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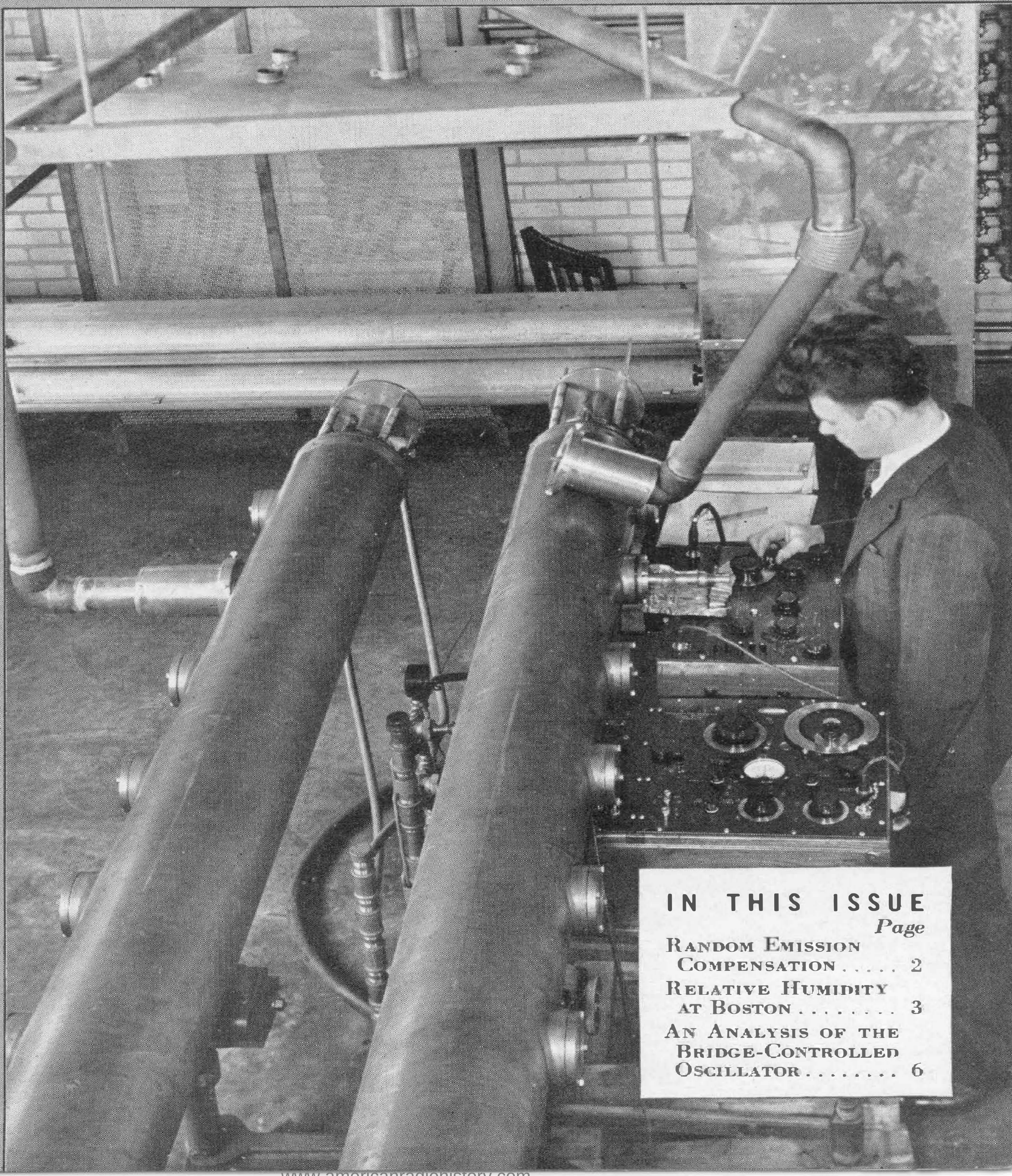
ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS



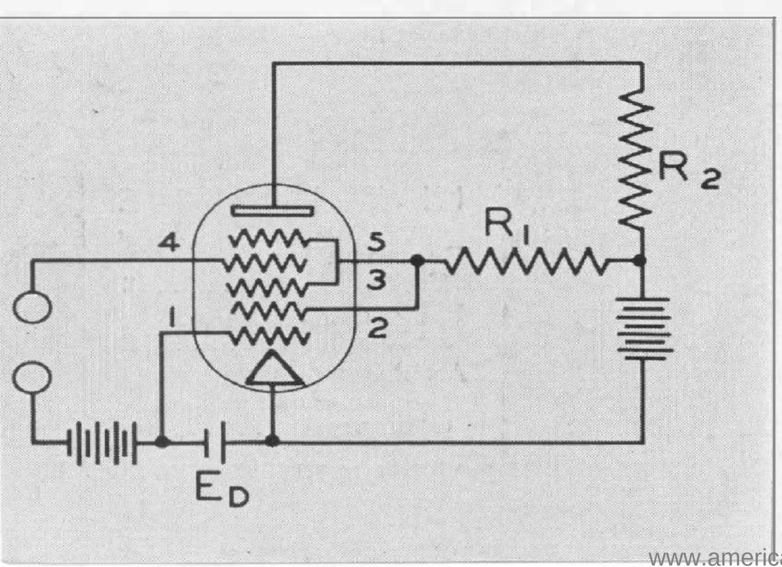
IN THIS ISSUE

RANDOM EMISSION COMPENSATION

● **OWING TO ITS AMPLIFYING PROPERTIES** and its high input resistance, the vacuum tube is ideally suited to the problem of measuring d-c potentials. Inherently stable circuits employing degeneration and a closely regulated power source are required if the vacuum-tube voltmeter is to be used for measuring small potentials. As a further refinement, it is necessary to shield magnetically and electrostatically the most sensitive tube or tubes of the circuit; all leads entering the shielded compartment must be carefully filtered; shock mounting is needed to avoid microphonics.

When these precautions have been taken, the sensitivity may be increased to the point where irregularities in the electron stream are the dominant cause of unwanted fluctuations in the output. These irregularities cannot be eliminated. They are due to the very nature of electron emission: electrons are freed from the cathode or filament in a random fashion; they push and jolt one another in a mad scramble to escape the heated emitter very much like popcorn on a hot stove and it is only because of their vast numbers that in normal usage they present a seeming constant flow.

FIGURE 1. Schematic diagram showing tube with grids connected to compensate for random emission.



Since the random fluctuations cannot be eliminated, the only recourse is to devise a compensating mechanism and this immediately suggests the use of a multi-electrode tube wherein several avenues are available for getting at the electron stream.

Pentagrid-converter-type tubes are supplied with several grids interposed between the cathode and the plate. Such a tube can be connected as shown in Figure 1 at no sacrifice in gain, and, if the operating potentials are properly chosen, fluctuations in emission will produce no change in the output voltage. The mechanism of compensation operates as follows: an increase in electronic emission causes more current to flow through R_1; the voltage at grids No. 2, No. 3, and No. 5 is reduced because of the voltage drop in R_1. Since grid No. 5 is between the control grid (No. 4) and the plate, the current flow at the plate is affected by two compensating effects: the increase in electronic emission and the decrease in grid No. 5 voltage. As a net result, the current flow at the plate remains unchanged in spite of random fluctuations in the electronic stream.

Figure 2 illustrates the degree of compensation that may be expected. To simulate random fluctuations the filament voltage of a 1D7-G type tube was changed over what is really an enormous range, considered in terms of normal emission fluctuation. Since we are interested in the ability of the device to measure small voltages, the change in output, due to filament voltage changes, was corrected by introducing a voltage at the control grid. This "equivalent" voltage is plotted in the figure and the

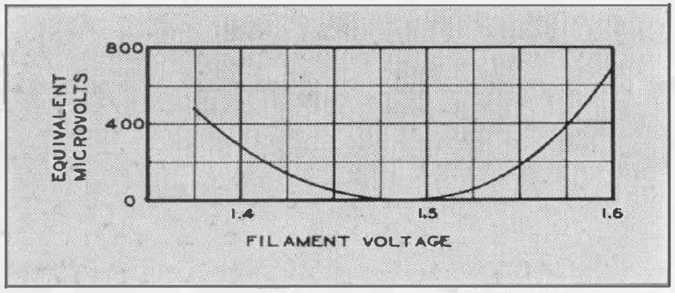


FIGURE 2. Plot showing range over which compensation is effective.

slope of the curve is the criterion of the effectiveness of compensation. The tube of course should be operated at the inflection point of this curve. At the time these data were taken, it was also ascertained that similar results could be obtained with a heater-type of tube (6A8), and it can be expected that other types of pentagrid-converter tubes would yield equally satisfactory results.

High stability can often be attained by using additional stages of amplification and introducing practically complete degeneration over the entire amplifier. But any fluctuation in the voltages that exist in the path common to the control grids (contact potentials, etc.) is not degenerated out because the source of these voltages is not included in the degenerative loop.

Fortunately, when the circuit of Figure 1 is adjusted to compensate for changes in emission, it is equally balanced for changes in any voltage (E_D) which is common to both control grids. In other words the transconductance of the two grids (No. 1 and No. 4) to the plate are equal but of opposite polarity.

Consequently, the circuit of Figure 1 not only compensates for fluctuations in emission, but it can also be used to supplement the over-all degeneration and the heater supply regulator in the attempt to achieve the high stability so essential in measuring small d-c potentials and currents. — A. G. BOUSQUET

RELATIVE HUMIDITY AT BOSTON

● **IN THE ARTICLE** on "The Effect of Humidity on Electrical Measurements," reprinted in the General Radio *Experimenter* last month, mention was made of the fact that, whenever the relative humidity exceeds 60% for a day, aluminum plate condensers have appreciable losses, and when the relative humidity passes 70% the balance of a capacitance bridge becomes unstable.

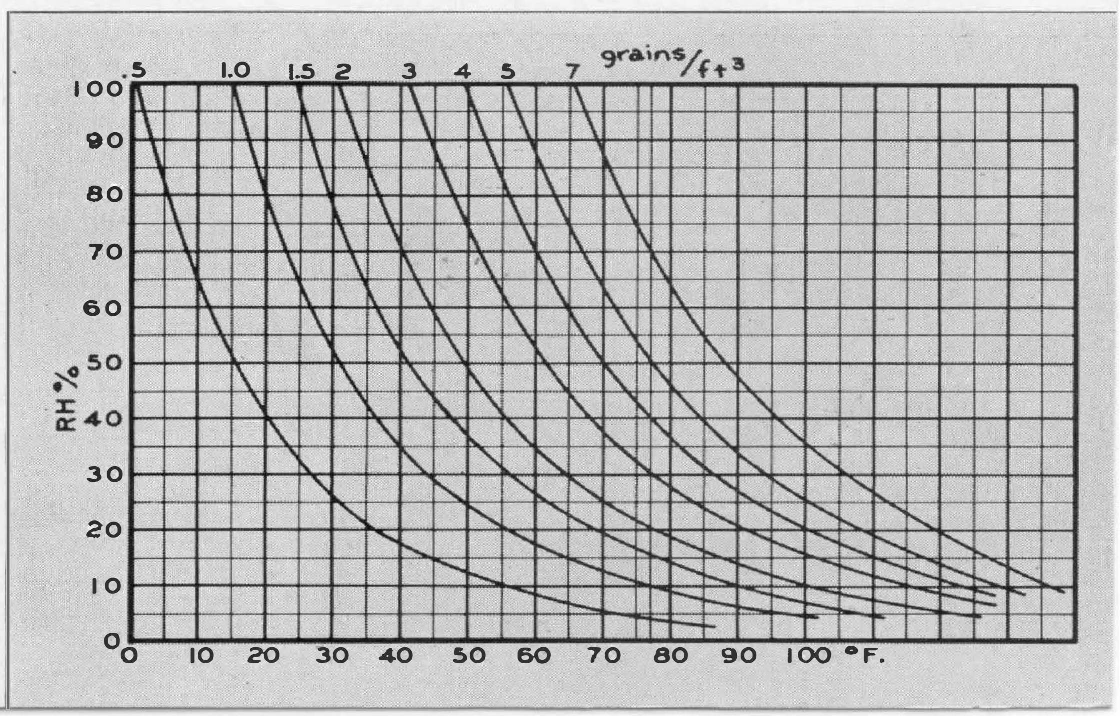


FIGURE 1. Curves showing the relation between relative humidity and temperature for various densities of aqueous vapor expressed in grains per cubic foot.

The question naturally arises, how often during the year do these conditions occur? This of course depends on the location of the apparatus. In New England the humidity indoors is high only during the summer months of July and August, while in the tropics the humidity is always high.

For the last two years a record has been kept of the relative humidity in a room whose temperature is kept at 25°C. except when the outdoor temperature is higher. The relative humidity remains below 30% for the six winter months, November through April, and rises to an average of 60% in July. A value of 60% is exceeded once in May and October, about once a week in June and September, and almost continually in July and August. A value of 70% is exceeded about once a week in July and August.

The relation between the relative humidity indoors and outdoors is determined by the temperatures of the two locations. Assuming that the weight of water in a unit volume remains constant, the change of relative humidity with temperature is given in Figure 1. As an example, assume that conditions outdoors are 70% RH at 40°F. Then entering the chart at this point and following down the curve of 2 grains per cubic foot gives 20% RH at 77°F. (25°C.).

Values of relative humidity and temperature are observed by the U. S. Weather Bureau at many points in the United States and published monthly in Weather Bureau Reports and daily in some newspapers. The monthly averages for Boston are given in Figure 2 for the average over a period of years and also for the year 1943, which appears to be a reasonably normal year. Average relative humidity is essentially constant at 72% with only a slight rise in August and September. This condition is mainly due to the fact that New England has an approximately constant monthly precipitation of about 3 inches. Proximity to the ocean is a contributing factor. This fact makes average relative humidity at constant temperature solely a

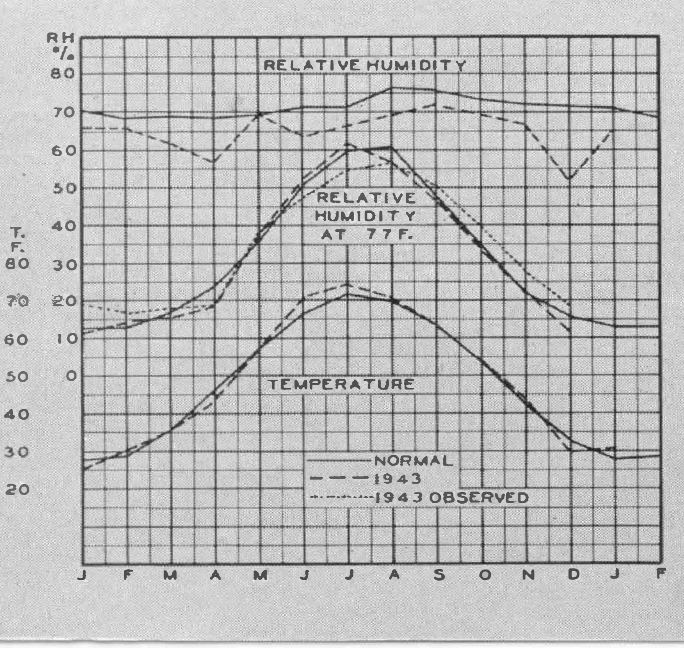


FIGURE 2. Curves of average monthly relative humidity and temperature at Boston. Note that the relative humidity at 77°F., calculated from outdoor values, agrees well with that observed in the constant-temperature room.

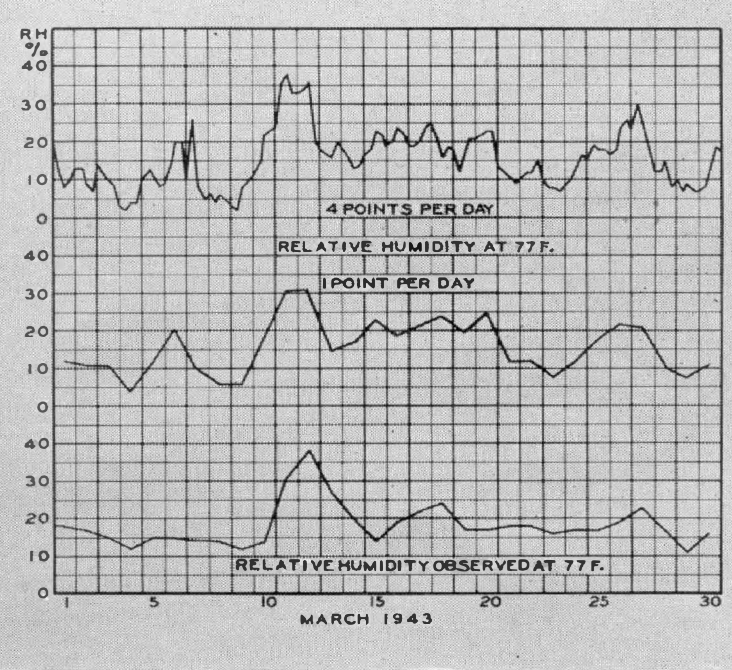


FIGURE 3. Curves of observed and calculated relative humidity at 77°F. for March, 1943, at Boston. The relative smoothness of the lower curve compared to the middle one illustrates the filtering and storage action of a large building.

function of outdoor temperature. The curve of relative humidity at 77°F. (25°C.), obtained by means of the curves of Figure 1, follows exactly the curve of temperature. An average value of 60% can occur only during the summer when the outdoor temperature is at least 70°F. The average values observed in the constant temperature room are also plotted in Figure 2. Their agreement with the calculated values justifies that calculation. There is an interesting time lag between the calculated and observed curves which can perhaps be explained as indicating a storage of moisture in the building. This would reduce the humidity in the early summer and increase it in the early winter.

Daily values of relative humidity and temperature show much greater variations than monthly values, as is well shown in Figure 3 for March, 1943. The diurnal changes are such that temperature tends to have a maximum value and relative humidity a minimum value shortly after noon. The wide fluctuations in relative humidity are caused partly by the temperature changes and partly by changes in the water content of the air. This is shown by the upper curve of Figure 4, which gives the relative humidity at the constant temperature of 77°F. (25°C.). The fluctuations have a longer period than before. The major changes still appear even when the daily average values are plotted as shown in the middle curve of Figure 4. The lower curve of Figure 4 shows the relative humidity as observed in the constant temperature room. Here the fluctuations are smaller and of still longer period. This is caused by the filtering and storage action of the building.

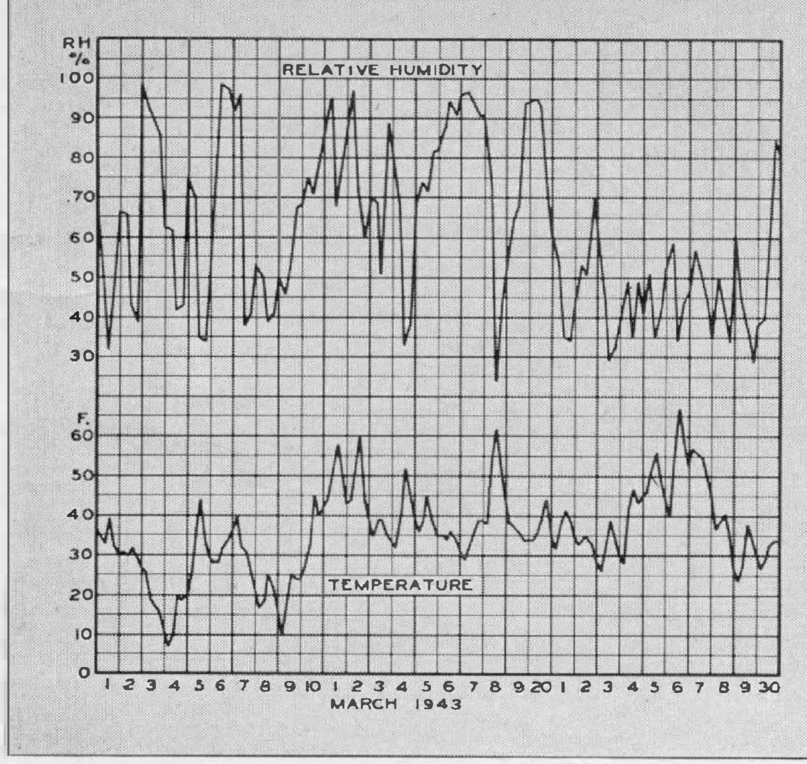


FIGURE 4. Daily values of relative humidity of temperature for March, 1943, at Boston. Over short periods of time relative humidity drops when temperature rises, as would be expected for constant water content of the air.

This comparison of observed values of indoor relative humidity with values calculated from outdoor data furnished by the U. S. Weather Bureau indicates that, whenever values of relative humidity are given in the daily newspapers, it is possible with the lag of only one day to determine indoor relative humidity without depending upon a hair hygrometer or wet and dry bulb thermometers. In many cases this method will be found satisfactory for indicating when aluminum plate condensers will begin to introduce errors in dissipation factor in capacitance bridge measurements and when the bridge balance itself will become unstable. — ROBERT F. FIELD

AN ANALYSIS OF THE BRIDGE-CONTROLLED OSCILLATOR

● **THE BRIDGE-CONTROLLED OSCILLATOR***, particularly as used with quartz bars in frequency standards, has a high degree of inherent stability of frequency. The principal properties of this circuit can be analyzed as follows:

Referring to Figure 1, the impedances involved are those of the bridge, *R*-1, *R*-2, *R*-3, *R*-4, and $+jX_4$ (the effective resistance and the net reactance of the quartz bar, operating very near to series resonance), the resistance of the source *R*-6, and the resistance *R*-5 of the bridge output load, which is assumed to be very high compared with all of the preceding resistances.

For the bridge, the attenuation factor can be written:†

$$\beta = \frac{E_{out}}{E_{in}} = \frac{AR_4 - jBX_4}{MR_4 + jNX_4} \quad (1)$$

where

$$A = R_5(R_2R_3 - R_1R_4) \quad (2)$$
$$B = R_1R_4R_5 \quad (3)$$

$$\begin{aligned} M = {} & (R_1 + R_2)(R_3R_4 + R_5R_6) \\ & + (R_3 + R_4)(R_1R_2 + R_5R_6) \\ & + (R_5 + R_6)(R_1R_4 + R_2R_3) \quad (4) \\ & + R_5(R_1R_3 + R_2R_4) \\ & + R_6(R_1R_2 + R_3R_4) \end{aligned}$$

and

$$\begin{aligned} N = {} & R_4(R_1 + R_3 + R_5)(R_2 + R_6) \\ & + R_1R_4(R_3 + R_5) \quad (5) \end{aligned}$$

For the system, the condition for oscillation is

$$\mu\beta = 1 \underline{/0}. \quad (6)$$

If there is a phase-shift in the amplifier, we can write*

$$\mu = \mu_1 + j\mu_2 \quad (7)$$

Inserting (1) and (7) in (6), we obtain:

$$(\mu_1 + j\mu_2)\frac{AR_4 - jBX_4}{MR_4 + jNX_4} = 1 \quad (8)$$

and, separating reals and imaginaries:

$$\mu_1AR_4 + \mu_2BX_4 - MR_4 = 0 \quad (9)$$
$$\mu_2AR_4 - (\mu_1B + N)X_4 = 0 \quad (10)$$

If there is no amplifier phase-shift, $\mu_2 = 0$, so that

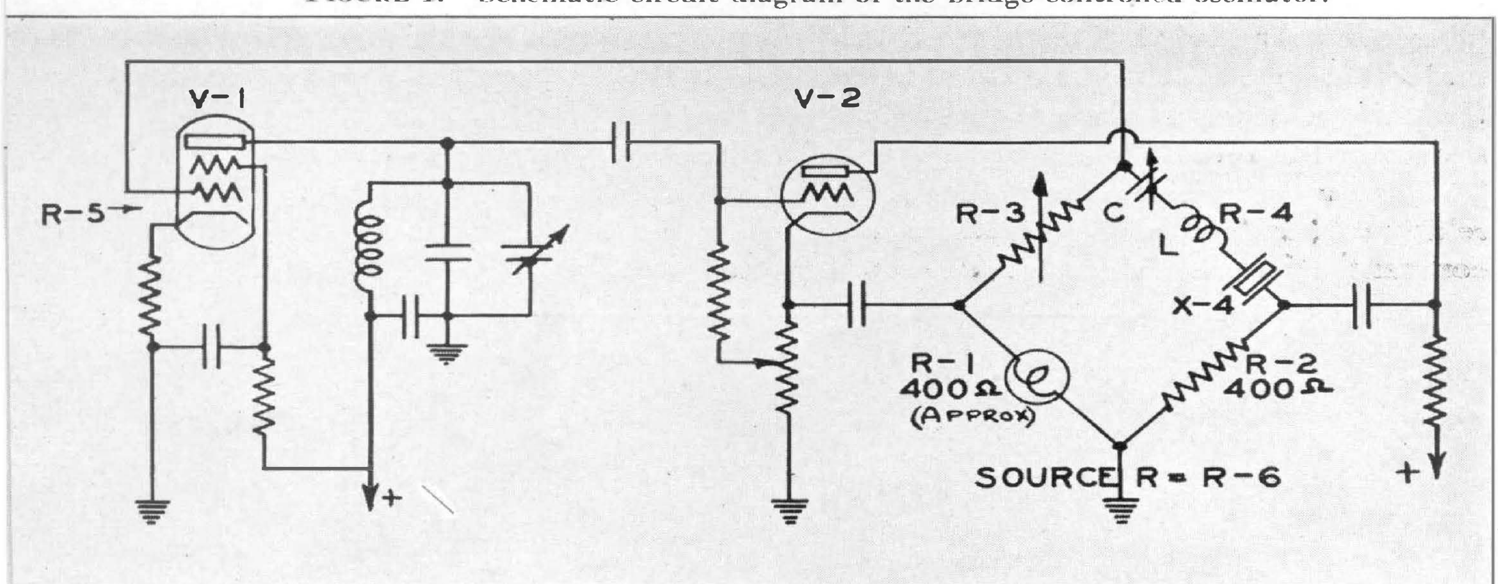
$$\mu_1 = M/A = \mu_a \quad (11)$$

*J. K. Clapp, "A Bridge-Controlled Oscillator," General Radio *Experimenter*, April, 1944.

†K. S. Johnson, "Transmission Circuits for Telephonic Communication," pp. 284–285.

*L. A. Meacham, "The Bridge-Stabilized Oscillator," Proc. I.R.E., Vol. 26, No. 10, p. 1278, October, 1938.

FIGURE 1. Schematic circuit diagram of the bridge-controlled oscillator.



and

$$X_4 = 0 \qquad (12)$$

where μ_a is the magnitude of the amplification of the amplifier, from bridge output to bridge input. The frequency is then independent of the circuit except the crystal and the crystal must operate at exact series resonance.

If μ_2 is very small, so that θ, the phase angle of the amplifier, is small, from (9) and (10) we obtain

$$X_4 = \frac{\mu_2 A R_4}{\mu_1 B + N} = \frac{M R_4}{\mu_1 B + N} \cdot \frac{\mu_2}{\mu_1}$$
$$= \frac{M R_4}{\mu_a B + N} \tan^{-1} \frac{\mu_2}{\mu_1}$$
$$= \frac{M R_4 \theta}{\mu_a B + N} \qquad (13)$$

since θ is small and $\tan \theta \cong \theta$.

For the crystal, in the region near series resonance, we can express the frequency deviation from resonance as a fraction of the resonant frequency:

$$\frac{f - f_0}{f_0} = \frac{X_4}{2\omega L_4} = \frac{X_4}{2 Q R_4} \qquad (14)$$

where X_4 is the *net* crystal reactance, that is, the difference of the inductive and capacitative reactances, and $Q = \omega_0 L_4 / R_4$.

Substituting (13) in (14) we obtain:

$$\frac{f - f_0}{f_0} = \frac{1}{2Q} \cdot \frac{M\theta}{\mu_a B + N} \qquad (15)$$

We can now find the effects of changes in the amplifier on the frequency. For changes in phase only (μ_a remaining constant),

$$\left.\frac{df}{f_0}\right|_{\theta} = \frac{M d\theta}{2Q(\mu_a B + N)} \qquad (16)$$

For changes in amplification only (phase remaining constant):

$$\left.\frac{df}{f_0}\right|_{\mu a} = -\frac{B M \theta d\mu_a}{2Q(\mu_a B + N)^2} \qquad (17)$$

For the oscillator previously described, we have:

$R_1 = 400\,(1 - K)$ ohms $= R(1 - K)$
where K = fraction that R_1 is lower than R_2.
$R_2 = 400$ ohms $= R$
$R_3 = R_4 = 2800$ ohms
$= 7R$ (for a particular 50 kc bar)
$R_6 = 800$ ohms $= 2R$ (very nearly)
$R_5 = 1$ megohm $= 2500\,R$
$Q = 100{,}000$
$\mu_a = 300 \qquad \Delta\mu_a = \pm 30$ (10%)
$\theta = 0 \qquad \Delta\theta = \pm 0.1$ radian.

For the bridge constants we get, in terms of R = resistance of the fixed ratio arm:

$A = 17500 R^3 K$ where $R_1 = R(1 - K)$
$B = 17500 R^3$
$M = 150240 R^3$
$N = 70217 R^3$

Inserting these in (16) and (17), we obtain:

$$\left.\frac{df}{f_0}\right|_{\theta} = \frac{4.29 d\theta}{Q(\mu_a + 4.01)} \qquad (18)$$
$$= +1.5 \times 10^{-8}$$

for

$\Delta\theta = +0.1$ and $\mu_a = 300 - 30 = 270$,

and

$$\left.\frac{df}{f_0}\right|_{\mu a} = -\frac{4.29\theta d\mu_a}{Q(\mu_a + 4.01)^2} \qquad (19)$$
$$= +1.7 \times 10^{-9}$$

for $\Delta\mu_a = -30$ and $\theta = +0.1$; this reduces to zero if there is no amplifier phase-shift ($\theta = 0$).

These results indicate that a change of amplification of 10% produces only 2 parts in a billion change in frequency in the presence of an amplifier phase-shift of 0.1 radian (6 degrees). If the amplifier phase-shift is made smaller, this change is correspondingly reduced. Changes in phase of the amplifier will produce 2 parts in one hundred million change in frequency, for a phase variation of 0.1 radian (6 degrees), with the gain at its subnormal value of 270.

The results also show that for best performance the phase-shift of the amplifier should be kept as small as possible, the gain should be high, and the *Q* of the crystal should be high. The values given above are readily realizable in practice; in fact, substantially higher gains and higher *Q*'s can easily be obtained, resulting in better performance than that outlined here. — J. K. CLAPP

COVER PHOTOGRAPH

● **NUCLEAR DISINTEGRATION,** or atom-smashing, has been made possible largely by the development of the cyclotron, which produces high-velocity particles without the use of correspondingly high voltages. The acceleration necessary to produce the desired velocities is imparted to the ions by radio-frequency fields. The production of the radio-frequency energy and its transfer to the dees, or accelerating electrodes, is mainly a radio engineering problem.

The photograph on the front cover, taken at the Massachusetts Institute of Technology, shows the TYPE 821-A Twin-T Impedance-Measuring Circuit and the TYPE 605-B Standard-Signal Generator being used to measure the admittance of the transmission lines which couple the radio-frequency-oscillator to the dees.

Rapid progress is being made in cyclotron development in many laboratories, and designs are changed frequently. The lines shown in the cover photograph are part of an older model. An interesting paper on the present M. I. T. cyclotron appears in the *Journal of Applied Physics*, Volume 15, Nos. 1 and 2, January and February, 1944.

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