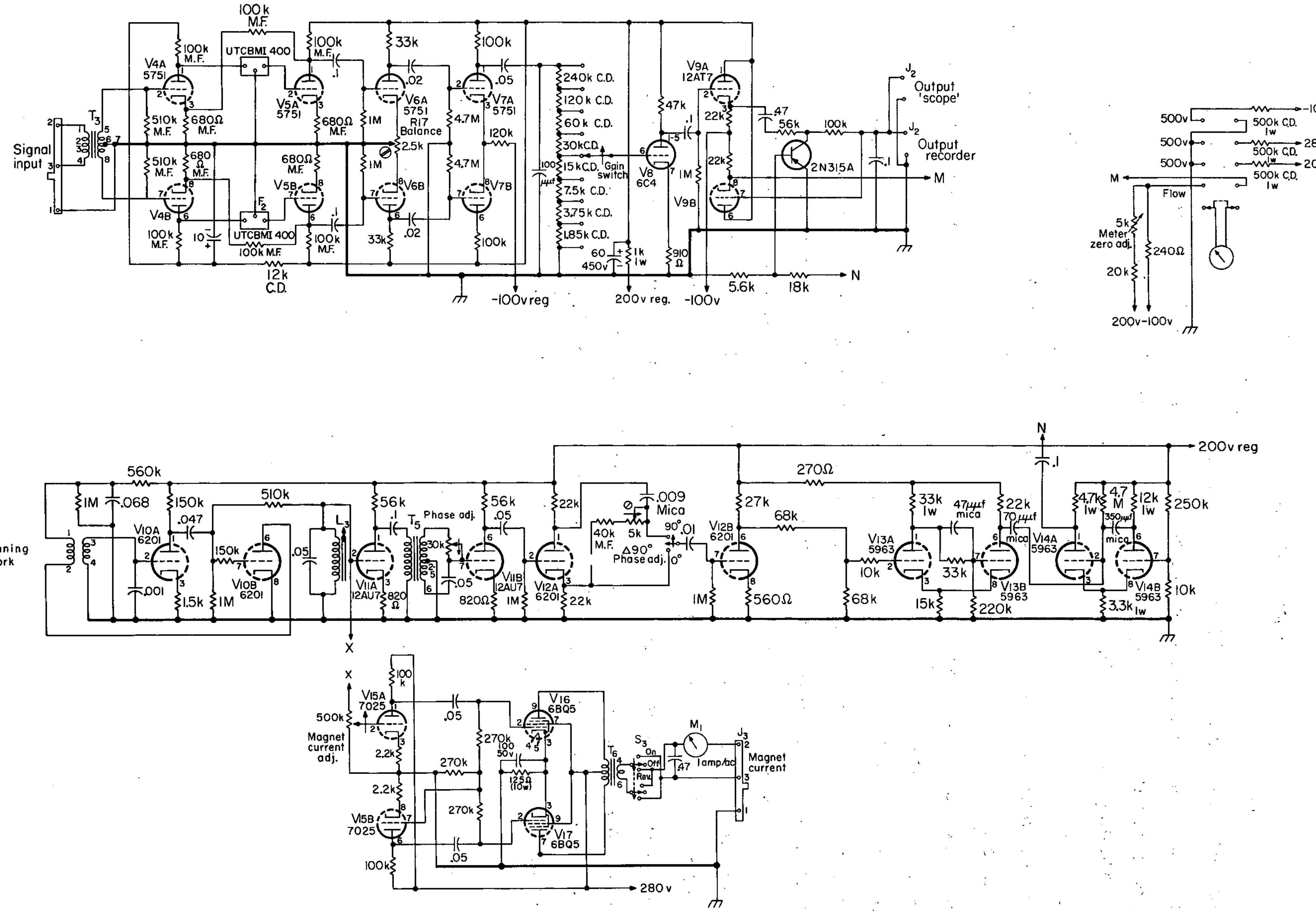
The authors will supply additional information upon request.

## APPENDIX

The authors constructed a sine-wave flowmeter as described in the Proceeding of the National Academy of Science.[7] The performance of the instrument was greatly improved by the following modifications:

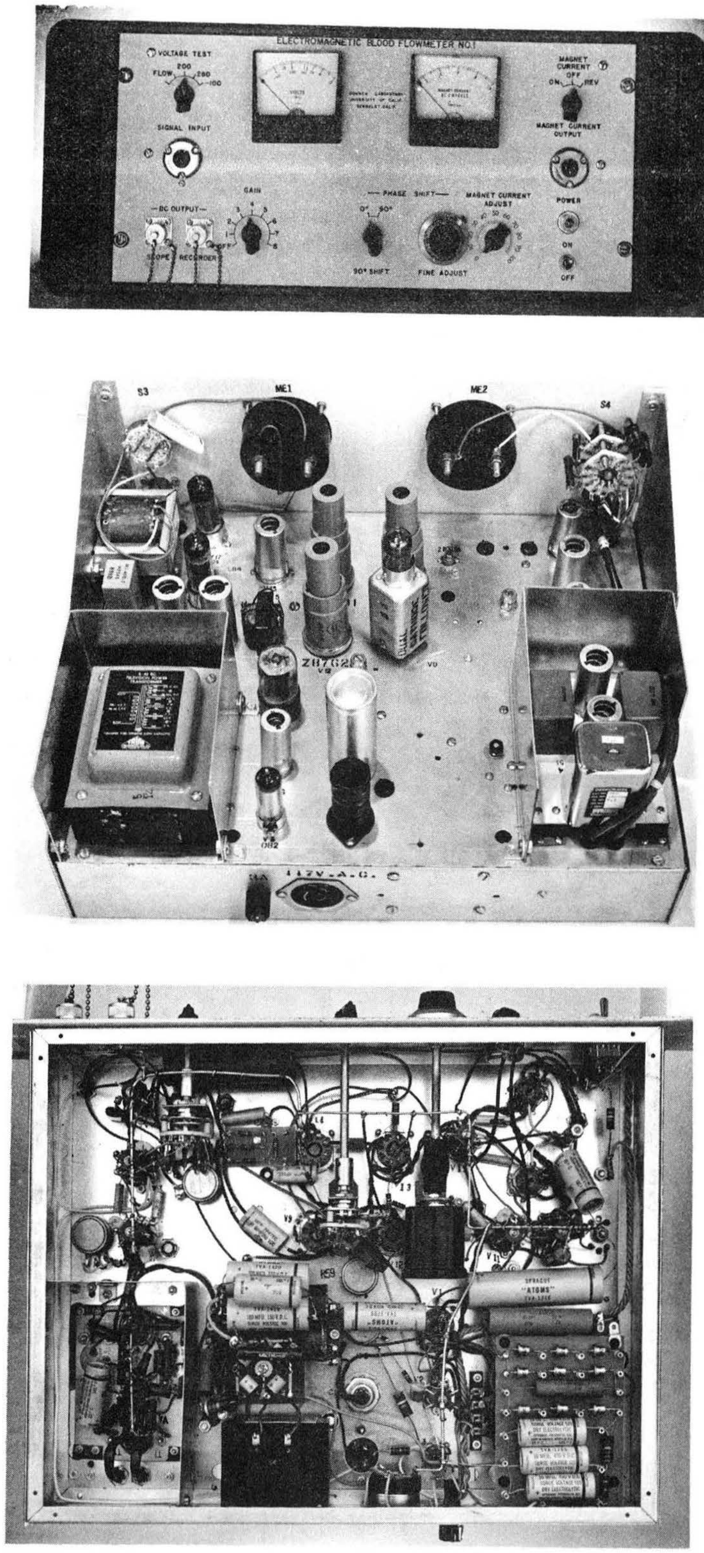
1. The 90-deg phase shifter was redesigned.
2. A 10-turn helipot was used for fine adjustment of the phase shift.
3. The operating condition of the squaring circuit and the one shot was changed.
4. A new switching transistor was used. This eliminated the use of the 1.5-v battery.
5. The chopper drive transformer was replaced with a cathode follower.
6. The input transformer was changed to a Triad G 10. (This may not be advisable because of the nature of the sine-wave flowmeter.) It is, however, necessary to use an input transformer with at least three (and still better, five) shields. The Triad G 40 originally used is not normally supplied with more than one shield.
7. A position on the voltage test switch was modified to indicate flow.
8. A reversing switch was added to the magnet-current output.

The modified sine-wave flowmeter is shown schematically in Fig. 24. The photographs of the instrument and its layout are shown in Fig. 25.




MU-408

Fig. 24. Modified sine-wave flowmeter circuit. Here $T_3$ is a Triad G-10 transformer, $T_5$ is a Triad A4X transformer, $T_6$ is a Merit A2905 transformer, and $L_3$ is a United Transformer Company HVC7 variable inductor. A Philamon Laboratory MJ400T tuning fork was used.




ZN-2534

Fig. 25. Modified sine-wave flowmeter: (top) panel; (middle) top oblique view; (bottom) bottom view.

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