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How to make a highly accurate clock that utilizes tunnel diodes

Conducted by C. L. Stong

Anyone can now build an electronic chronometer roughly the size of an alarm clock that will keep time within five seconds per year and run for months on a single mercury battery. The construction is made possible by tunnel diodes, the semiconductor device first described five years ago by the Japanese physicist Leo Esaki. Except in its use of semiconductors, the new chronometer closely resembles the quartz crystal clocks described earlier in this department; its hands are turned by a synchronous motor that operates on a submultiple frequency of alternating current derived from a crystal-controlled oscillator [see "The Amateur Scientist," September, 1957, and June, 1961]. The instrument was designed by R. L. Watters of the General Electric Research Laboratory, primarily to demonstrate the usefulness and reliability of tunnel diodes.

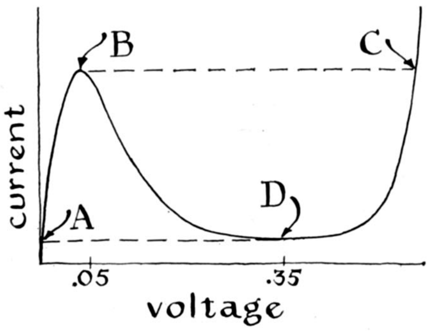
"For reasons not altogether clear," writes Watters, "tunnel diodes have not been greeted with enthusiasm by experimenters, in spite of the fact that when they are supplied with less than a thousandth of a watt, they can function as amplifiers, oscillators and switches through an impressively broader range of frequencies than vacuum tubes or transistors can. Part of the explanation may lie in their strangeness. They have only two terminals compared with the three or more of vacuum tubes and transistors. The techniques of using them differ accordingly. Moreover, the notion seems to have got around that tunnel diodes are not so reliable as the older devices. My experience in applying them to timing devices and similar apparatus that make rigorous demands on reliability does not support this. When used as interlocked oscillators for lowering the frequency of alternating current, for example, tunnel diodes are at least an order of magnitude better than multivibrators employing vacuum tubes or transistors. Any slight change in temperature or abrupt disturbance in the supply voltage to a vacuum tube multivibrator designed for dividing a frequency by 10, for example, may cause the unit to start dividing by 9 or 11. Tunnel diode oscillators divide by 20 routinely and during some experiments have operated without error for hours while dividing by a factor of 100! For this reason tunnel diodes have found an ideal application in clocks of the Marrison type for reducing the high frequency of the crystal-controlled oscillator to the low frequency required by the synchronous motor. The construction of such a clock can serve as a good introduction to these new circuit elements and perhaps suggest other applications for their remarkable properties.

"Like all rectifying devices, including check valves in water pipes, tunnel diodes conduct differently in different directions. They exhibit their most interesting property when conducting in the forward direction. A small voltage must of course be present to induce current in the forward direction, just as some pressure must be applied to force water through a check valve. In a typical tunnel diode the current increases as the applied potential is increased from zero up to .05 volt. As the voltage is increased from .05 volt to .35 volt, however, an astonishing effect is observed: the current decreases! Conversely, as the voltage is lowered through this range, the current increases, an effect that one would expect only if the circuit contained a generator or other source of electrical energy.

"Esaki explained this phenomenon in terms of the tunnel effect, a theoretical concept introduced to describe the behavior of an electron that does not have enough kinetic energy to penetrate an electric field but nonetheless manages to 'tunnel' through the barrier. The potential barrier is imagined as a hill and the electron as a wave that extends through the hill but decreases sharply in amplitude. The resulting shape of the wave is interpreted as meaning that the electron gets through the hill without having been pushed over it. The effect of positive and negative resistances associated with tunnel diodes is shown by the accompanying graph [*top of next page*], in which increasing current is plotted upward on the vertical co-ordinate and increasing voltage from left to right on the horizontal co-ordinate. Observe that as the voltage increases from zero the current rises to point *B*, as one expects of ordinary circuits. From .05 volt to .35 volt, however, the current drops to *D*, in apparent defiance of Ohm's law. Beyond .35 volt the current again increases with increased voltage.

"If the diode interposed no positive resistance, the current would increase without limit, independent of the voltage, and the absence of resistance (zero resistance) would be represented by the vertical co-ordinate of the graph. Similarly, if the diode behaved as an infinitely high resistance, or open circuit, the graph would coincide with the horizontal co-ordinate. Intermediate values of resistance would be plotted as straight lines at intermediate angles, their slope representing the resistance. In this graph the continuously changing slope indicates how the resistance of the tunnel diode changes with applied voltage. At the origin of the co-ordinates (no voltage applied to the diode) the graph rises almost vertically, indicating that the diode has little resistance. At points *B* and *D*, representing applied potentials of .05 and .35 volt respectively, the graph becomes horizontal, indicating infinite resistance. The upward slopes from *A* to *B* and from *D* to *C* indicate the ranges of applied voltage through which the diode exhibits finite values of positive resistance, and the downward slope from *B* to *D* represents the voltage range through which the tunneling effect and phenomenon of negative resistance appear.

"Any device characterized by nega-



Graph of tunnel diode characteristics

tive resistance, whether electrical or mechanical, can be made to generate oscillations if it is coupled to a resonator. In the electrical case this could be a capacitor connected to an inductance; in the mechanical it could be a flywheel linked to a coiled spring. Even short lengths of wire act as small inductances as well as small resistances; adjacent parts of even the simplest circuit constitute a capacitor. Indeed, the simplest tunnel diode oscillator consists of nothing more than the diode, a battery and a rheostat [*see bottom illustration on this page*].

"Assume that such an apparatus has been assembled and that the rheostat has been adjusted so that the average voltage across the diode corresponds to a point on the horizontal co-ordinate of the first graph between *B* and *D*. At the moment the battery is connected the voltage will start to rise across the diode. The rise will not be instantaneous, because a portion of the energy will appear in the form of a growing magnetic field around the conductors. As the portion of the voltage that appears across the diode rises, current will increase to *B*. At *B* the diode becomes an infinite resistance and the voltage across it rises instantly to point *C*, as indicated by the upper broken line in the graph. The magnetic field surrounding the conductors then starts to collapse and generates an opposing potential that in effect gradually lowers the voltage across the diode at a rate indicated by the graph between *C* and *D*. At *D* the negative-resistance effect appears, the voltage across the diode drops abruptly to *A* and the next cycle begins.

"The action can be observed by connecting the vertical electrodes of a cathode-ray oscilloscope across the diode and the horizontal electrodes to an oscillator for sweeping the beam of the oscilloscope across the screen at a uniform rate and in synchronism with the oscillating diode. When the oscilloscope is properly adjusted, the resulting pattern resembles a Z drawn with a vertical rather than a diagonal stroke. The upper bar of the Z represents the time that the diode spends in the high-voltage state, as indicated by the region from *C* to *D* of the graph. The vertical bar of the Z represents the instant at which the voltage snaps from *D* to *A*, and the lower bar the time spent by the diode in the region of positive resistance between points *A* and *B* [*see illustration on opposite page*].

"The frequency at which a tunnel diode oscillates this circuit is determined by the resistance of the total circuit, the included inductance and the magnitude of the battery voltage. The trick in applying tunnel diodes as oscillators consists mostly of connecting a resonant circuit of the desired frequency to the diode and suppressing the influence of those parts of the circuit that resonate at unwanted frequencies. The components used in the chronometer, their physical placement on the chassis with respect to one another and the shielding that surrounds them were all selected to accomplish this objective.

"The circuit of the chronometer consists of three sections: the crystal oscillator, frequency dividers and the power amplifier, together with its associated motor. The components are appropriate for use with either a 100-kilocycle or a 120-kilocycle quartz crystal, except that each crystal requires a minor change in the oscillator circuit. Moreover, a 50-cycle motor must be used with the 100-kilocycle crystal and a 60-cycle motor with the 120-kilocycle crystal.

"A sheet-metal chassis some six inches square and two inches high accommodates all wiring and circuit components. I combined two units measuring 6½ by 3⅛ by 1½ inches, but a single one of adequate size that provides *complete* shielding from external electrical disturbances will suffice. Power for driving the motor is provided by a transistor amplifier that is mounted on the terminal board of the motor. The accompanying circuit diagram and photograph show the wiring and the physical arrangement of the parts [*see pages 160 and 162*].

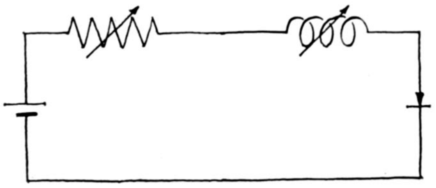
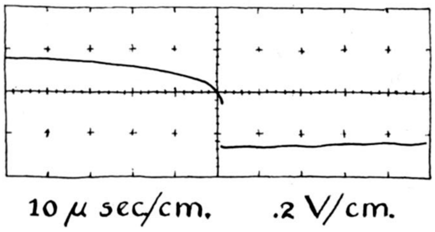


Diagram of tunnel diode oscillator



Oscilloscope pattern of oscillating diode

"The accuracy of the chronometer depends on the performance of the quartz crystal. For maximum frequency stability the crystal should not be subjected to wide variations in temperature. Preferably one should use a vacuum-mounted GT-cut quartz crystal that has been aged, such as those manufactured by the Northern Engineering Laboratories of Burlington, Wis. Vacuum-mounted DT-cut crystals are less expensive and may be substituted. When using a suitable DT-cut crystal, one can expect a frequency change of about one part per million for a 10-degree-centigrade temperature change. Other electrical properties of quartz crystals, such as the equivalent series-resonant resistance, are important in this application; this article should therefore be mentioned when the reader is ordering a crystal for use in the chronometer.

"The schematic diagram shows one small fixed capacitor and two small variable capacitors connected to one side of the crystal, a total of 110 micromicrofarads that can be increased or decreased through a range of about five micromicrofarads in either direction. The combination serves as the load capacitor and is appropriate for a GT-cut crystal. For a DT-cut the five-micromicrofarad range is inadequate. It can be increased by substituting a trimmer capacitor of wider range such as a JFD VC-23G. If this expedient proves to be inadequate, small fixed capacitors can be added as required. Small changes in the frequency of the crystal are made by altering the setting of the trimmer capacitors. They serve as the fast-slow adjustment of the chronometer.

"The clock motor operates on less than 300 millionths of a watt. It is the modest power requirement of this motor that enables the clock to operate for six months on a fresh mercury battery. If extended battery life is not a consideration, the experimenter may substitute a conventional two-watt clock motor by adding an appropriate transistor amplifier to the output. Orders for the low-power motor should be addressed to the attention of J. H. Robinson, Clock and Timer Department, General Electric Company, Ashland, Mass.

"The assembled clock is placed in operation by adjusting the several circuits so that the motor runs on the desired submultiple of the crystal frequency and indicates the correct time. The tools for making the adjustments include two milliammeters, one of which indicates two milliamperes full scale and the other one milliampere; a high-impedance voltmeter calibrated to indicate about two volts full scale; a 1.5-volt dry cell; an oscilloscope (preferably calibrated); a 5,000-ohm, 10-turn helipot; a 1,000-ohm variable resistor and an assortment of clip leads.

"Proper voltages (biases) are first applied to the diodes, and the frequencies of the oscillators that function as frequency dividers are adjusted to the desired values. In the case of a chronometer that operates from a 100-kilocycle crystal oscillator, the first divider oscillator is designed to operate just below 10,000 cycles per second. When the high frequency of the crystal unit is coupled to this tunnel diode, every 10th pulse from the crystal arrives just in time to advance the action of the diode slightly and thus force it to oscillate precisely 10,000 times per second. Similarly, the output of the 10,000-cycle unit is superimposed on the succeeding diode, which in the absence of external disturbance is designed to operate just below 1,000 cycles per second. The remaining stage is similarly interlocked to its predecessor and reduces the frequency to 50 cycles per second.

"To make the required adjustments disconnect the battery lead from the motor and the 2.5-millihenry choke from the transistor. Connect a clip lead across the oscillator tunnel diode. Set the 100-ohm variable resistors in the divider circuits at maximum resistance. Replace the mercury battery with the 1.5-volt dry cell in series with the two-milliampere milliammeter and the helipot, set at maximum resistance. With the oscilloscope connected between the ground and point A, as indicated in the circuit diagram, adjust the first divider so that it spends half of the operating period in the high-voltage condition. The adjustment is made by lowering the settings of the 100-ohm variable resistor and the helipot. This is a matter of trial and error. The desired oscilloscope pattern is shown in the accompanying illustration [*page 159*]. The second and third dividers are similarly adjusted. Then, using the calibrated sweep rate of the oscilloscope to measure the time, adjust the period of the first divider circuit to about 100 microseconds by altering the setting of the 13-to-25 microhenry inductor and similarly adjust the inductors of succeeding divider circuits for ratios of 10:1 and 20:1. The latter ratio is associated with the UTC choke.

"The division ratios are determined simply by counting the number of pulses displayed by the oscilloscope. The UTC choke requires extra attention. If it is adjusted from a low value upward, a mechanical shock will increase its inductance. Similarly, if it is adjusted to a low value, a mechanical shock will decrease it further. For proper adjustment the knob of the unit should be rotated plus and minus 10 degrees on each side of the desired value and then gradually centered. Two expedients are available if the highest setting of the UTC inductor is inadequate. First, select for this func-

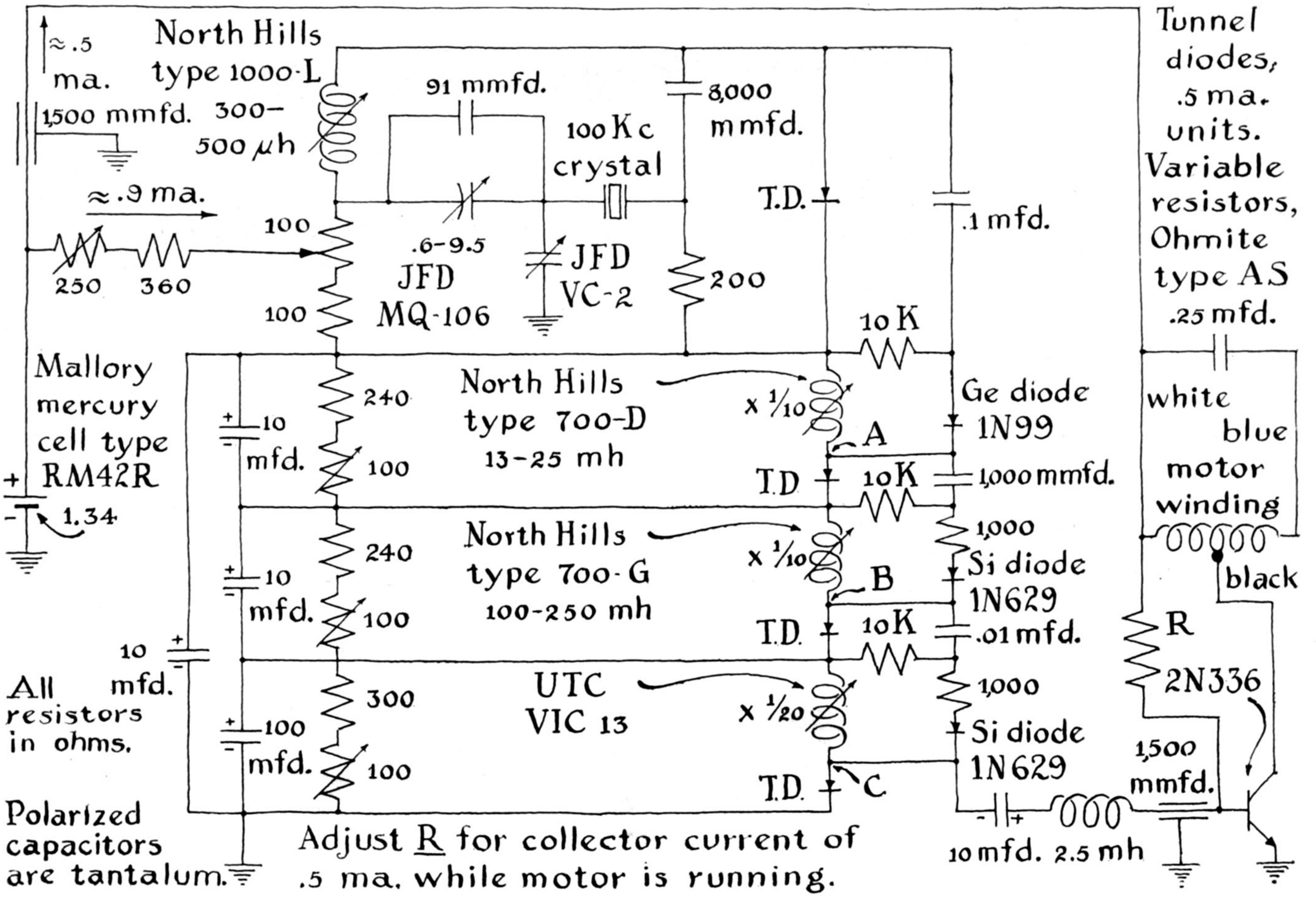
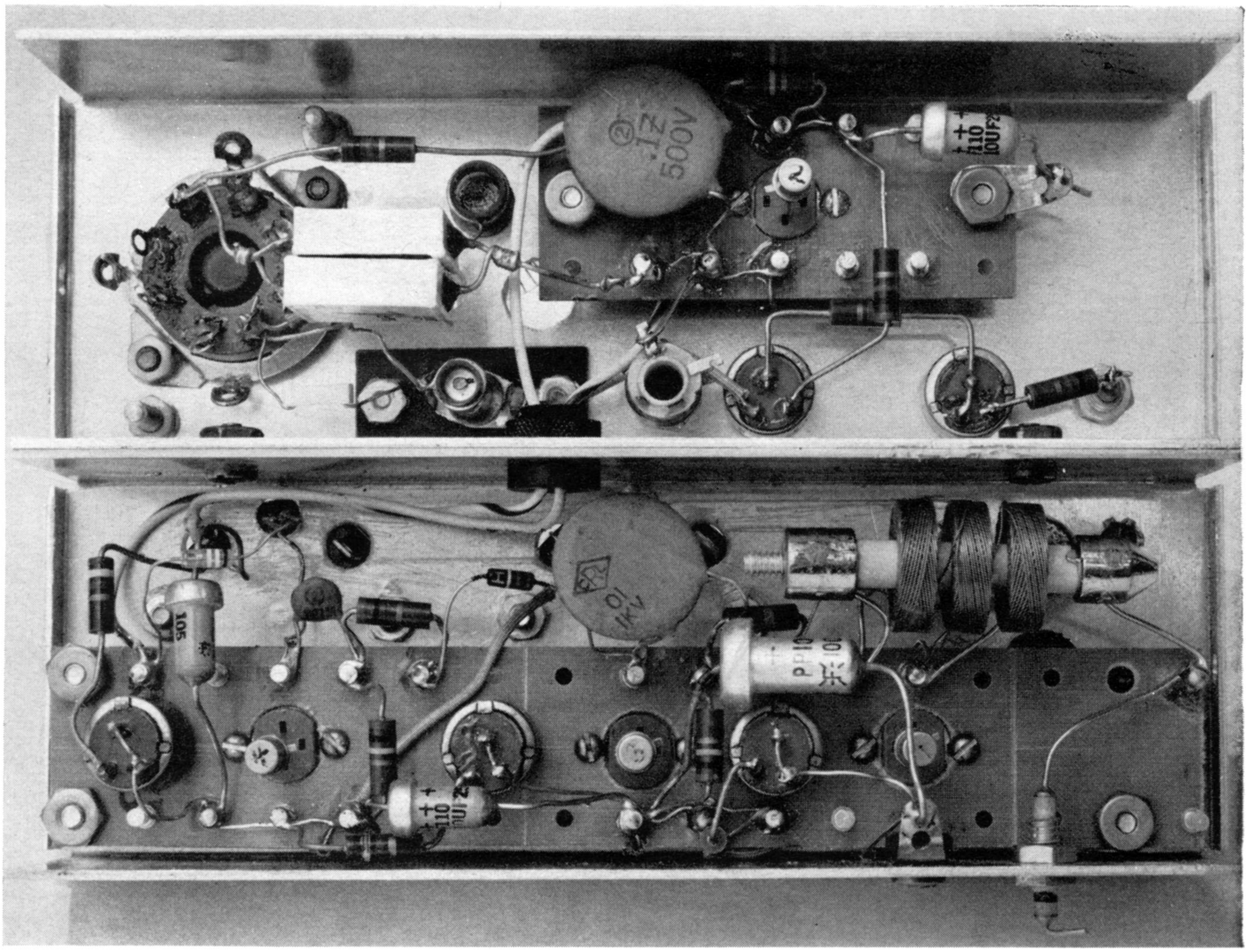


Diagram of the tunnel diode clock circuit tion the tunnel diode that is marked with the highest current value by the manufacturer. (These tunnel diodes come so marked.) Then, if the unit still refuses to operate properly, replace the 1,000-ohm resistor that is connected to the associated IN629 diode with a resistor of higher value, up to 7,500 ohms, but do not use more resistance than is necessary.

"Vary the helipot and note the current range through which the correct frequency ratios obtain. The sequence of adjustments of the inductors and the 100-ohm resistors should be repeated until the current range for proper operation of the last two counters is a maximum. Record the current range (.85 to one milliampere) as well as the current required for the 50 per cent duty cycle (.95 milliampere). This information is essential for making subsequent adjustments.

"Next, disconnect the 1.5-volt dry cell and reset the helipot to maximum resistance. Remove the clip lead that was across the oscillator tunnel diode and connect it between the ground and the junction of the 100-ohm and 200-ohm fixed resistors in the oscillator circuit. This short-circuits all the divider circuits. Set the 300-to-500 microhenry inductor at minimum inductance. Connect the oscilloscope between the ground and the junction between the oscillator tunnel diode and the 8,000-micromicrofarad capacitor. Reconnect the battery and adjust the helipot and the 100-ohm control in the oscillator circuit so that the oscillator is running and draws the same current (.95 milliampere) as was recorded for the 50 per cent duty cycle. Again vary the helipot and note the current range for oscillation. This should easily bracket the divider-current range (.85 to one milliampere).

"Disconnect the dry cell, remove the clip lead and connect a high-impedance voltmeter across the battery input terminals. Reconnect the 1.5-volt dry cell and adjust the helipot and the 250-ohm variable resistor so that voltage at the battery input terminals is 1.35 volts and the current is that corresponding to a 50 per cent duty cycle (.95 milliampere) in the dividers. Make sure that the crystal oscillator is operating. The three divider inductors should be trimmed to maintain the proper division ratios while the input voltage is decreased by increasing the resistance of the helipot. Now adjust the 250-ohm resistor and the helipot so that the input voltage indicated is again 1.35 volts but the current is larger (although somewhat less than the maximum for proper operation). Connect the 2.5-millihenry choke to the transistor. Connect the motor circuit to a separate mercury battery in series with the one-milliampere milliammeter and the 1,000-ohm variable resistor, set at zero resistance. Select a biasing resistor (*R*) for the transistor so that the motor draws approximately .5 milliampere while running. The required resistance will be on the order of 40,000 ohms. Doubtless it will be necessary to readjust the 100-ohm resistor in the 20-



Chassis of the clock seen from below

to-1 divider circuit so that the associated tunnel diode spends half of its time in the high-voltage condition, as it did before the transistor was connected. Remove the temporary power supplies and reconnect the motor circuit. Install the mercury battery. (Incidentally, I use two battery holders so that a battery can be replaced without stopping the chronometer.) If the quartz crystal oscillator does not start, it may be necessary to adjust the 250-ohm variable resistor. After the crystal goes into operation the resistance is promptly restored to its former value.

"The chronometer will now run when the 'start' control of the motor is operated. After the hands have been set to the correct time and the rate of the crystal oscillator has been regulated, the instrument is ready for service. The rate should be adjusted first. The 5,000-kilocycle carrier frequency that is broadcast by the National Bureau of Standards' radio station WWV can be used as a reference. A signal from the crystal oscillator can be picked up by inserting a small coil consisting of a few turns of magnet wire through the hole in the chassis near the oscillator coil. The output of this coil is amplified to drive a frequency multiplier set for the 50th harmonic. The output frequency of the multiplier will be close to 5,000 kilocycles. It is mixed with the incoming signal of WWV

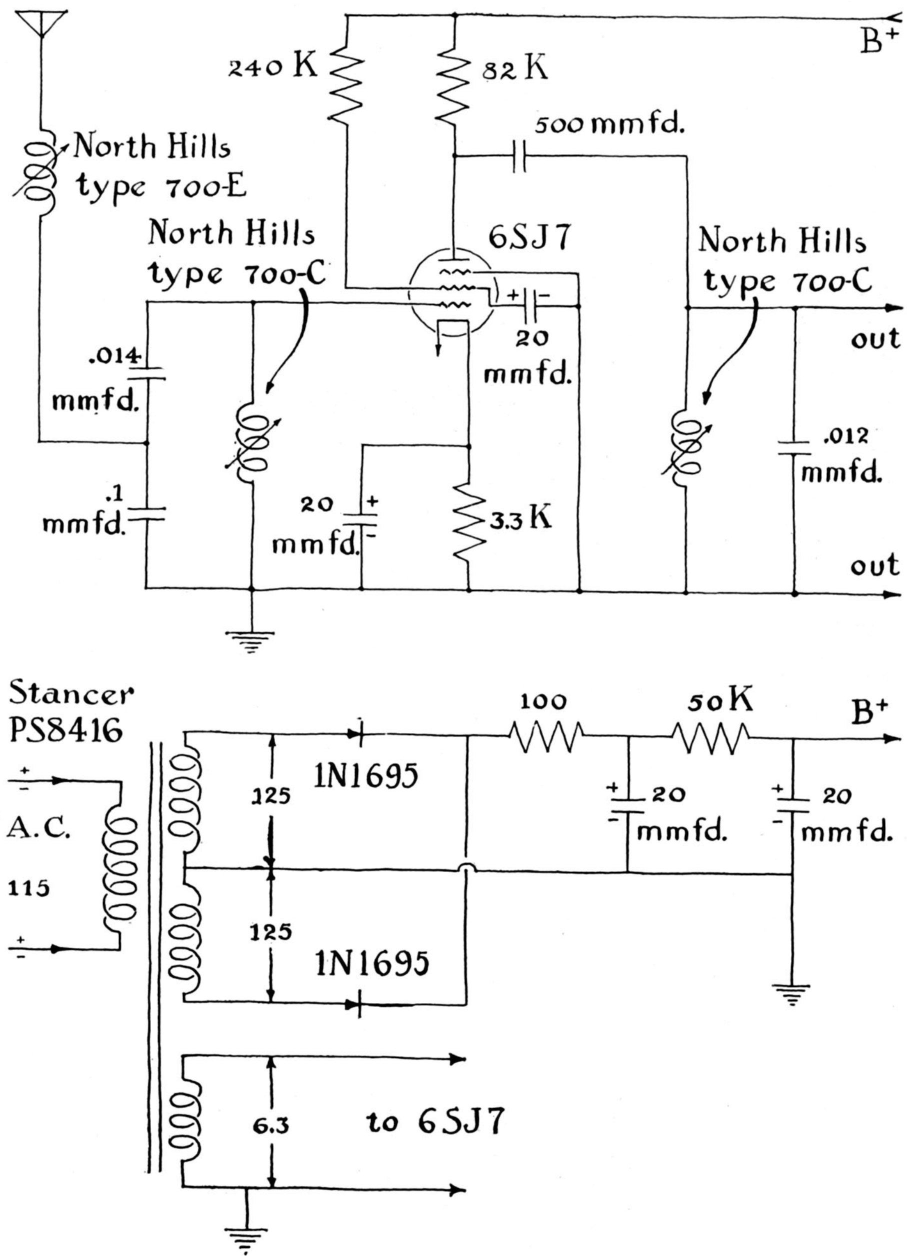
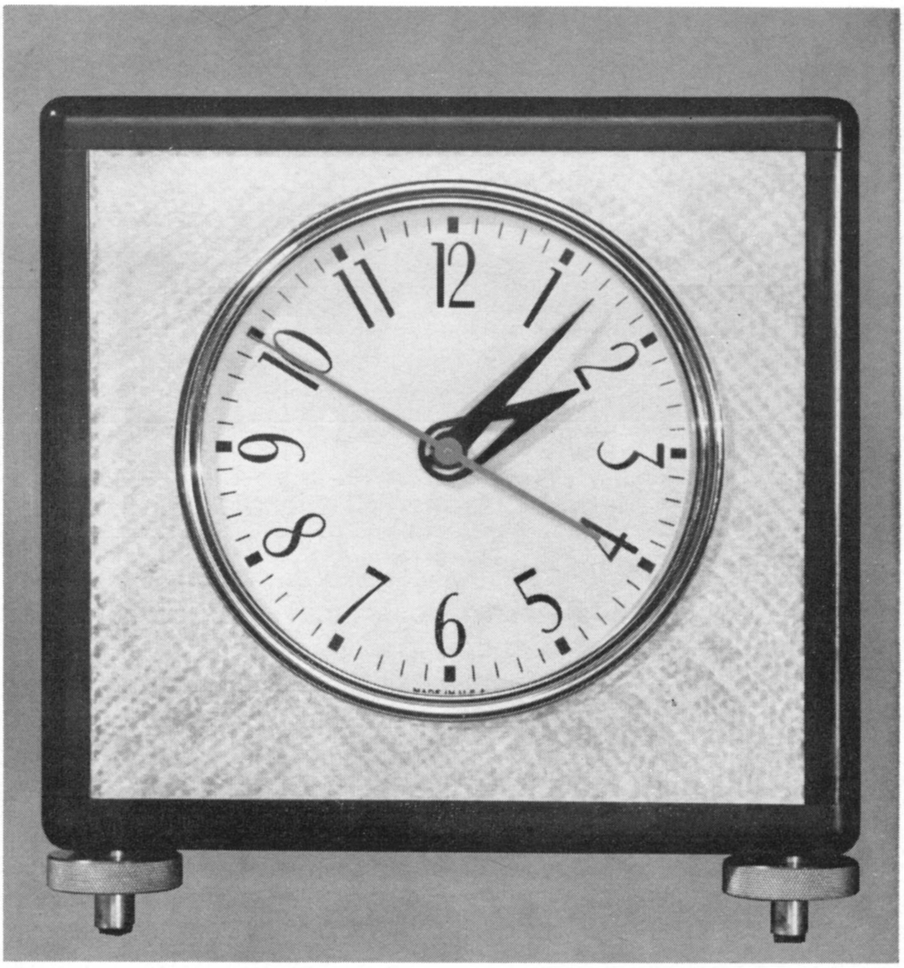


Diagram of circuit for clock radio receiver and the resulting beat frequency is observed on an oscilloscope. Adjust the oscillator for zero beat with the carrier frequency. At Schenectady, N.Y., it is possible by this method to regulate the chronometer to within a few parts in 10 million of the WWV signal.

"I usually start the chronometer so that the second hand is about five seconds ahead of the seconds signal of WWV. Then, by temporarily decreasing the setting of the 250-ohm variable resistor (the resistor connected in series with the battery), the last frequency divider is made to operate at a division ratio of 21 to 1 instead of 20 to 1. When the second hand falls into step with the correct seconds signal, the resistor is quickly restored to its former setting. A word of caution: The gears of the motor have some backlash, so always read the time at the same second each minute. I make adjustments just as the second hand crosses 12.

"The carrier frequency received from WWV at locations more than 100 miles from the transmitter are subject to unpredictable error. The signal is received after one or more reflections from the constantly moving ionosphere and the frequency is accordingly altered by a Doppler shift. Some of the very-low-frequency radio stations maintained by the Navy blanket the nation with direct signals unaffected by the ionosphere and regulated to the same accuracy as WWV. Stations such as NAA at Cutler, Me. (14.7 kilocycles), and NSS at Annapolis, Md. (22.3 kilocycles), are examples. They can be picked up by means of a single-tube receiver [*see illustration on page 164*]. The frequency of these stations is evenly divisible by 50. The triggered horizontal sweep of the oscilloscope can therefore be synchronized with the chronometer output frequency for displaying the radio signal on the screen. Zero beat is indicated when the oscilloscope pattern stands still.

"A somewhat more formal paper that supplements this account of the chronometer is now available. Requests for copies should be addressed to: R. L. Watters, Semiconductor Studies, General Electric Company, P.O. Box 1088, Schenectady, N.Y."



The clock as it appeared after its completion