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Accutron—A Chronometric Micro-Powerplant

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SOCIETY OF AUTOMOTIVE ENGINEERS

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ACCUTRON MASTER TIMER FOR MOON PACKAGE

NEW YORK, April, 1969 — A programmed long-duration Accutron master timer is part of the Early Apollo Scientific Experiments Payload (EASEP) to be landed on the Moon by the first United States astronauts to reach the lunar surface.

EASEP, which includes two scientific experiments systems, the Passive Seismometer and the Laser Ranging Retro-Reflector, is scheduled to be carried to the moon by the Apollo 11 mission, tentatively planned for July launch from Cape Kennedy.

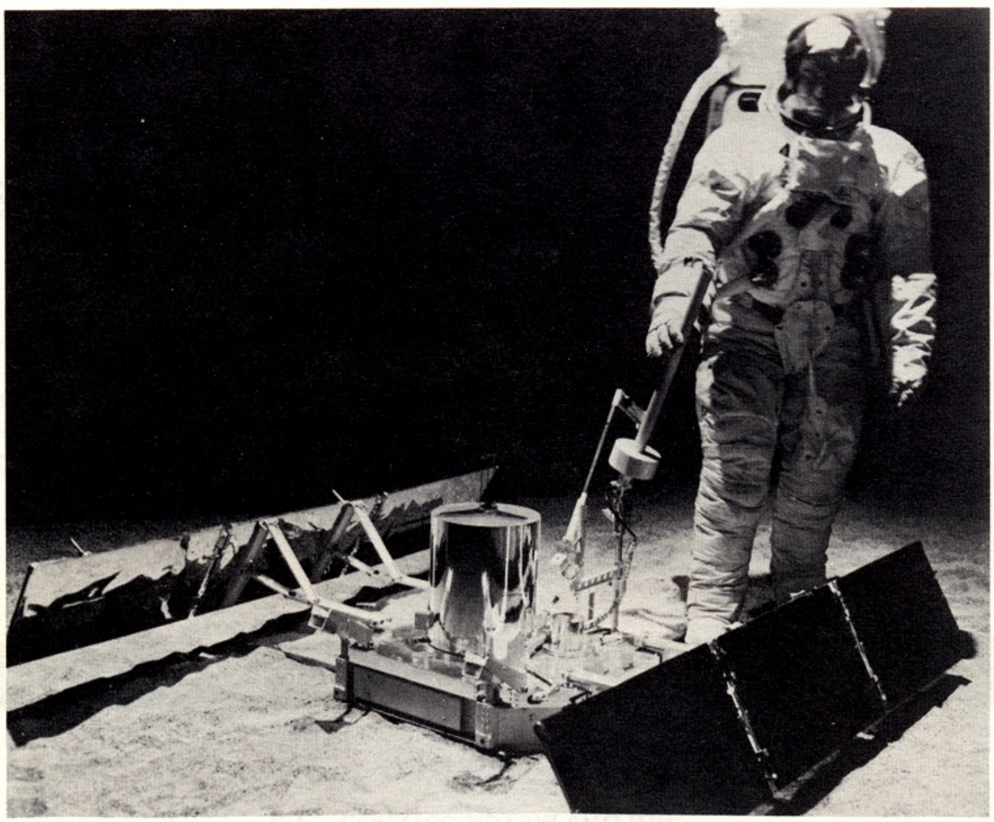
The master timer, which employs a 360-cycle tuning fork as its time base, is incorporated in the 100-pound Passive Seismometer "package", a self-contained seismic station equipped with panels of solar cells and its own radio transmitter. On the moon, the Passive Seismometer will detect and report the slightest movements of the lunar crust as well as "moon-quakes" caused by motions of the moon's interior.

The Accutron timer, which is independently powered by tiny mercury oxide cells, will be programmed to trigger shut-offs and other pre-scheduled events over a 12-month period, according to Egbert Van Haaften, director of Bulova Watch Company's Timer Laboratory.

He said that EASEP is less complex than the Apollo Lunar Surface Experiments Package (ALSEP), a full geophysical station to be placed on the moon by the second and third manned moon-landing missions of the National Aeronautics and Space Administration's Project Apollo.

Both ALSEP and EASEP were developed, designed and built by the Bendix Aerospace Systems Division and both incorporate Accutron long-duration master timers, he pointed out.

"Different configurations of Accutron tuning-fork timers, clocks and switches have been ordered for and successfully used by NASA's space program, starting in 1958," Van Haaften said. "Consequently, we are especially proud that our Accutron timers will be among the first American equipment to be landed on the moon by Apollo astronauts."



ON THE MOON — The deployment of the astronauts' training model of EASEP's Passive Seismometer shows how an astronaut on the Moon will emplace the self-contained seismic station equipped with an Accutron master timer. EASEP is powered by panels of collapsible solar cells. It is designed to report the Moon's seismic conditions via radio broadcasts for 12 months after the astronauts have returned to Earth. Consequently the long-duration master timer will be programmed to trigger shut-offs and other events throughout that period.

Accutron® — A Chronometric Micro-Powerplant

William O. Bennett
Bulova Watch Co., Inc.

ACCUTRON* WRIST TIMEPIECE MECHANISM

Tuning Fork - The greatest difference between Accutron timepieces and conventional watches lies in the use of a tuning fork in place of a balance wheel and hairspring as the time standard. The Accutron tuning fork is shown in Fig. 1. This part is more complex than tuning forks employed for other purposes, as can be seen from the photograph. Its application to a wrist timepiece is responsible for its relatively complex construction since it must have unusual characteristics to permit exposure to a wide variety of environmental conditions. Furthermore, it must be relatively small for installation in a mechanism which must fit within a conventional man's wrist watch case.

This tuning fork would be classified as the weighted type, because of the mass attached to the end of each tine. These two masses constitute the permanent magnet portions of the electrodynamic transducer system employed to drive the tuning fork and control its amplitude. These masses are so mounted that their centers of gravity are directly above the constricted sections of the tines adjacent to the base of the fork. This results in the horizontal velocity vectors of the two masses being substantially in the same line, thereby reducing the amplitude of the vertical component of vibration of the tuning fork on its mounting plate to a minimum.

Tuning forks normally have straight tines. As shown on Fig. 1, this fork has a "knock-kneed" appearance, resulting from the inward bow of each tine. One tine is bowed to economize on space by permitting the cylindrical power cell or battery to intrude upon the space nominally occupied by the tuning fork, without touching the adjacent tine. The other tine is curved for symmetry. Unlike most tuning forks, which usually employ a mounting extending beyond the base of the fork, the mounting stem by which the Accutron tuning fork is attached to the pillar plate extends inwardly between the tines. This inward stem not only economizes on space for the fork but brings the mounting member as close as possible to the vibrating masses, thereby providing optimum decoupling between tuning fork and pillar plate for a given mounting elasticity. In addition, there is a clearly visible constriction in the mounting stem at the point where it joins the fork base. This constriction is of sufficient stiffness to maintain the fork in proper alignment, yet decouples the tuning fork base sufficiently from the mounting plate as to eliminate any effects of unavoidable small differences in frequency between the tuning fork tines. Without the elastic decoupling provided by this mounting system, the timepiece

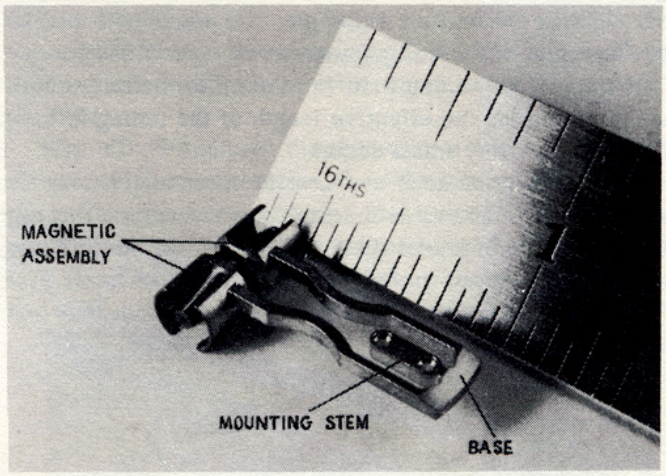


Fig. 1 - Accutron tuning fork

*Registered trademark, Bulova Watch Co., Inc.

ABSTRACT

This paper describes the Accutron mechanism, its construction and functioning. It is characterized by a tuning fork, electromagnetically driven with energy from an electrochemical cell, or battery, by means of a transistorized electronic circuit. Vibratory motion of the tuning fork is converted into rotary motion, to drive a series of gears. It can be used as a chronometric motor for applications where low speed, tiny size, and power output of the order of microwatts can be obtained. One example is the use of the basic Accutron movement, supplemented by suitable gearing, to perform switching functions in certain satellites months or years after launching, at a time which is preset on suitably calibrated dials.

rate would be affected by being placed on surfaces reflecting different amounts of restraint to the assembly.

The mechanical design of these tuning forks requires careful calculation to avoid overstressing of the material, with resulting fatigue effects and drifting of tuning fork frequency with time. Careful design and control of manufacturing processes have resulted in tuning forks which have a drift in frequency less than 10 ppm/year -- well under 1 sec per day. Changes of fork frequency due to variations in temperature is avoided by the use of NiSpan-C, a precipitation hardened nickel alloy having a thermoelastic coefficient which can be made substantially zero over a fairly wide range of temperatures, by proper processing and heat treatment. This material is further characterized by low elastic hysteresis, resulting in a tuning fork requiring minimum power for its operation.

The Accutron mechanism was designed for use as a wrist timepiece. While the frequency of the Accutron tuning fork is far less affected by the wearers' habits and by the condition of lubrication in the movement than the frequency of the best balance wheels and hairsprings, provision must nevertheless be made for field correction of tuning fork rate. Such corrections rarely exceed several seconds per day and a very simple calibrated regulating system on the tuning fork itself provides the necessary small range of adjustment. The regulating system is shown on Fig. 2.

Each tuning fork tine is provided with a regulator, held friction tight by a riveted attachment on the magnetic element. The visible serrations on each regulator serve as calibrations for observing the amount of rotation of these regulators and also provide convenient means for rotating each, against the friction which prevents accidental rotation. Rotation of these regulators moves a small portion of the mass of the tuning fork, in relation to the tuning fork base, thus making the effective length of the tuning fork adjustable to a very small degree.

The serrations on each regulator form seven divisions (four projections and three indentations). Moving either regulator the width of one of these divisions alters the tuning fork frequency 23 ppm, resulting in a rate change of 2 sec /day. Rotation away from the tuning fork base causes an effective lengthening of the tine and results in a decrease in tuning fork frequency. For rate changes of a few seconds per day it is satisfactory to move only one regulator. For larger corrections in rate, both elements should be adjusted to avoid unbalancing the tuning fork tines.

Fig. 3 shows the arrangement of the tuning fork with associated electronic circuit as mounted on the pillar plate of the timepiece movement. The view shown is from the dial side. The tuning fork is caused to vibrate continuously by means of the electronic circuit which meters driving current pulses to the transducer system, energy being supplied by a self-contained power cell or battery, not visible in this picture. The tuning fork vibrates at its natural frequency of 360 cps, at a fixed amplitude established by the system parameters. All circuit elements and connections are mechanically attached to two complex plastic molded parts. These two coil form assemblies are joined by three wires, passing under the base of the tuning fork, and constitute a complete module which can be replaced in the field if circuit trouble is experienced, since field repair of the circuit elements is not practical.

Vibratory-To-Rotary Motion Conversion - The vibratory motion of the tuning fork is converted into rotary motion for turning the hands, by a ratchet and pawl system of simple construction. Fig. 4 shows the arrangement of the essential parts of the indexing mechanism, from the train (or rear) side of the movement. One tine of the tuning fork has attached to it a straight spring tipped with a tiny jewel which engages ratchet teeth on an "index wheel," advancing this wheel one tooth for each complete oscillation of the tuning fork. A pawl holds the index wheel in position during the return stroke of the index jewel. The pawl finger and jewel are similar to the index finger and jewel, except that the pawl finger is attached to the pillar plate of the movement. The shaft of the index wheel is provided with a pinion for turning the timepiece hands through a suitable train of gears.

The use of a ratchet and pawl mechanism to obtain rotary motion from oscillatory motion is, of course, not new. Nevertheless, the design and construction of a ratchet and pawl system to meet the requirements of the Accutron device

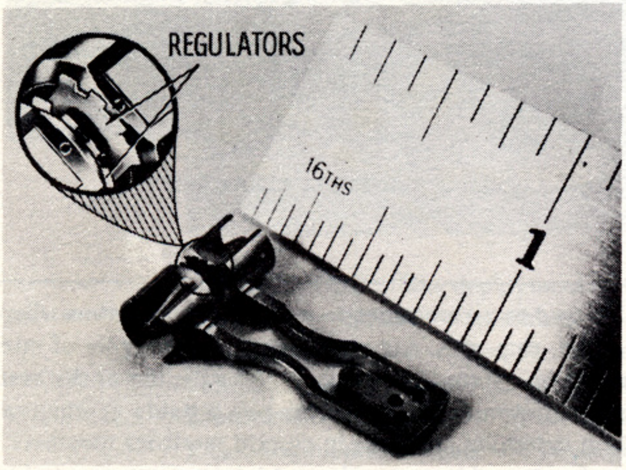


Fig. 2 - Tuning fork showing regulator enlarged

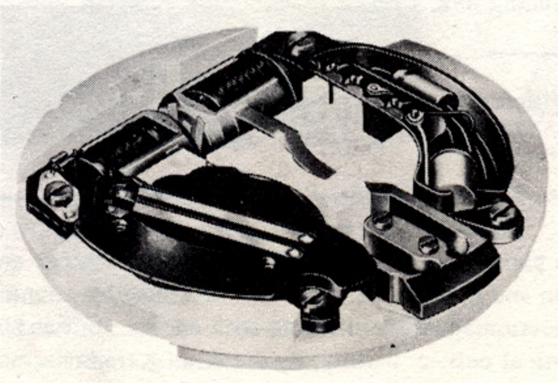


Fig. 3 - Tuning fork and associated circuit elements

presented several interesting and challenging technical problems:

1. Absolute synchronism between tuning fork vibrations and index wheel revolutions must be maintained, unlike many ratchet and pawl applications where varying numbers of teeth may be "gathered" during each cycle of the oscillating mechanism and accurate indexing is not required.

2. Design and construction of the indexing mechanism must provide for reasonable variations in both the stroke and the end points of travel of the indexing jewel, yet advance the index wheel one tooth per stroke, unlike most applications where one or both end points of travel of the indexing ratchet are rigidly fixed by mechanical stops.

3. This indexing mechanism must function reliably and without significant wear at high frequency, specifically 360 times per second (over 11 billion times in a year), as compared with the usual slow moving applications of the ratchet and pawl mechanism.

Unlike conventional watches, the Accutron timepiece owes its accuracy and reliability to basic engineering and design, rather than to the skill of the artisans responsible for producing and assembling the mechanism. Nevertheless, the ingenuity of the design of the Accutron indexing mechanism is frequently lost sight of, in view of the incredibly small parts required in solving the three basic problems outlined above. The index wheel, for example, is only 0.095 in. in diameter and 0.0015 in. thick. It is made of beryllium copper alloy, fully precipitation hardened. This wheel has 300 perfect ratchet teeth, the straight sides of which measure only 0.0004 in. high x 0.0008 in. long. The rectangular index and pawl jewels are of synthetic ruby 0.007 x 0.007 x 0.002 in., polished on all six sides and attached to their supporting spring fingers by heat cured epoxy cement. The spring fingers are about 1/8 in. long, of spring material 0.0006 in. thick x 0.005 in. wide. Although these various tiny elements are easily damaged in handling, assembly, and repair, the indexing mechanism when protected by the timepiece case is rugged because of, not in spite of, the tiny dimensions of the parts involved.

Fig. 5 shows the relationship between the index wheel and the two jewels in contact with it. Also indicated are the forces which result from the preloading of the spring fingers to which the jewels are attached. The spring forces of the index and pawl jewels not only hold them in firm contact with the index wheel teeth, these forces also exert a torque on the wheel in a direction opposite to its forward motion. This tendency to "draw" the index wheel back against one of the jewels is very important to the reliable operation of the Accutron indexing mechanism. In actual practice, each cycle of vibration of the tuning fork causes the index wheel to advance 1-1/2 teeth beyond the initial position, then "draw" back 1/2 tooth for a net advance of exactly one tooth per cycle. Furthermore, the mechanism will tolerate a variation in tuning fork amplitude of about ± 50% before improper indexing occurs. The following discussion will show how this is accomplished.

Fig. 6 is a diagrammatic representation of the dynamic sequence of events in the indexing mechanism, for three widely different amplitudes of vibration of the tuning fork. The mechanism is so constructed and adjusted that, when the tuning fork is at rest, with an index wheel tooth engaged by the pawl jewel (and held there by the "draw" effect described above), the index jewel is located several teeth away in a position halfway between two teeth. The amplitude of travel of the index jewel is conveniently expressed in terms of tooth length. Fig. 6A shows the idle position, as described.

Figs. 6B and 6C show a complete cycle of oscillation at an amplitude of one tooth (1/2 tooth right to 1/2 tooth left of the rest position). In moving to the right 1/2 tooth, the index jewel picks up tooth No. 7, and on its return stroke to the left it drives the wheel far enough for the pawl jewel to drop off the end of tooth No. 2, so that the wheel is advanced one tooth. Further oscillations at the one-tooth level of amplitude would advance the wheel exactly one tooth per cycle.

Figs. 6D-6F indicate the sequence of events at an amplitude of two teeth (one tooth to the left and one tooth to the right of the rest position). The index jewel, in going one tooth to the right, drops off tooth No. 7, and goes halfway along tooth No. 8. On the return stroke, however, the first half tooth of travel accomplishes no movement of the

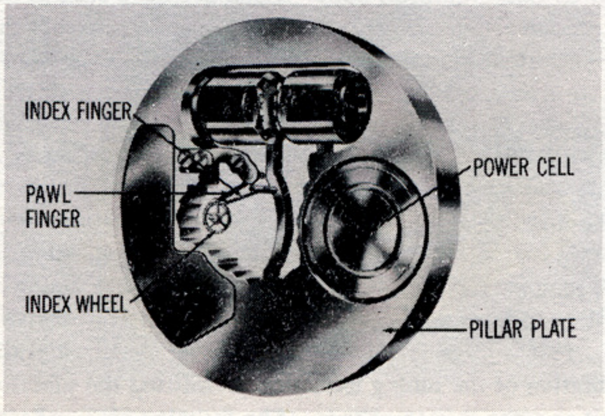


Fig. 4 - Accutron indexing mechanism - (rear view)

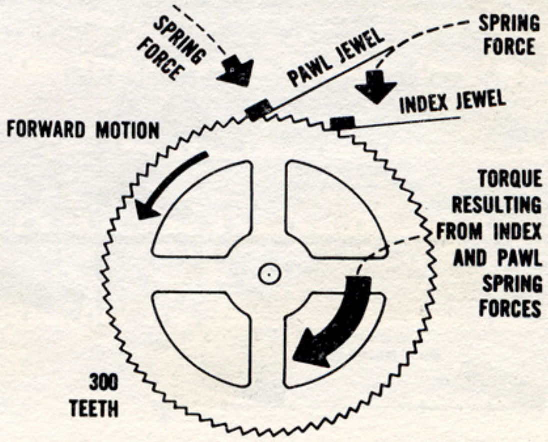


Fig. 5 - Diagram of indexing mechanism

index wheel, since the index jewel does not begin to drive the wheel until it strikes tooth No. 7. In Fig. 6E, tooth No. 2 has passed beyond the pawl jewel; but after the start of the return stroke the "draw" effect exerts torque on the wheel to bring it back 1/2 tooth to the position shown in Fig. 6F. Thus, with a two-tooth amplitude of travel of the index jewel, one tooth rotation of the index wheel results per cycle of oscillation of the tuning fork.

Figs. 6G and 6H show the effect of the three-tooth amplitude. The index jewel, in going to the right 1-1/2 teeth, picks up tooth No. 8. At the other end of the stroke, it has moved tooth No. 8 into the position where tooth No. 5 was. The pawl jewel has dropped off the end of tooth No. 4, resulting in a three-tooth advance of the index wheel.

It can be seen that for any amplitude from just over one tooth to just under three teeth amplitude, the index wheel advances one tooth for each vibration of the tuning fork. When the total travel of the index jewel reaches three teeth on the index wheel, this wheel advances more than one tooth for each tuning fork vibration; in fact, it advances three teeth, and under conditions where the tuning fork reached such an amplitude the hands would advance at three times their proper rate.

The amplitude of vibration of the tuning fork is nominally such that the index jewel travel is about two teeth. From the above discussion it has therefore been shown that the indexing mechanism will tolerate about ± 50% variations in tuning fork amplitude from this nominal value before the timepiece hands fail to advance in exact synchronism with the vibrations of the tuning fork.

One of the less obvious but nevertheless very important adjustments in the assembly of the ratchet and pawl mechanism to permit it to function as described, is that which assures that the relative position of the two jewels is exactly as shown on Fig. 6A. Maintaining an exact number of index

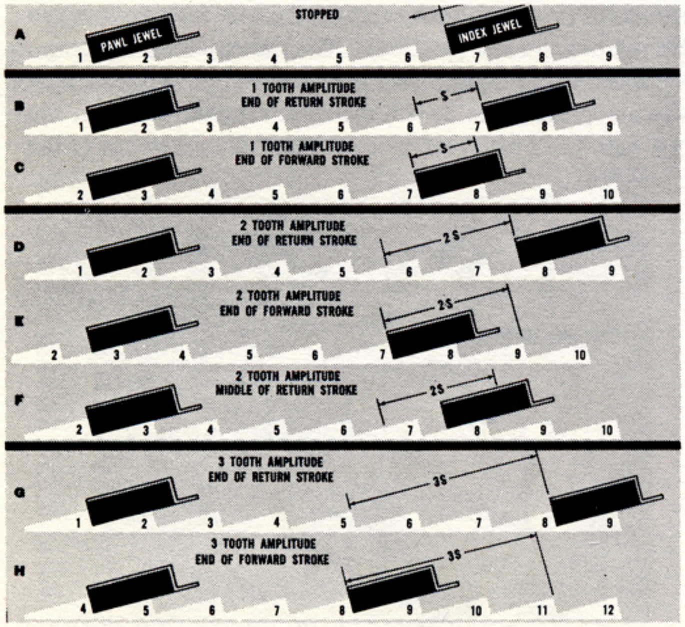


Fig. 6 - Diagram of indexing mechanism operation

wheel teeth between the two jewels is not necessary. However, the index jewel must rest in the middle of a tooth in the idle condition. An obvious expansion of the diagrams shown in Fig. 6, but with the index jewel resting at points other than in the center of a tooth as in Fig. 6A, will readily show a rapid narrowing of the optimum ± 50% amplitude tolerance as the phase relationship of the two jewels deviates from the proper value. The minute teeth and the small dimensional adjustments required, make a normal approach to establishment of the critical relationship between the two jewels in question a near impossibility. Instead, a reduced voltage is applied to the electronic circuit, during adjustment, to cause the index jewel to oscillate at very slightly over one tooth amplitude. The pawl finger is attached to a movable support which has a cam adjustment permitting the pawl jewel position to be advanced or retarded. With slightly over one tooth amplitude of the index jewel as described, the pawl jewel position is varied until the index wheel revolves steadily -- proof that the two jewels are now in the proper phase relationship. Clamping screws on the pawl finger support are tightened to assure that this element cannot move in service.

Electro-Dynamic Transducer System - Reliable operation of the Accutron indexing mechanism, as described above, is dependent upon the tuning fork amplitude being controlled so as to remain at or near a predetermined value under all conditions of use as a wrist timepiece. The transducer system driving the tuning fork is the key to the amplitude control system, since it not only drives the tuning fork electromagnetically, under the action of current pulses delivered by an electronic circuit, but also permits the circuit to sense the amplitude of the tuning fork.

The elements of the transducer system are shown on Fig. 7, with one assembly partially sectioned to show the details of its construction. The moving part of each transducer includes a cup-like part of magnetic material (actually of low carbon steel) together with a conical permanent magnet mounted inside the magnetic cup. Associated with each cup and magnet assembly is a coil of wire, fixed to the plate on which the tuning fork is mounted, and positioned in the annular space between the inside of the cup and its permanent magnet. Each of these coils is wound with 8000 turns of No. 55 insulated wire. These transducers are similar in construction to permanent magnet loudspeakers, except that in the Accutron construction the magnet moves instead of the coil as in a speaker. One transducer contains a single coil of wire, identified as a drive coil; the other transducer contains a drive coil and an additional coil identified as a phase sensing coil.

The drive coils receive the current pulses required to maintain the tuning fork oscillations. In addition, vibration of the magnet and cup assemblies attached to the tuning fork tines induces an alternating voltage in the respective coils. This voltage is directly proportional to the amplitude of vibration of the tuning fork, thus permitting the electronic circuit to sense this amplitude. The function of the phase sensing coil is to control the instant in each cycle during which the driving current pulse is delivered to the drive coils. The electromechanical transducers, therefore, serve a triple purpose:

1. They convert pulses of electrical current into mechanical impulses which drive the tuning fork.

2. They provide the means by which the electronic circuit may sense the tuning fork amplitude.

3. They control the instant in the tuning fork cycle during which the driving current pulse is delivered.

The tuning fork frequency is, of course, fixed within very narrow limits; the mechanical dimensions of the transducer elements can be readily controlled as can the flux in the air gaps and the number of turns of wire on each of the three coils. The conversion factor between the a-c voltage induced in the transducer system and the mechanical amplitude of the tuning fork is therefore predetermined by the design of the transducer elements and can be maintained within narrow limits in mass production. The following paragraphs describe the manner in which this transducer system, coupled with an electronic circuit, controls the mechanical amplitude of the tuning fork at the optimum value for reliable operation of the mechanical indexing system which turns the timepiece hands to indicate time.

Operation of Electronic Circuit - Fig. 8 shows the electronic circuit employed to drive the tuning fork, in combination with the electrodynamic transducer system. The transistor shown is germanium, type PNP. It is used in this application as a switch, rather than as an amplifier. It is caused to conduct current from emitter to collector, once each cycle, thus delivering pulses of current through the two tuning fork drive coils connected in series, as shown on the schematic circuit diagram. The transistor, in this common emitter circuit, can pass collector current only when current is flowing in the base circuit. Key elements in the base circuit operation are the 0.3 mfd capacitor with the 3.9 megohm resistor across it. It is this R-C combination which permits the circuit to drive the tuning fork in a normal manner over a wide range of temperatures, although the transistor characteristics are known to vary widely with temperature.

Operation of the base circuit to trigger the transistor once each cycle is most readily explained by assuming the tuning fork to be vibrating at substantially its normal amplitude. The diode characteristic of the emitter-to-base of the transistor permits the alternating voltage induced in the phase sensing coil to charge the capacitor to a voltage higher than the cell voltage. The base of the transistor is therefore biased positively relative to the emitter by means of the R-C combination mentioned above, during most of each tuning fork cycle, thus maintaining the collector circuit in a quiescent condition. The resistor is provided to cause a portion of the charge on the capacitor to leak off, values of R and C being so chosen that the time constant of the combination is long compared to one tuning fork cycle. During a relatively short interval in each cycle as the voltage induced in the phase-sensing coil approaches its peak (negative) value, the base becomes negative with respect to the emitter and a pulse of current flows from the emitter to the base of the transistor to replace the charge on the capacitor. It is this base current pulse which makes the collector circuit conducting for a brief period, once each cycle.

The 0.01 mfd capacitor in the base circuit, not previously mentioned, prevents self-oscillation of the circuit. Since the phase-sensing coil and one of the drive coils are wound on a common coil form, they are closely coupled magnetically. High frequency feedback oscillations resulting from this close coupling are effectively prevented by the 0.01 mfd capacitor connected as shown on Fig. 8.

The effect of driving impulses upon the frequency of any mechanical vibrating system is zero for instantaneous impulses applied at the point of maximum velocity. This point falls midway in the oscillatory swing. Impulses of finite duration will have a negligible effect upon the frequency of the tuning fork if the impulses are symmetrical about the point of maximum velocity of the tines. Since the voltage induced in the phase-sensing coil of the transducer is proportional to the instantaneous velocity of the tuning fork tines, the base potential reaches its maximum negative value at the exact midpoint of the oscillations of the tines (middle of swing). Driving pulses therefore occur at this time, thereby

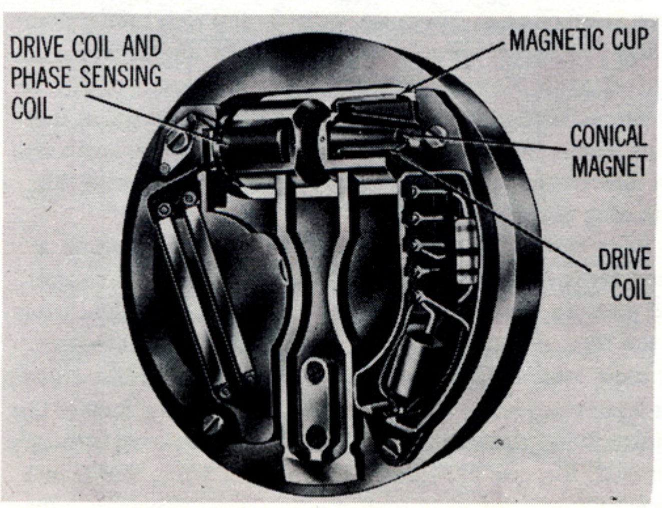


Fig. 7 - Cutaway view of electrodynamic transducer system

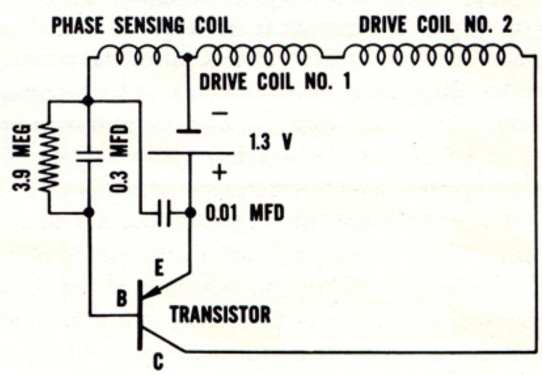


Fig. 8 - Schematic diagram of Accutron circuit

minimizing any disturbance to the natural frequency of the tuning fork.

The operation of the Accutron amplitude control system is similar in principle to the functioning of a permanent magnet d-c motor. In the latter, the back emf at no load is opposite in potential and almost equal in voltage to the operating voltage applied across the brushes, resulting in operation at very low current and practically fixed speed for a given operating voltage. Furthermore, the speed is nearly independent of load, for light loading, since a small reduction in speed results in a large increase in driving current in proportion to the relative change in speed.

The amplitude of the alternating voltage induced in the Accutron drive coil circuit, equivalent to the back emf of the motor discussed above, is typically about 90% of the cell voltage. This is $0.9 \times 1.3 = 1.17$ v. The collector circuit of the transistor is rendered conductive by the base circuit when the voltage in the drive coils is approximately at its maximum instantaneous value and opposite in polarity to the cell voltage. Under these conditions, the net voltage is 0.13 v. The two drive coils have a total resistance of approximately 13,000 ohms. If the transistor were a perfect switch, the pulse current under these conditions would be $0.13/13 \times 10^3 = 10^{-5}$ amp or 10 microamp.

It seems obvious that a mechanical disturbance which caused the tuning fork amplitude to drop 10% below its nominal value would reduce the amplitude of the alternating voltage induced in the drive coils by this same percentage, resulting in approximately doubling the current in the driving pulses and a rapid return of the tuning fork amplitude to its nominal value, because of the large increase in driving energy per cycle at the reduced amplitude. Similarly, a 10% increase in tuning fork amplitude, resulting from a mechanical disturbance, would reduce the driving current pulses to zero and the mechanical amplitude would drop rapidly to its nominal value.

In practice the amplitude control system functions approximately as outlined in the above simplified explanation. The driving current pulse is not, of course, instantaneous nor is it completely independent of the characteristics of the individual transistor used. Nevertheless, the system functions about as described. The transistor collector circuit is quiescent for about 70% of each tuning fork cycle. During the 30% of a cycle the current is flowing, the net voltage is changing slightly, due to its sinusoidal characteristic. Furthermore, by using transistors which have a base-current-to-collector-current gain above a certain minimum value, operation of the circuit is substantially independent of transistor characteristics, over a wide range of temperature.

The voltage of the cell which powers the Accutron circuit is, in fact, the primary control for the tuning fork amplitude. In principle, the system described above converts the mechanical amplitude of the tuning fork into an alternating voltage, compares this induced voltage to the cell voltage and maintains the difference at approximately a fixed value, predetermined by the system parameters. The cell used was chosen for its voltage characteristic. It is basically a mercury cell, of slightly special construction for this application. This cell has a nearly constant potential of 1.3 v for approximately 99% of its useful life, after which its potential drops rapidly to zero and the timepiece stops. This cell provides well over one year of operation under the normal conditions of environment to which a wrist timepiece is exposed. The electrodynamic transducers, the transistorized circuit and the special mercury cell therefore combine to maintain the Accutron tuning fork at the mechanical amplitude required for reliable functioning of the indexing system, and to return it rapidly to the prescribed amplitude in the event that the amplitude is changed by a mechanical disturbance.

CHARACTERISTICS OF ACCUTRON MECHANISM

Performance characteristics of this mechanism and the effects of various environmental conditions on its performance are discussed in the following paragraphs. It might be mentioned that this device, in its commercial version, is marketed as a man's wrist timepiece with a guarantee that it will not gain or lose more than a minute per month in normal use. This is not intended to indicate that the instantaneous rate will not exceed 2 sec per day, gaining or losing, under any combination of environmental conditions. The cumulative effects of occasional brief exposure to a variety of abnormal environmental conditions will rarely change the nominal rate as much as a minute a month and the guarantee of specific accuracy is therefore entirely practical for normal use as a wrist timepiece. The following effects must nevertheless be considered when using this mechanism as a chronometric motor for technical applications, where constant exposure to abnormal environmental conditions may be a requirement.

Acceleration - The rate of the tuning fork changes 4.5 sec/day per g, parallel to the axis of the fork. The rate is faster when the force due to the acceleration is directed from the base toward the free ends of the tines; slower when the force is reversed in direction. The tuning fork rate is practically unaffected by acceleration at right angles to the tuning fork axis. However, accelerations of approximately 20 g's perpendicular to the plane of the tines or 10 g's in the plane of the tines, perpendicular to the fork axis, will cause the fork to stop due to mechanical interference with the mounting plate.

Accuracy - The basic accuracy of the tuning fork in a fixed attitude and under fixed conditions of temperature and pressure is not influenced by pivot friction, lubrication, or the like, and its rate under these conditions is constant, for most practical purposes. Change in rate with time (drift) has been measured repeatedly for typical tuning forks of this construction, vibrated constantly by the associated circuitry and cell, the rate of change in each case being less than 1 sec/day/year. For its normal use as a wrist timepiece, the total effect of the mechanical loading of the fork by the indexing mechanism required to turn the hands, is approximately 1.5 sec/day. Variations in this figure due to changes in lubrication, or the like in the mechanical system are therefore very small. Regulation of timekeeping, under fixed conditions of environment and attitude, is readily accomplished to less than 1 sec/day.

Altitude - The effect of altitude and pressure on the rate of this device is shown on Fig. 9. As shown, the device gains at increasing altitudes, the effect being directly proportional to the reduction in pressure. The rate of change is 0.71 sec /day/in. Hg change in pressure. This effect is caused by the change in density of the moving air column which, in principle, forms part of the mass of the vibrating tuning fork.

Except for the change in rate, the device in comparatively unaffected by a reduction of pressure. Extended operation under high vacuum conditions has presented no problem, although there is a small reduction in operating current resulting from the elimination of air damping.

Attitude - The frequency of the tuning fork is unaffected by changes in attitude, if the tuning fork axis remains horizontal. With the tuning fork axis vertical, the rate will change 4.5 sec/day in comparison with the rate with the fork axis horizontal. The rate in the "tines down" position is faster than when the fork is horizontal; the rate "tines up" slower than the rate in the horizontal position.

The reason for the attitude effect is that in the tines down position, for example, the effect of gravity on the weighted tines is added to the elastic return force of the tuning fork, to make the frequency higher than if the gravity effect were absent as, for example, in the horizontal position of the fork. These timepieces are normally regulated to lose 1.5 sec/day in the horizontal position to compensate for the frequent occurrence of the "tines down" position (12 down) when worn in the usual manner on the outside of the wrist. If worn on the inside of the wrist, the timepiece must be regulated to gain 1.5 sec/day in the horizontal position for optimum performance.

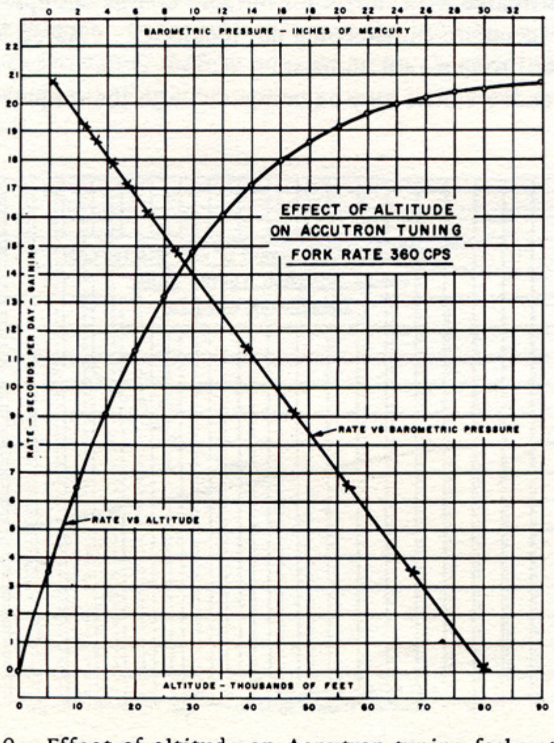


Fig. 9 - Effect of altitude on Accutron tuning fork rate 360 cps

Magnetism - Figs. 10 and 11 show the effects of exposure to d-c magnetic fields of various strengths, for two different directions in relation to the orientation of the tuning fork. The tuning fork, in addition to being fitted with permanent magnet elements, is ferro magnetic and its frequency is, of course, affected by the presence of magnetic fields. The residual effect upon rate, for the field strengths shown, is nevertheless small.

Fig. 12 shows the demagnetizing effect of exposing the permanent magnet system to a-c magnetic fields of various strengths. Exposure to a field of 200 gauss demagnetizes the magnets about 10%. This would have little practical effect upon the operation of the timepiece, other than to increase the mechanical amplitude of the tuning fork 10%, thereby causing a slight increase in driving current. Exposure to a-c or d-c fields above about 200 gauss should be avoided because of the demagnetizing effect shown.

The stray magnetic field, adjacent to any point on the wrist watch case in which this device is normally housed, is a maximum of 28 gauss. This is a d-c field, modulated by a very slight a-c field at 360 cps.

For various technical applications where the presence of the stray magnetic field is objectionable or where operation in relatively high strength magnetic fields is required, the small size of this basic device makes the use of magnetic shielding practical.

Power Source - This mechanism normally is operated by a self-contained cell capable of supplying power for more than a year. Nominal current at room temperature is 6 microamp. Operating current rises rapidly with temperature due to the characteristics of the transistor and for applications requiring extended operation at high temperature, a

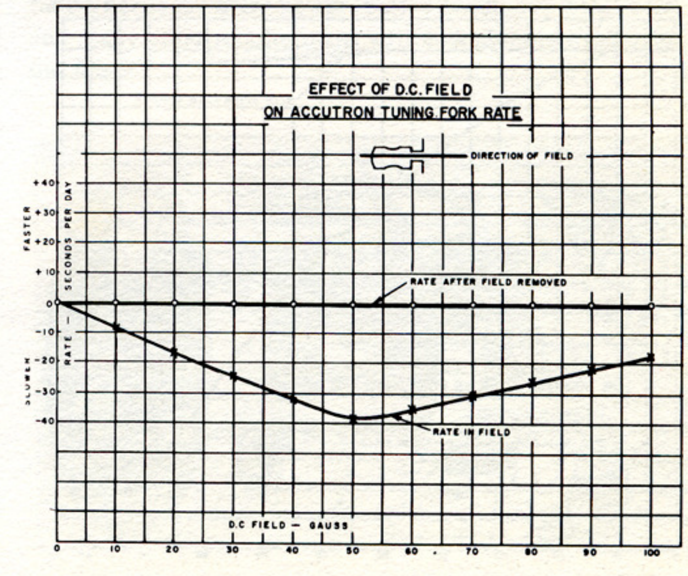


Fig. 10 - Effect of d-c field on Accutron tuning fork rate

silicon transistor must be employed to prevent premature exhaustion of the cell. This device requires a relatively constant 1.3 v d-c from a low resistance source for reliable operation.

Shock - Various devices are employed in the Accutron movement to provide protection from damage by shock. Stops are provided to prevent the tuning fork from being damaged by excessive flexing in any direction and there is a guard around the index and pawl fingers, near the associated jewels, which reduces the tendency of these members to be disturbed by heavy shocks. The effects of shock vary somewhat with direction, nevertheless shocks of the order of a few thousand g's will rarely affect the device.

Starting - Applying electrical power to the circuit driving the tuning fork results in its starting, after a brief delay, if it is not connected to the mechanical indexing system. When loaded by the mechanical system the tuning fork is not self starting; it must be mechanically started by a light tap on the supporting case. In other words, if the device under discussion is used as a chronometric motor, provision must be made to start it, other than the application of electrical energy.

For those applications where repeated starting and stopping are required, the circuit within the device can be altered to permit dropping the mechanical amplitude rapidly to a point at which the indexing mechanism will not operate, or to cause the amplitude to return to its normal operating value, the lower amplitude being obtained by closing an external switch to connect two terminals attached to the device. The "motor" can thus be started or stopped by the usual simple switch, although the device in the stopped condition is not totally inoperative and continues to draw normal current.

Temperature - Circuit elements in the wrist timepiece application of this mechanism are chosen to provide reliable operation from 20-120 F. At lower temperatures the base-current-to-emitter-current gain may, for some transistors, result in failure of the amplitude control circuit to maintain proper tuning fork amplitude. Under such conditions the mechanical indexing system may be unreliable or cease functioning. For special low temperature requirements, use of selected germanium transistors or a reduction of the value of the resistor in the base circuit below its normal value of 3.9 megohms (to increase the height of the base current pulses) can provide reliable operation to -40 F. Below this temperature, the internal resistance of the self-contained mercury cell rises rapidly and it is unsatisfactory as a source of energy.

Above about 130 F unreliable operation can be expected due to excessive changes in the characteristics of the germanium transistor. For wrist timepieces, this upper limit for temperature is not a problem, since the timepiece would be very uncomfortable to the touch if it reached such a temperature. For special high temperature applications, silicon transistors of the PNP type can be employed by suitable alterations in the circuit, providing operation to 210 F.

Fig. 13 shows the performance of a particular tuning fork. Noteworthy is the typical increase in frequency at temperatures below 0 C (32 F) and above 60 C (140 F), although there is negligible change in frequency between these two temperatures. The rise in frequency at extreme temperatures cannot, at present, be avoided.

Torque Output - The following indicates the torque output which can be obtained from the presently designed Accutron mechanism, measured at the center arbor which turns one revoultion per hour:

1. Recommended max torque for accurate timekeeping and continuous operation for minimum one year operation on self-contained cell -- 0.07 oz in.

2. Estimated max torque for reliable continuous operation -- accurate timekeeping not required -- 0.42 oz in.

3. Stall torque -- 0.75 oz in.

The above values may be compared with the torque sup-

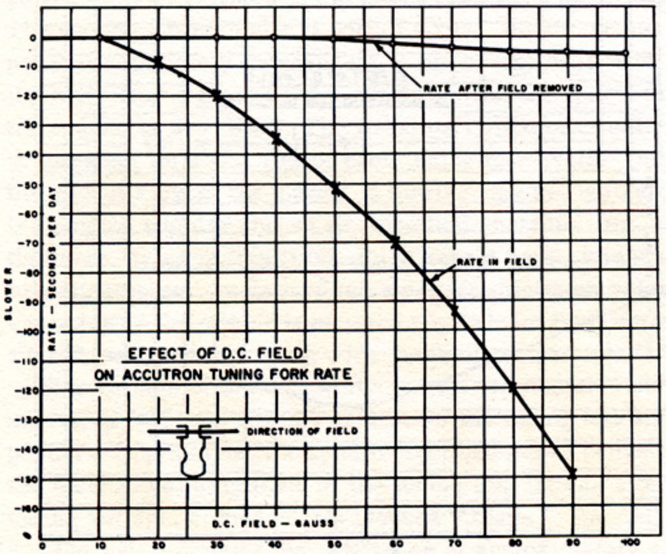


Fig. 11 - Effect of d-c field on Accutron tuning fork rate

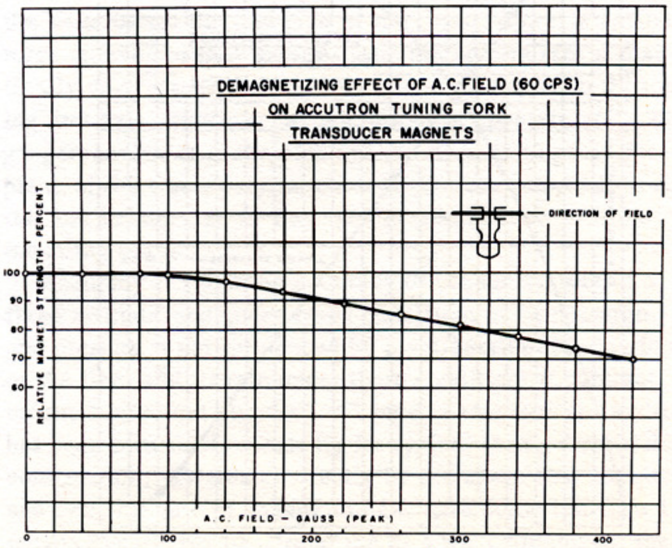


Fig. 12 - Demagnetizing effect of a-c field (60 cps) on Accutron tuning fork transducer magnets

plied by the mainspring to the center arbor of a conventional man's wrist watch movement approximately the size of the Accutron movement. This torque is 0.14 oz in., only a small fraction of which could be delivered to perform useful work, if it were desired to use the watch movement as a chronometric motor. Also of interest is the relatively high efficiency of the Accutron mechanism as a motor. Operating at 0.42 oz in. torque output, the electrical input is 21.6 microwatts. The efficiency is 24%, as compared with 0.1-0.2% for typical small synchronous motors requiring from 0.5-2 w and used for operating time switches, elapsed time meters, and so forth.

The timekeeping properties of the Accutron mechanism, used as a chronometric motor, are affected by the mechanical load applied. Accuracy is relatively unaffected below .07 oz in. torque output. However, at 0.42 oz in. output the rate is approximately 50 sec/day faster than at no load. Obviously, a redesigned movement with a substantially larger tuning fork would be required to deliver relatively large amounts of torque without significant change in tuning fork frequency.

Vibration - This tuning fork based device must be provided with vibration isolation if reliable operation is required under conditions which include vibration. Used as a wrist timepiece, the wrist of the user provides this isolation, the most violent vibrations from power tools and other sources being absorbed by the user's body and not transmitted to the timepiece. At frequencies up to 100 cps, 20 g's can be tolerated by the device without significant effect. At 150 cycles, the limit is about 10 g's, and at 200 cycles the device will not operate reliably above 2 g's. It is not damaged by 100 g's at 5-2000 cps sinusoidal vibration and will resume proper functioning upon removal from the vibration environment. Under such vibration the indexing mechanism causes the output shaft to advance at an abnormal rate and the device may operate at many times its normal output speed.

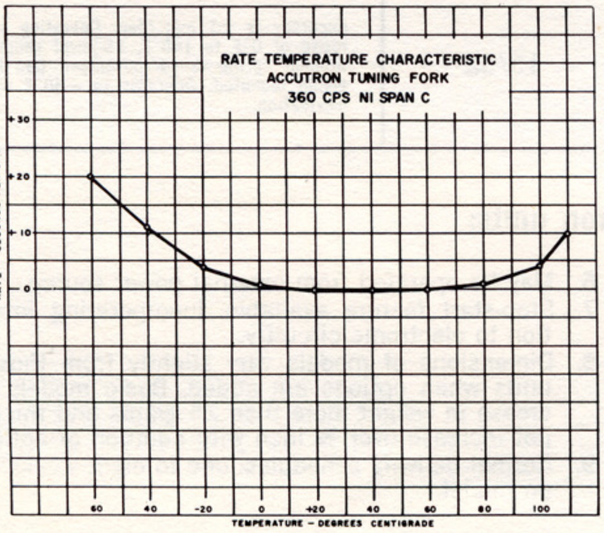


Fig. 13 - Rate temperature characteristic Accutron tuning fork 360 cps Ni Span C

APPLICATIONS OF ACCUTRON MECHANISM

Previous sections have outlined the operation of the present Accutron movement, its operating characteristics, and its reaction to abnormal environmental conditions. For technical applications this device is most useful when time accuracy, small size, and low operating current are important, and where low output shaft speed and torque are not objectionable.

One example of an application employing this device is shown on Fig. 14. This shows a time switch mechanism, driven by an Accutron movement. This device can be preset to provide a double pole double throw switch function at any time from two months to five years after setting. A self-contained cell provides the necessary operating power.

A larger, more powerful Accutron mechanism is under consideration for future production. At present, however, it is not obvious that the range of applications of the basic mechanism would be greatly expanded by the substantial increase in size and power input requirements which would, of necessity, result from, say, a hundredfold increase in output power. Furthermore, such larger mechanism would not necessarily be able to withstand the effects of abnormal environmental conditions better than the present small device. The present mechanism, however, is easily damaged in the uncased condition and adjustment and handling of the basic device should be performed only by a skilled watchmaker. Furthermore, provision must be made in any device driven by the present movement, to avoid forcing the output shaft ahead or back, once cased and ready for use. This requires special attention to setting devices for hands or switches, although in most instances careful design can avoid troubles resulting from forcing the Accutron movement during setting.

This device, in its present form, was developed for one primary purpose -- for use as a wrist timepiece. As designed, it has found many uses as a low speed chronometric motor. A broad line of Accutron mechanisms to fill a variety of future needs for more power, better accuracy, lower cost, and many other requirements will undoubtedly evolve in the future.

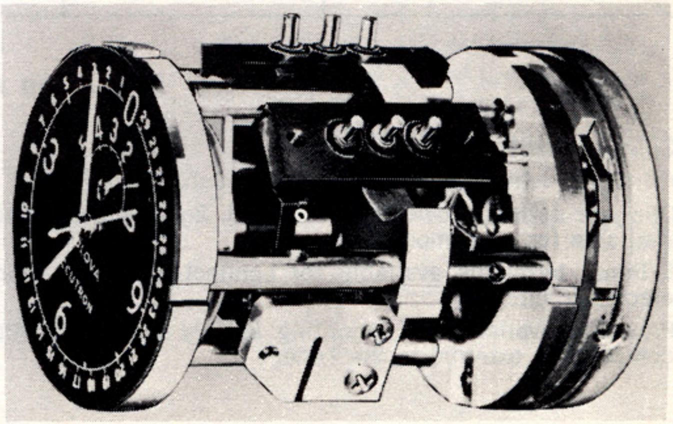
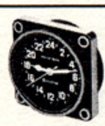
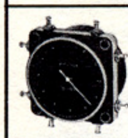
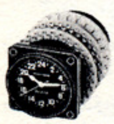


Fig. 14 - Accutron based five year time switch mechanism

Clocks, timers and switches based on the ACCUTRON mechanism*

ITEM	MODEL TE-	WT. GRAMS	FRONT DIM. IN.	THICK IN.	DESCRIPTION
 CLOCK 1 In. Dial	10	33g	$1\frac{5}{16}$ x $1\frac{5}{16}$	.55	Basically a timepiece, featuring a 24-hour dial with coaxial hour, minute and second hands. For use in data recording devices, aerial cameras and instrumentation when power is not readily available.
 CYCLE TIMER	11	42g	$1\frac{5}{16}$ x $1\frac{5}{16}$	.68	A Cyclical Timer that features one or more contact closures which can be set in combination at either the same or different speeds of either 1 revolution per minute, 1 per hour or 1 per 12 or 24 hours.
 5 YEAR SWITCH (2 mo.-5 yr.)	12	82g 97g 97g 97g	$1\frac{5}{16}$ x $1\frac{5}{16}$	2.00 2.35 2.35 2.35	A Delay Switch Timer providing contact closure from 5 days to 5 years. Dial face shows graduations indicating time remaining. Used in satellites, etc. where space, weight and power are at premium.
 CLOCK $1\frac{7}{8}$ In. Dial	13	82g	$2\frac{3}{8}$ x $2\frac{3}{8}$	.53 .99	Like TE-10, but larger dial face. Options: Front setting, stop-start features; 1-31 day calendar, or 0-999 day display with 24-hour dial. Cycle time closure provides closures at specific intervals. Can be externally powered.
 CALENDAR CLOCK	14	42g	$1\frac{5}{16}$ x $1\frac{5}{16}$	.68	Has 24-hour display dial with 1-31 day date, with hour, minute and sweep second hands. Options as in Model TE-13 Series. Ideally suited for remote or unattended areas, and where no power source is available.
 DIGITAL OUTPUT TIMER	16	With 1 module: 65g Each addtl. module, add 25g	$1\frac{5}{16}$ x $1\frac{5}{16}$	With 1 module: $1\frac{11}{32}$ Ea. addtl: add $\frac{7}{16}$	Up to 6 modules provide discreet contact closures every second, minute, hour and day (up to 60 days). Solderable eyelet terminals permit wiring to any closure or combination. Basic timer includes 1 module. Options available.
 AERIAL CAMERA CLOCK *NOT AN ACCUTRON MECHANISM	17	20g	$1\frac{5}{32}$ dia.	15/32	Accuracy is ± 1 min./day. Operating temperature range of 0°F to 160°F, 15-jewel shock resistant, 36-hour spring-wound movement. Can be back or clamp mounted. Operates to -30°F with special lubrication.

Notes on Accutron units:

1. Silicon transistors in all units.
2. All timers rear setting; optional front setting on TE-13.
3. One-year battery provided as standard; 2-year battery also available for most models.
4. External terminals available for connection to Accutron electronic circuitry.
5. Provision available for mounting battery and electronic components external to the Timer.
6. May be operated from external power source.
7. Stop-start feature available, incorporating internal addition to electronic circuitry.
8. Dimensions of models vary slightly from those of basic units when options are added. Basic models do not increase in weight more than 25 grams and thickness does not increase over ¾ inch with addition of options.
9. Normal delivery schedules: one to eight weeks, depending on model.

BULOVA TIMER LABORATORY

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