gives more surface for sealing and always permits perfect alignment in assembling the apparatus.

The combination seal and suspension bearing (H) for the band and the adjustable needle valve (I) for admission of the liquid from the upper reservoir to the still column have been described previously.[2]

* Contribution No. 613 from the Central Research Department, Experimental Station.
[1] These rings can be obtained from Linear, Inc., State Road and Levick Street, Philadelphia 36, Pennsylvania.
[2] R. G. Nester, Anal. Chem. 28, 278 (1956).

Inexpensive High Resolution Wheatstone Bridge

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IN order to measure small changes in precision resistors undergoing environmental tests a bridge with very high resolution was needed, but a standard bridge was not financially justifiable. We therefore constructed the bridge shown in Fig. 1. The variation in balance condition with R_3 is

$$X(R_3)/X(0)=1-(R_1/R_2)\sum_{i=1}^{\infty}[-R_3/(R_1+R_2)]^i.$$

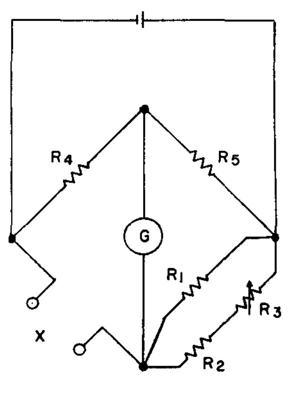

FIG. 1. Schematic diagram of high resolution Wheatstone bridge.

If R_2 is sufficiently larger than R_3 this series can be terminated after one or two terms, and an approximately linear variation of balance with R_3 is obtained.

In the actual application each of the resistors except R_3 was made from a parallel combination of several 1% deposited carbon resistors, and R_3 was a 0.1% linearity multi-turn variable resistor. They had values that permitted spanning a 2% range around 129 ohms with a resolution of 0.002%; and a day to day stability of the same order when used to measure the standard resistors for calibration.

The bridge was constructed for less than $50.00.

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Vacuum Tube Electrometers Using Operational Amplifiers

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VACUUM tube electrometers are used to measure current from transducers of the current-source type, for instance photocells and ion chambers. They can measure a current of 10^{-14} amp or less. Although excellent commercial vacuum tube electrometers exist, scientific instruments often require built-in electrometers with special characteristics. This note describes two general purpose electrometers using operational amplifiers, that is, packaged differential dc amplifiers with voltage gain of 1000 or more. The use of operational amplifiers results in a saving in design, construction, and maintenance time[1] over the adoption of previously published vacuum tube electrometer circuits.[2]

In the illustrated circuits, the input current develops a voltage across R of IR. The output of the amplifier which follows is 100% fed back to the input of the circuit, and the voltage developed across the meter circuit at the amplifier output is IR. A large enough value of R is used so that IR is large compared to the drift in the input

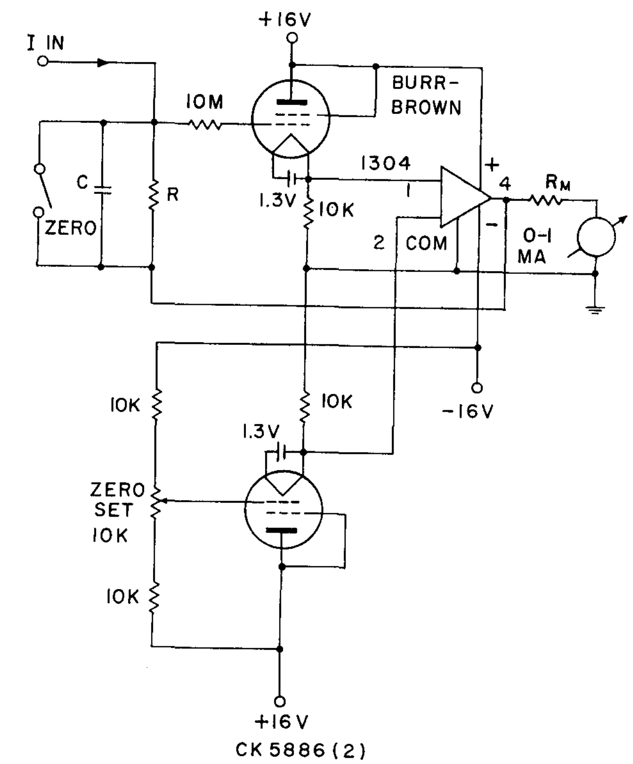

FIG. 1. Electrometer using Burr-Brown model 1304 transistor operational amplifier (Burr-Brown Research Corporation, Tucson, Arizona). R_M is adjusted to give full-scale deflection for a maximum value of current to be measured.

stage. Since drift is a few millivolts per hour or less, a value of IR of a few tenths of a volt or more is practical. The speed of response is controlled by the capacitor C; the resulting time constant for circuit response is RC. For stable operation, $RC=1$ sec is sufficient, although faster response is often practical. The feedback arrangement reduces the effective input resistance to a value R/A where A is the gain of the amplifier. A small value of R/A is useful in reducing time lags due to input capacitance to ground.

A switch which permits the application of filament current to the electrometer tubes before plate voltage is applied to the tubes may improve the operation of the circuits when currents less than 10^{-12} amp are to be measured. In Figs. 1 and 2 all supply voltages are referred to ground.

Figure 1 shows a battery-operated electrometer using a transistor operational amplifier. The input stage uses a balanced cathode follower with two low grid-current tubes. The maximum value of IR is about ±10 v before the amplifier overdrives. The grid current at the input is less than 2×10^{-13} amp and can be reduced a factor of ten by reducing the voltage on the electrometer tubes to $+6$ v.

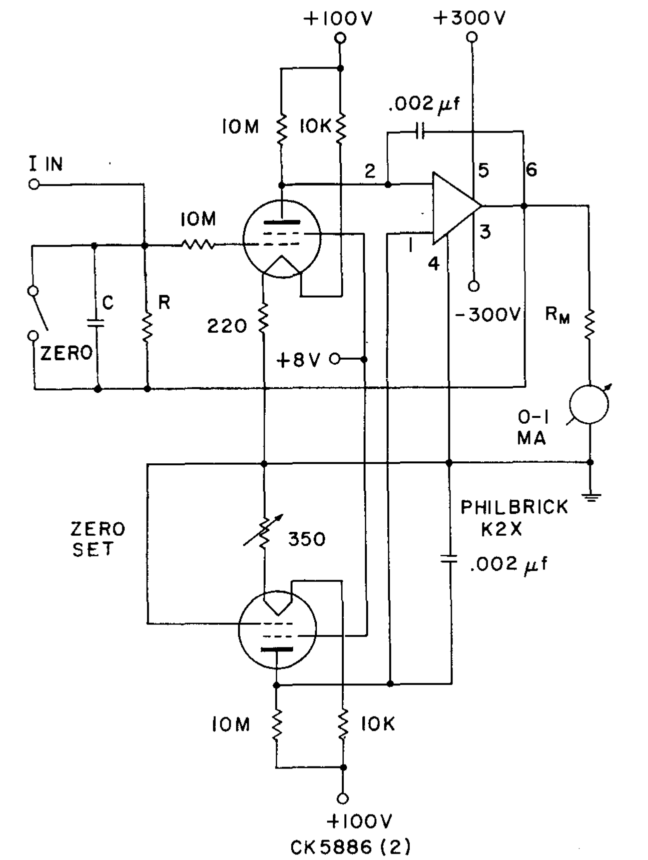

FIG. 2. Electrometer using Philbrick operational amplifier model K2X (George A. Philbrick Researches Inc., Boston, Massachusetts). R_M is adjusted to give full-scale meter deflection for a maximum value of current to be measured.

When using mercury cells for filament and plate voltage, zero drift referred to the input is less than 1 mv/hr after warmup. Drain is 10 ma at each filament and 16 ma for each of the 16-v batteries.

Figure 2 shows an electrometer using a vacuum tube operational amplifier. The input stage is a balanced amplifier using two low grid-current tubes. The maximum value of IR is ±100 v or more; the instrument may be used to cover three or four decades of current measurement with a single input resistor by changing the output meter sensitivity to accommodate the different scales. This possibility often eliminates switching at the high impedance input. When high megohm resistors are used for R, however, some nonlinearity may result due to the voltage coefficient of the resistors if voltages as high as 100 v are applied.[3] The grid current at the input is less than 5×10^{-14} amp. When using a regulated supply ($\pm1\%$) for the 100-v source and an unregulated supply ($\pm10\%$) for the 300-v source, zero drift is less than a few millivolts per hour. Some correction of the amplifier phase characteristic is necessary to prevent oscillation (0.002-μf capacitors).

[1] K. Eklund, Rev. Sci. Instr. **30**, 328, 331 (1959).
[2] R. H. Vacca, *1956 National Symposium on Vacuum Technology Transactions* (Pergamon Press, New York, 1957).
[3] A. B. L. Whittles, Rev. Sci. Instr. **31**, 208 (1960).

Simple Transistor-Operated Oven-Temperature Regulator*

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IN recent work in our Laboratory, a need arose for an electronic circuit to regulate the temperature of a small molecular beam oven. The maximum oven dissipation is 100 w, and the maximum operating temperature is 1500°C. Many circuits for similar applications have been described by several authors, but the advent of the power transistor, working at low voltage and high current, seemed to offer new possibilities for this purpose. A particularly simple circuit that has held the temperature of a test oven constant within ±1°C over long periods has been designed. An optional addition to this basic circuit has also been developed, in case a higher degree of regulation should be desired.

The simpler circuit is shown in Fig. 1. The heating element of the furnace is designated R_L. The transistors T_1, T_2, and T_3 are operated without the use of dc bias elements and, as a consequence, their operating points