ATOMIC CLOCKS

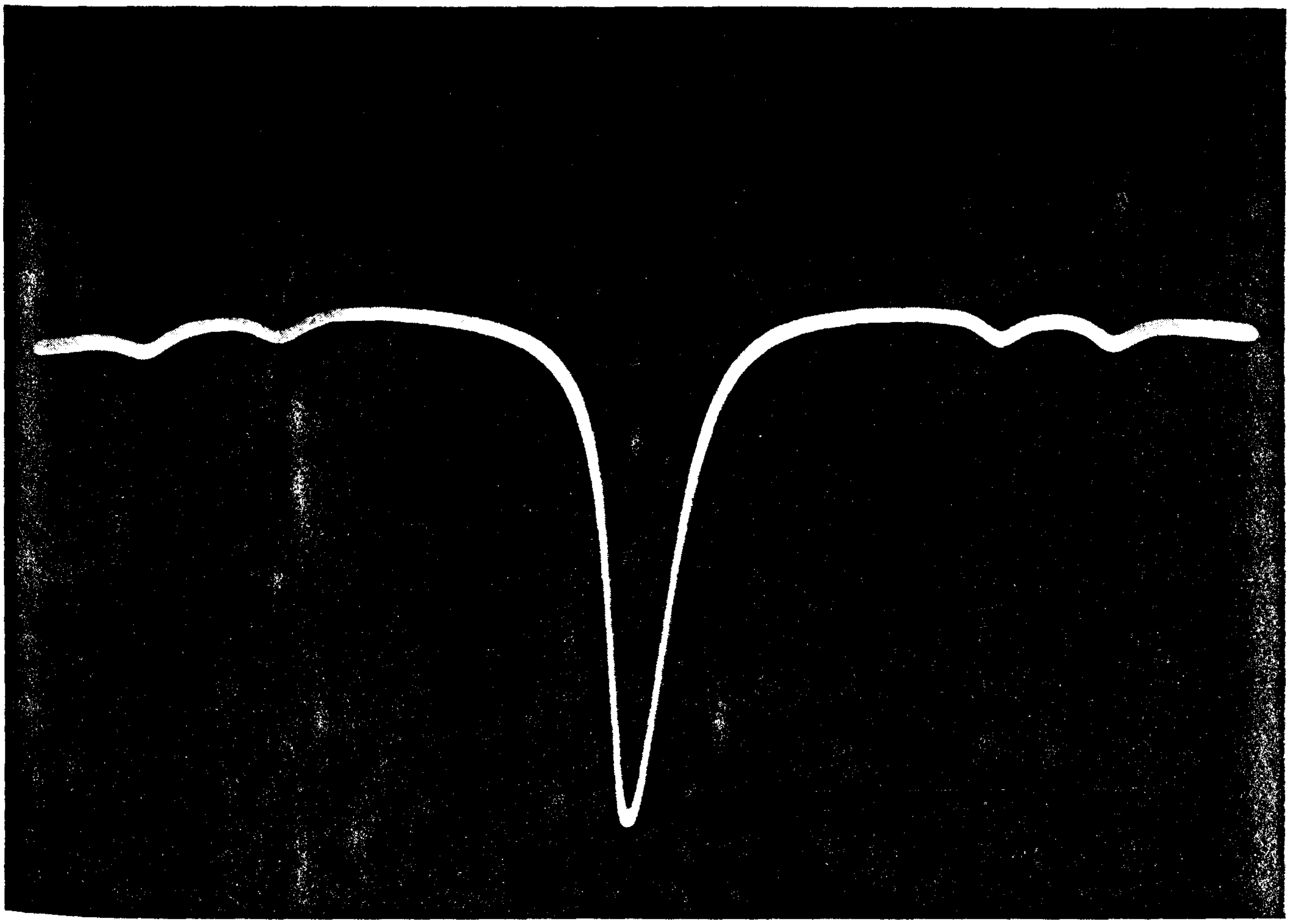
The "pendulums" which regulate them are the vibrating parts of atoms or molecules. So steady are these oscillations that atomic clocks keep better time than the spinning earth itself

by Harold Lyons

Philosophers and scientists in all ages have been fascinated by the mysteries of time—its relentless, arrow-like flight in one direction, its psychological vagaries, the difficulty of measuring it with absolute precision. In our atomic age the last of these aspects affords the most intriguing speculation and exploration. Because "the pendulum's swing is a variable thing," and the motions of the earth and stars are inconstant, today "the atom's vibrating has the highest rating" among chronologers. Let us then consider atomic clocks.

Most of us, when we ask for the right time, are satisfied with an answer accurate to a few seconds or so. For the "split-second" timing of a race, tenths of seconds will do. But in many areas of modern science and technology the question of the right time enters a different realm. In the laboratory we must deal with thousandths, millionths, even billionths of a second.

The measurement of any physical quantity reduces in the last analysis to a matter of counting units. To find the dis-



ABSORPTION CURVE of ammonia is recorded on an oscilloscope. The trace shows power received from a beam of radio waves transmitted through ammonia gas. Frequency varies along the horizontal axis. At the resonant frequency most of the wave energy is absorbed, as is shown by the dip in the curve. The range of frequencies indicated by the dip limits the accuracy of ammonia clocks.

tance between two points, for example, we choose some convenient yardstick and count the number of times it can be laid end to end from one point to the other. To find the elapsed time between two instants we choose a convenient unit, such as the time required by a certain pendulum to complete one swing, and count the number of swings in the interval. However, the swings of a pendulum are not precisely the same from one to the next. The central problem of exact time measurement is to find some periodic cycle that never changes, or changes so little that the variation can be disregarded. For ages immemorial we have reckoned time by the rotation of the earth relative to the stars. Now we have begun to seek more precise standards in the tiny world of molecules and atoms. There we find processes whose regularity makes it possible to measure time with undreamed-of accuracy.

The Clock on the Wall

Before looking into these cosmic clocks in more detail, let us consider briefly how ordinary clocks operate. In the household electric clock the "pendulum" is the cycle of the alternating current. Hence the accuracy of the clock depends on the steadiness of the rate of alternation of the current. For household purposes the 60-cycle rate maintained by the power-generating station is steady enough.

For higher precision, laboratories and observatories use quartz crystal clocks. Here a quartz crystal controls the frequency of an electronic oscillator, such as is used in radio broadcasting. A crystal of quartz, when subjected to an alternating electric field, tends to vibrate at its own specific, sharply defined rate. Placed in an oscillator circuit, the crystal imposes its steady natural frequency on the circuit. The resulting current can run a synchronous clock motor with an error of no more than one part in a billion or so, depending on the length of the interval involved. However, changes in temperature and other conditions produce tiny shifts in the crystal frequency, and as a crystal ages its frequency drifts.

Fundamentally all man-made clocks are set by some master clock in nature, which at present is the 24-hour rotation of the earth. The complete rotation is timed precisely by recording the instant a point on the earth passes under a chosen star in the sky on successive nights. The interval is divided into 86,400 parts, which gives the length of a second.

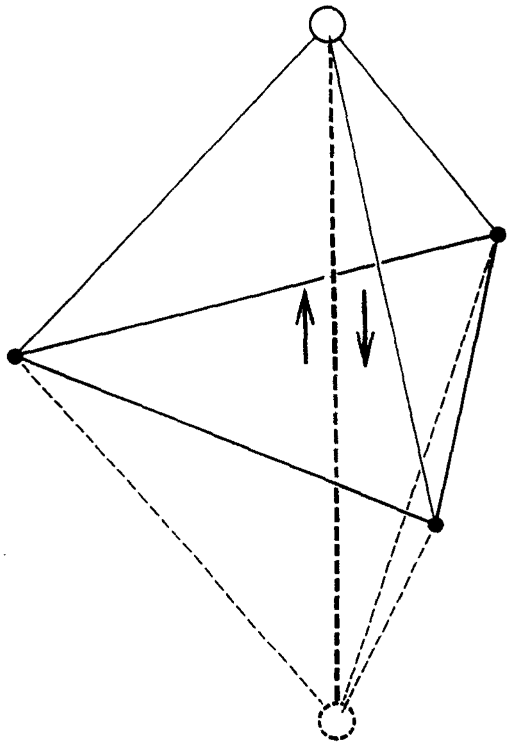
But in the computation of the length of the day, corrections have to be made for a number of irregularities, including wobbles in the earth's rotation on its axis. When all the corrections have been made, an insurmountable uncertainty still remains: the rate of rotation of the earth itself fluctuates unpredictably. So in the end there is an irreducible variation which can be as large as one part in 20 million.

All this explains why so much effort is being devoted to finding clocks which will keep better time than the earth and stars. The atomic clocks offer great advantages. The motions of atoms and molecules, which can serve as "pendulums," are absolutely pure and regular. Their rates are inexorably fixed by the laws of the atomic world.

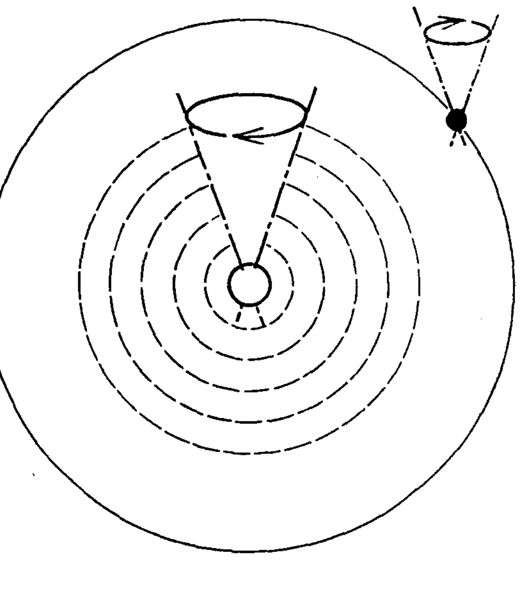
Some of the motions in the atomic world—*e.g.*, the vibrations of electrons that radiate visible light—are much too rapid to be counted. But there are atomic oscillations in the radio microwave region, with frequencies in the range of a few billion cycles per second, which can be counted accurately by present-day techniques and equipment.

The Ammonia Clock

The first atomic clock devised is the one based on vibrations of the ammonia



AMMONIA MOLECULE has the shape of a pyramid. Hydrogen atoms (*black dots*) form a triangular base. Nitrogen atom (*open circle*) is at apex. It can oscillate between positions above and below the base, traveling along the path marked by colored line.



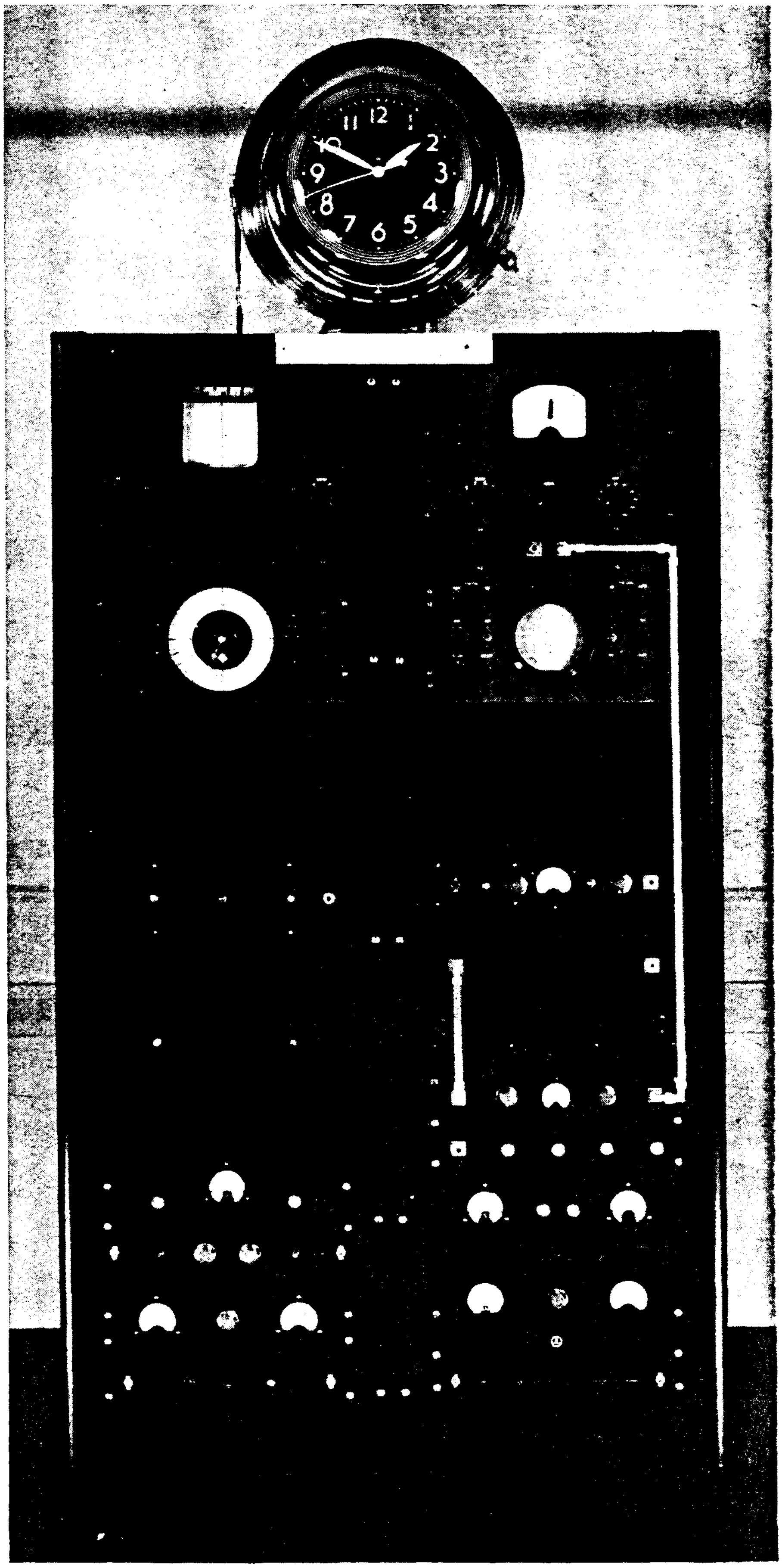
CESIUM ATOM has a single electron (*black dot*) outside of a number of filled electron shells (*broken circles*). The electron and nucleus are spinning magnets; each wobbles on its axis, as is indicated by colored arrow. Wobble is the ticking of a cesium clock.

molecule [see "Radio Waves and Matter," by Harry M. Davis; SCIENTIFIC AMERICAN, September, 1948]. This molecule, made up of three hydrogen atoms and one nitrogen atom, has the shape of a pyramid. The hydrogens are at the corners of the triangular base, and the nitrogen is at the apex [*see diagram on opposite page*]. According to the rules of classical physics, the forces between the atoms should hold the nitrogen in place at the top of the pyramid. But experiments have shown that the nitrogen can actually plunge down through the triangular base and come out to an apex position on the other side—a phenomenon which can be explained by quantum mechanics. The motion is merely hindered, not prevented, by the interatomic forces. And of course if the nitrogen can pass through in one direction it can also reverse its path; in other words, it can vibrate up and down through the base. As we should expect from quantum theory, the vibration can take place only at a sharply defined frequency, which happens to be 23,870 megacycles.

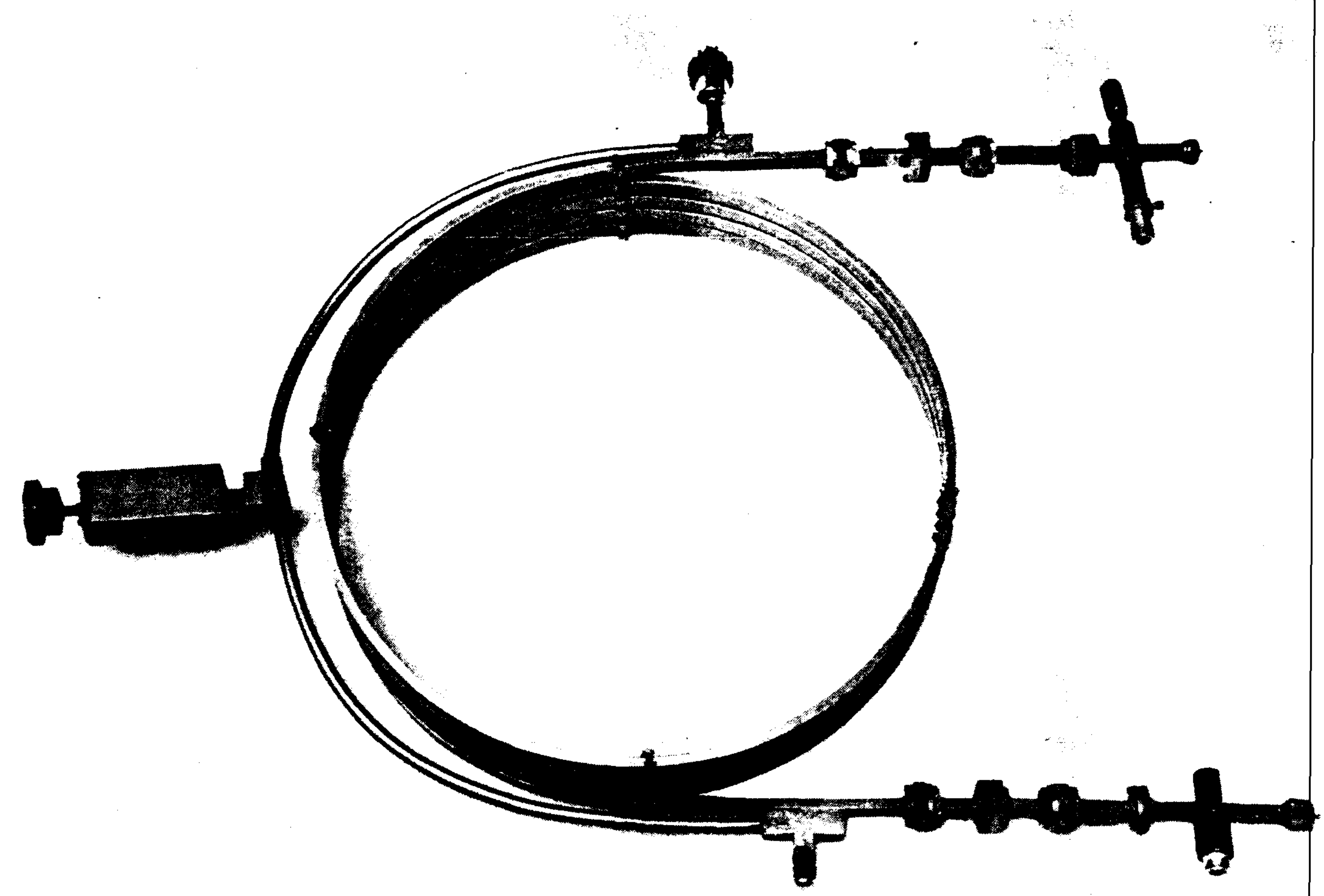
Whenever it is excited by a sufficient amount of energy, the ammonia molecule starts to vibrate with its characteristic frequency. It is like a pendulum which is set swinging by a push. If the push is supplied rhythmically, and in time with the natural frequency of the pendulum, the resulting swing is much more vigorous. That is, the molecule absorbs more energy from the source of supply and converts it into the energy of its own oscillator. A radio wave at a frequency of 23,870 megacycles makes the nitrogen atom absorb large quantities of energy and vibrate strongly.

In 1948 a group of workers at the National Bureau of Standards built an ammonia clock. Their design contains essentially two pendulums: a quartz crystal and a collection of ammonia molecules. The ammonia serves to correct small errors or irregularities in the crystal-controlled oscillator. The oscillator in turn runs an ordinary synchronous electric motor like the one in a kitchen clock. For this purpose its frequency has to be reduced to that of an alternating electric current suitable for running the motor—*i.e.*, to the neighborhood of 60 cycles per second. The crystal frequency is cut down to a precise fraction of the original by means of electronic circuits analogous to a train of gears which converts the rapid rotation of a small gear to the slower rotation of a large one.

The ammonia clock works as follows.



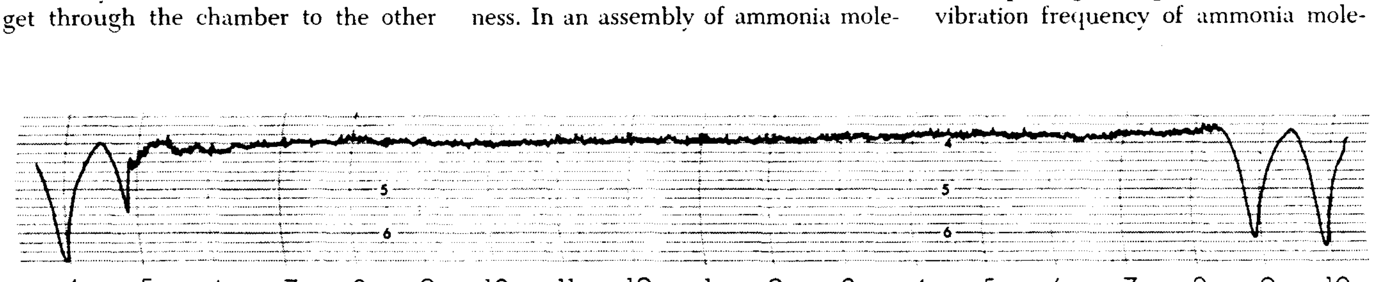
FIRST AMMONIA CLOCK was completed at the National Bureau of Standards in 1949. The wave guide that contains the ammonia gas can be seen wound around the face of the electric clock. The cabinet below houses crystal oscillator and other electronic circuits.



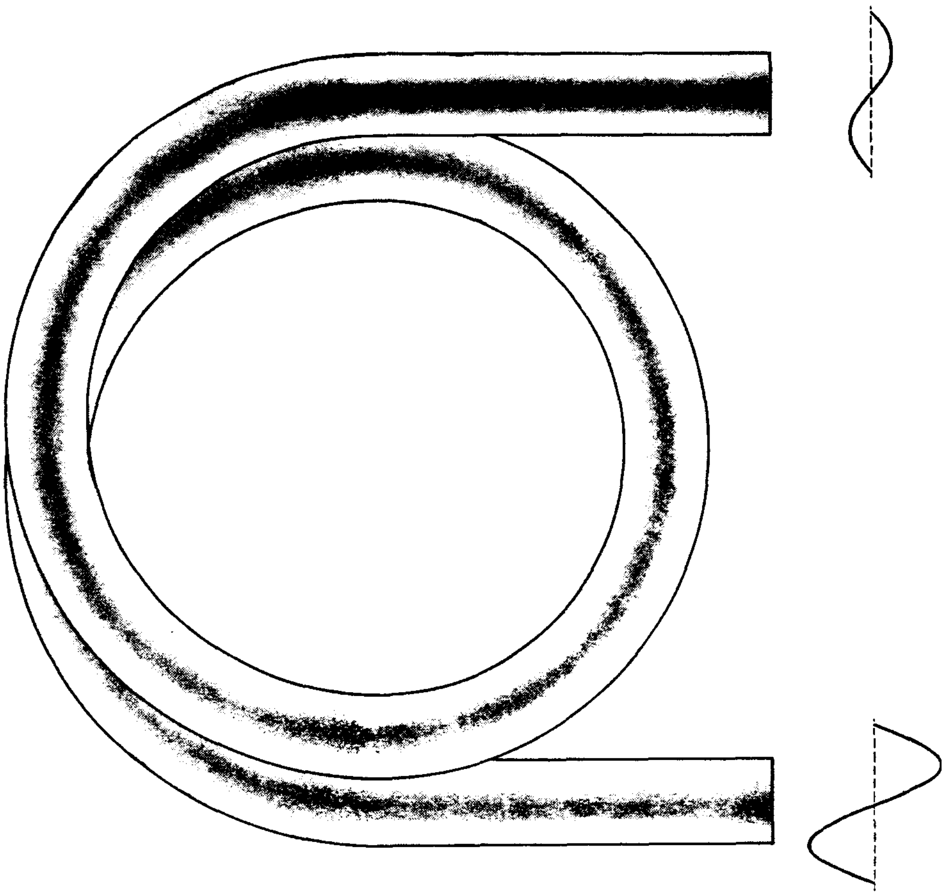
ABSORPTION CHAMBER for the ammonia clock is a hollow, rectangular, spiral wave guide which contains ammonia gas at low pressure. A radio signal is fed in at one end and detected at the other. When the frequency of the wave falls within the absorption

First the quartz crystal is set vibrating at a frequency which, when multiplied electrically, yields a frequency close to that of the ammonia molecule. These rapid oscillations are then converted into radio waves by means of a small antenna and are fed into a long chamber, or wave guide, containing ammonia gas. If the oscillations happen to be at the same frequency as that of the ammonia molecule, most of the radio energy will be absorbed by the ammonia, and little will get through the chamber to the other end. But if the two frequencies do not quite agree, most of the radio energy will pass through the chamber to a receiver at the far end. The receiver acts as a feedback mechanism, feeding a servomotor which adjusts the frequency of the oscillator circuit to agree with the ammonia vibration rate.

The feedback circuit has a time lag, and its corrections are not absolutely exact. The vibration of the molecules themselves exhibits an inherent fuzziness. In an assembly of ammonia molecules there is some spread of the rates of vibration. There are two chief reasons for this. First, the moving molecules of ammonia gas constantly collide with one another and with the walls of the chamber. At every collision the atoms of the ammonia molecule are subjected to outside forces which slightly spread the molecule's frequency from its normal value. The second factor in shifting the frequency is a Doppler effect. To radio waves passing through the chamber, the vibration frequency of ammonia mole-



STABLE PERFORMANCE of an ammonia clock over a 15-hour period is demonstrated by a record of its frequency changes. The frequency is measured on the vertical scale of the chart, each small division corresponding to a change of less than one part in 10 million. During the period from 5 p.m. to 8 a.m. the quartz crystal oscillator was locked to the frequency of the ammonia molecules.



band of the ammonia molecule the output signal is sharply reduced. At right is a schematic diagram of the unit showing the input signal at the bottom end and the output at the top.

cules moving away from the waves appears to be slightly lower than it actually is, and the frequency of molecules moving toward the waves appears to be higher. Both the collision and Doppler shifts are sufficient to give a measurable spread around the central frequency and thus to limit the possible accuracy of the ammonia clock.

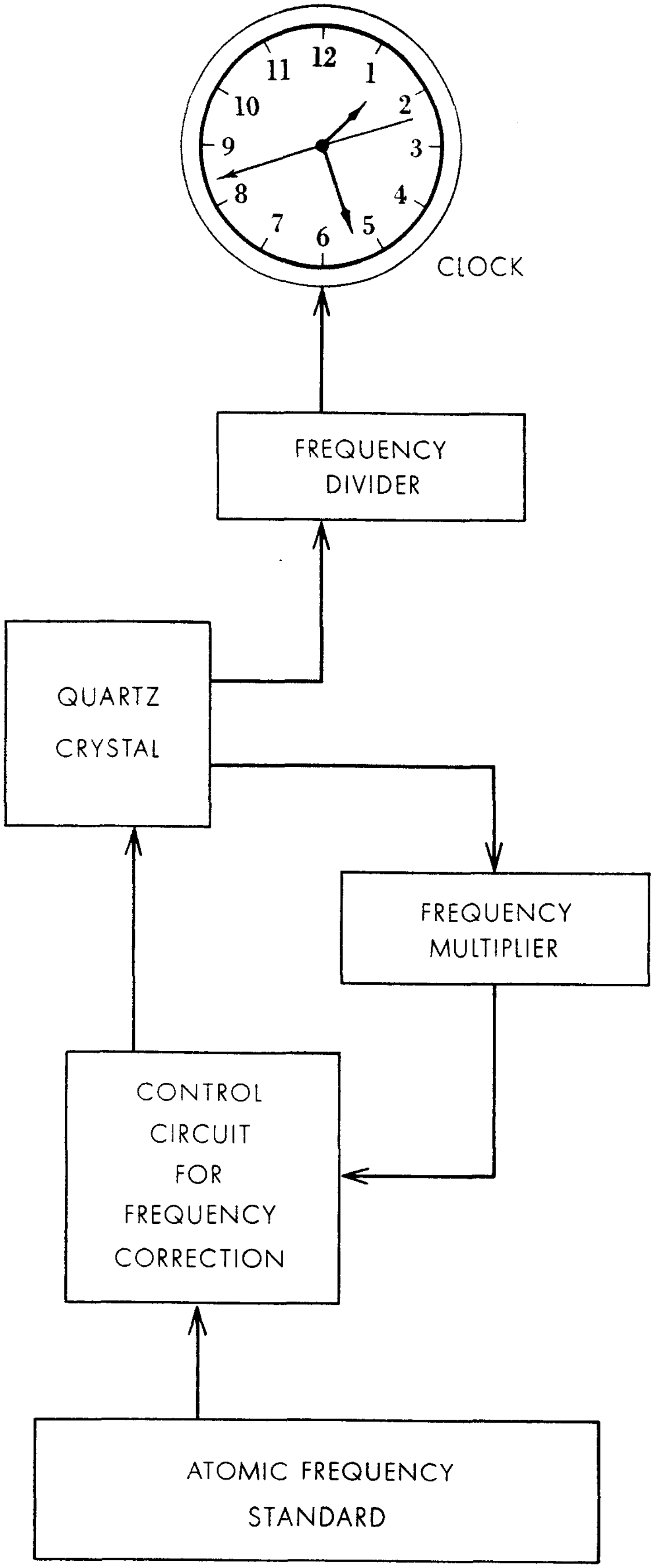
The accuracies that have been obtained are quite impressive, however. An improved version of the original Bureau of Standards ammonia clock is stable to within one part in 100 million. J. Rossel of the Swiss Laboratory for Time-Keeping Research has reported that a newer ammonia clock built there can be held steady up to two parts in a billion. K. Shimoda of Japan also has designed a new form of ammonia clock which can control frequency to two or three parts in a billion.

The Cesium Clock

Now an atomic clock of considerably greater precision—the most accurate yet built—has been made with cesium, a silvery metal which is liquid at room temperature. It was designed by the Bureau of Standards group who made the first ammonia clock.

The cesium atom, like the ammonia molecule, has a natural vibration whose frequency is in the microwave region. Its frequency is 9,192 megacycles. This puts it, very conveniently, in the range of three-centimeter microwaves, a region which has been intensively exploited for radar work. Thus the necessary equipment and techniques are ready to hand.

What can go on in the cesium atom at this comparatively leisurely pace? It turns out to be a magnetic process. Cesium is an alkali metal, which means that outside its filled electron shells it has a single outermost electron whose spin makes it a magnet. (The magnetisms of the electrons in the closed shells do not count, because they cancel one another.) The spinning nucleus of the cesium atom also is a magnet. Thus the atom contains two small, spinning magnets, each in the force field of the other. Neither magnet maintains a rigidly fixed direction. They are both like tops spinning in a gravita-



CONTROL CIRCUITS for an atomic clock are shown in this schematic diagram. Part of the output of a quartz crystal oscillator is reduced by a frequency dividing circuit to about 60 cycles per second and fed into an ordinary electric clock. Another part of the output is multiplied to the atomic vibration frequency and fed to a circuit which compares it with the atomic frequency itself. Any difference is translated into an electric signal which feeds back to the oscillator and brings its frequency into agreement with the atomic standard.

tional field. That is, they wobble or precess around a fixed line [*see diagram on page* 72]. The rate of precession is 9,192 megacycles per second. This represents, in effect, the ticking of the cesium clock.

If cesium atoms are placed in an electromagnetic field which oscillates at 9,192 megacycles, the electrons can absorb or emit energy and flip over to a different orientation. This change of energy state is the mechanism of the clock.

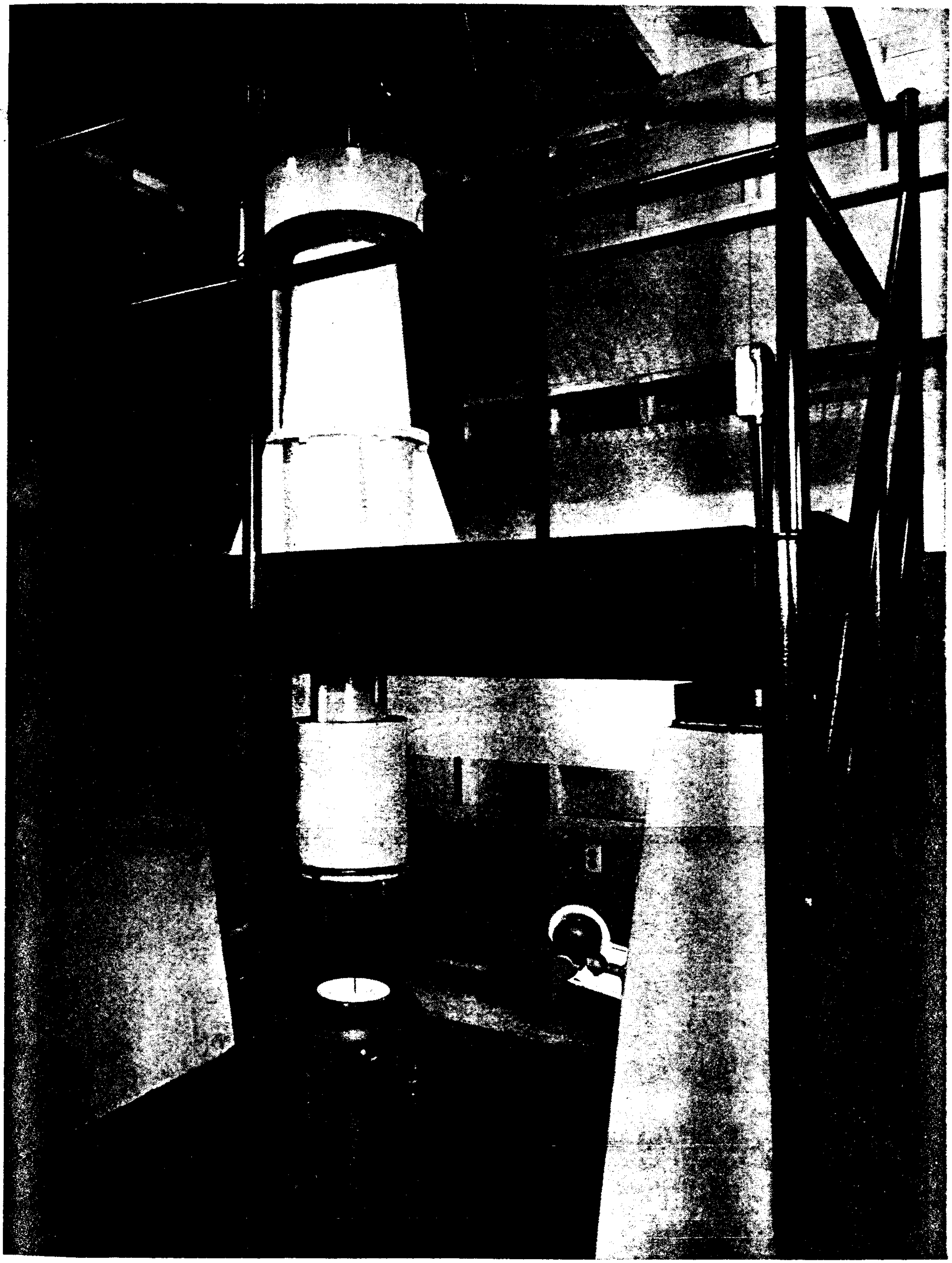
For the cesium clock the element is heated to the gaseous state in an electric furnace, and the cesium atoms are discharged through a small opening into a long, evacuated tube. They travel down the tube in a beam like a file of marching soldiers, thus avoiding collisions with one another. The beam is sent through a magnetic field which acts to select only atoms in certain energy states. Next the beam passes through a section where it is exposed to radio waves at the frequency of 9,192 megacycles. Finally it passes through a second magnet just like the first and then approaches a detector wire where the cesium atoms will produce a current if they hit it [*see diagram at top of page 80*].

If the radio field is on the correct frequency, large numbers of atoms in the beam change their energy. The second magnet now deflects these atoms so that they reach the detector. On the other hand, if the radio frequency does not agree with the natural frequency of the cesium atoms, they pass through the second magnet and are deflected so that few reach the receiver. As in the ammonia clock, the receiver actuates a mechanism which adjusts the oscillator frequency so as to keep the received current at a maximum.

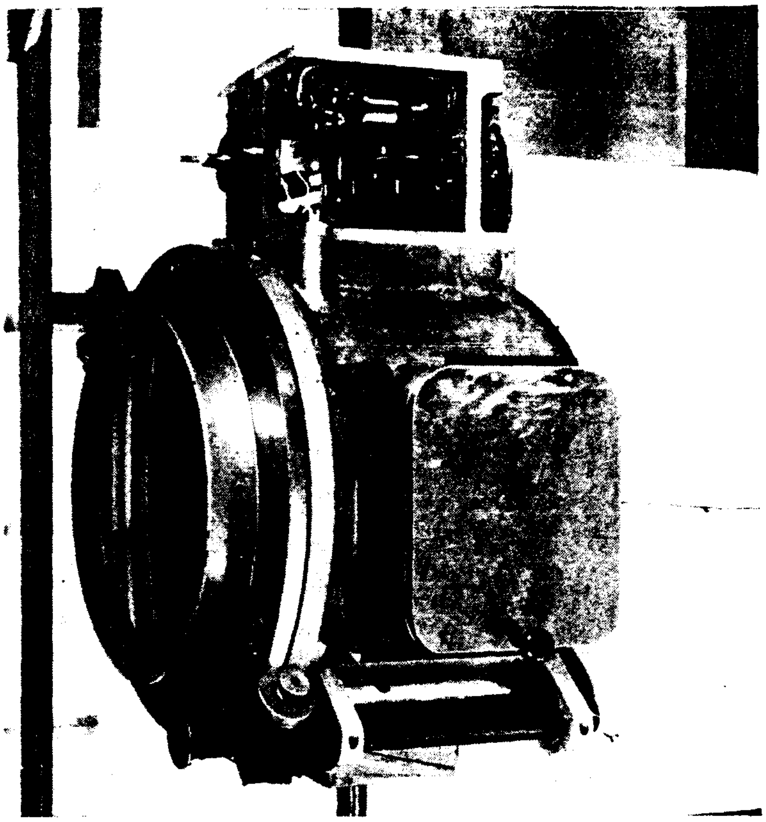
The cesium clock is extremely accurate because the spectrum line is very sharp. The device eliminates collisions between atoms and the Doppler effect, which broaden the absorption band in the ammonia clock. There is no Doppler effect because the radio waves attack the passing beam at right angles instead of moving along the same line of travel.

With precise control of the radio frequency it is possible to achieve accuracy to at least one part in 10 billion in the cesium clock. This would correspond to an error in timekeeping of one second in 300 years!

Already a cesium clock at the National Physical Laboratory in England has operated to an accuracy of one part in one billion. L. Essen and J. V. L. Parry have determined the center frequency of the cesium spectrum line in terms of a pro-



PHOTOGRAPHIC ZENITH TUBE makes pictures of stars as they pass directly overhead. The time between transits on successive nights determines the length of the solar day. The tube is fixed; below it is a basin of mercury which acts as a mirror. Because the mercury is liquid, it is absolutely level. The mirror reflects the light of stars to a photographic plate within the tube (*see picture at top of next page*). This instrument is at the U. S. Naval Observatory in Washington, D.C. A similar instrument is at Richmond, Fla.



LENS of photographic zenith tube has an aperture of eight inches. It is shown mounted on a housing which contains the photographic plate. The motor at top moves the plate to keep star image tracked for 20-second exposure. About 15 stars are photographed a night.

MERCURY MIRROR provides a flat and truly level surface. It is raised or lowered to focus the star image on the photographic plate under the lens. Above the surface of the mercury is a rod; its reflection can also be seen in the mercury. When the tip of this rod just touches the surface of the mercury, the image is in exact focus at the photographic plate.

visional, uniform time scale estimated by the Greenwich Observatory. Their answer is 9,192,631,830 cycles per second, with a possible error of 10 cycles. A cesium clock of at least this accuracy has also been built by the National Company in the U. S.

An ingenious scheme to improve the cesium clock's potential accuracy is being explored by Jerrold R. Zacharias and his group at the Massachusetts Institute of Technology. Zacharias plans to increase the length of exposure of the cesium beam to the radio waves, which will sharpen the absorption line. He proposes to do this by shooting the cesium atoms upward and exciting them with the radio field near the top of their trajectory, when they are about to fall and are moving slowly. His plan may give the cesium clock an accuracy to one part in 1,000 billion or better.

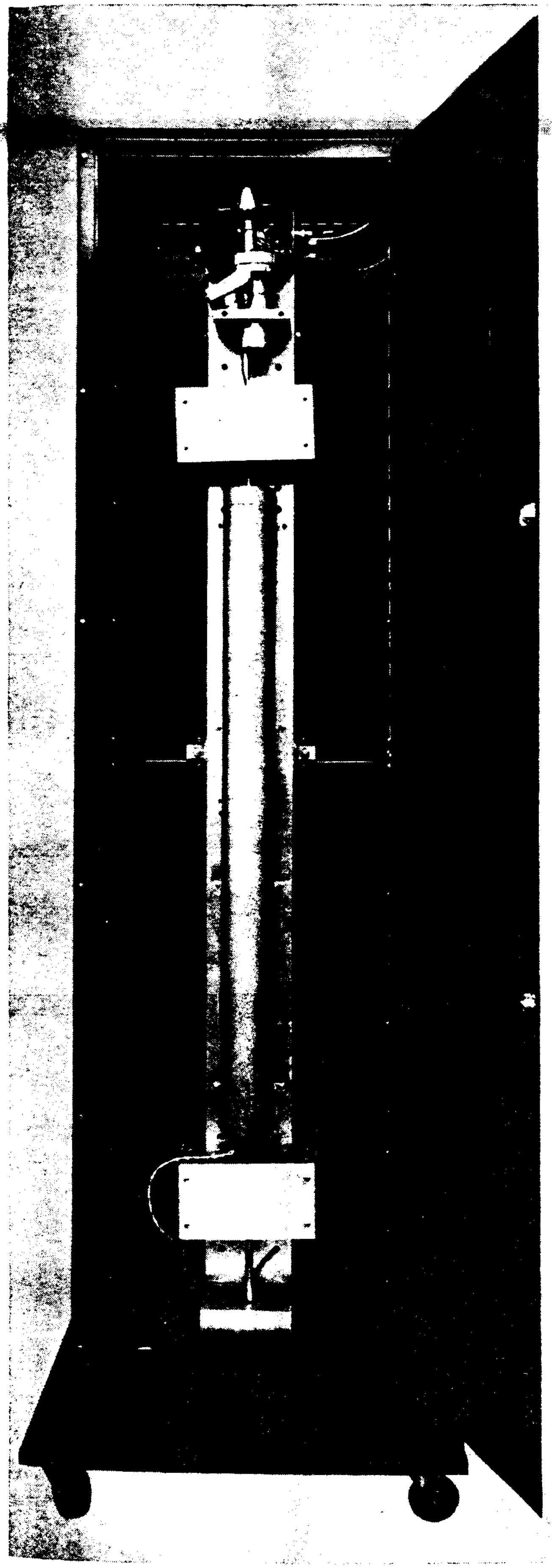
The Maser Clock

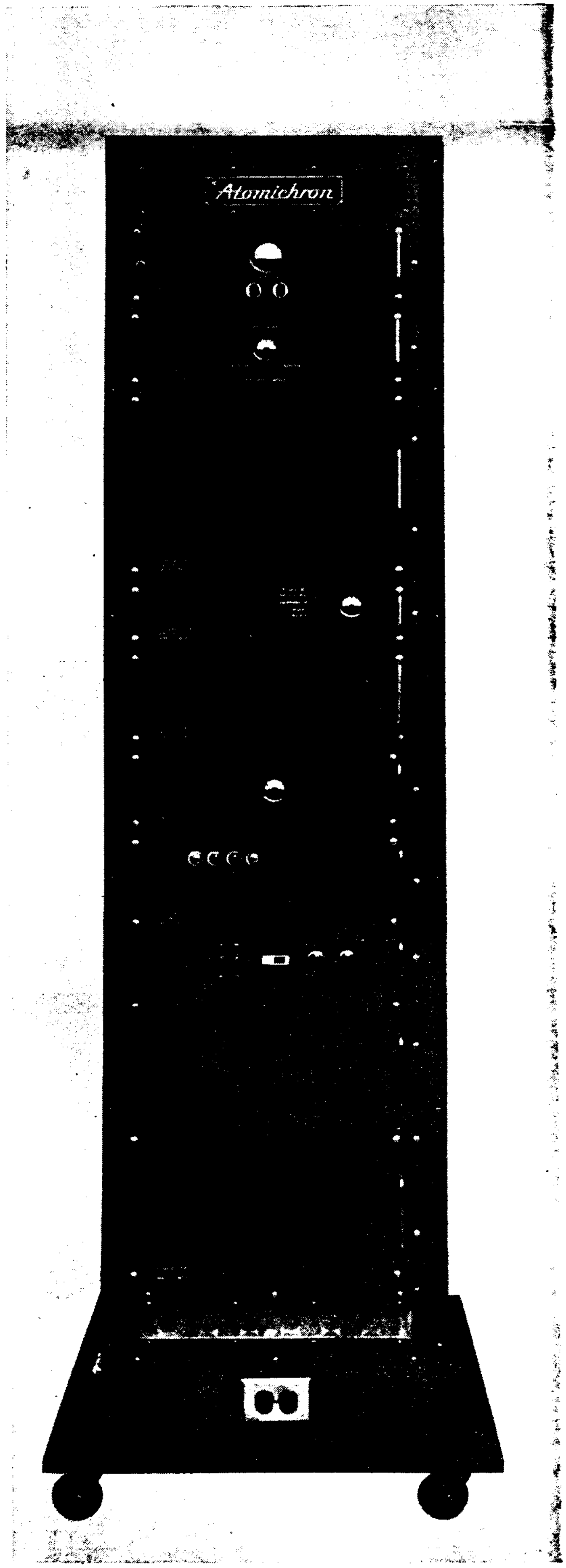
Why not tell time directly from an atom's own vibrations, instead of by the roundabout method of seeking its absorption frequency? The idea is indeed feasible, and a new atomic clock based upon it has been developed by C. H. Townes, J. P. Gordon and H. J. Zeiger at Columbia University. They call it the "maser" (for "microwave amplification by stimulated emission of radiation"). Their timekeeper is the ammonia molecule in the excited state, in which it emits rather than absorbs energy.

A beam of ammonia gas molecules coming from a high-pressure bottle enters a tube where it is first subjected to an electric field. This field acts as a focuser that disperses molecules in the low-energy, absorbing state and concentrates the emitters. The beam of emitters then flows into a "cavity resonator," where the molecules radiate their microwave energy. The size of this cavity is adjusted so that it resonates at precisely the frequency of the ammonia's radiation. Thus the energy emitted by the molecule is reinforced, and a strong oscillation is set up. The oscillation can be used to control the synchronous motor of an electric clock by means of a servomechanism.

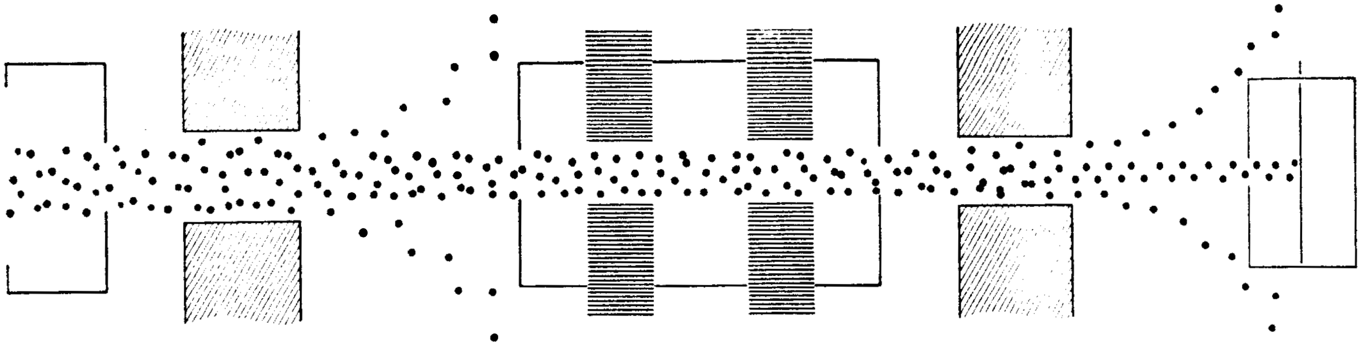
The maser has produced the purest oscillations ever generated—a signal very close to a single frequency. The frequency was stable to one part in 10 billion or better for more than an hour. This performance can probably be improved.

If the number of molecules fed into the maser's resonator is reduced below the level needed to sustain oscillations, and a small amount of energy in the





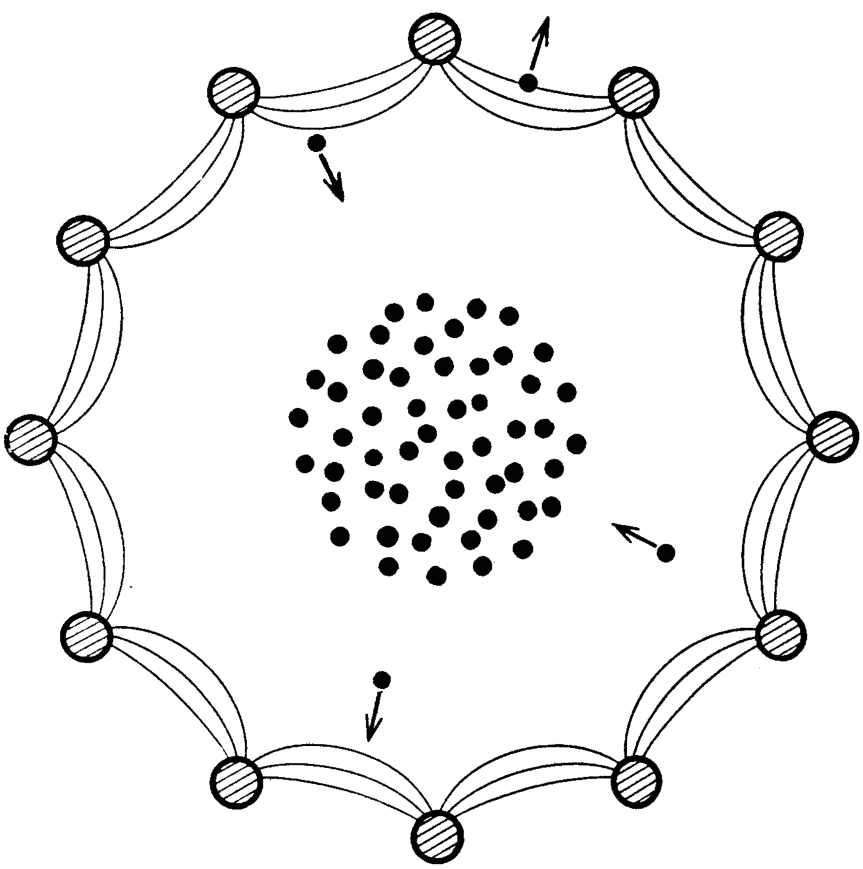
CESIUM BEAM EQUIPMENT at the Naval Research Laboratory in Washington is seen from the back at left and front at right. Cesium atoms are injected at the bottom and travel up the vertical tube to target chamber at top. Deflecting magnets are behind the two rectangular plates. This device is made by the National Company. It is the first commercial atomically controlled oscillator.



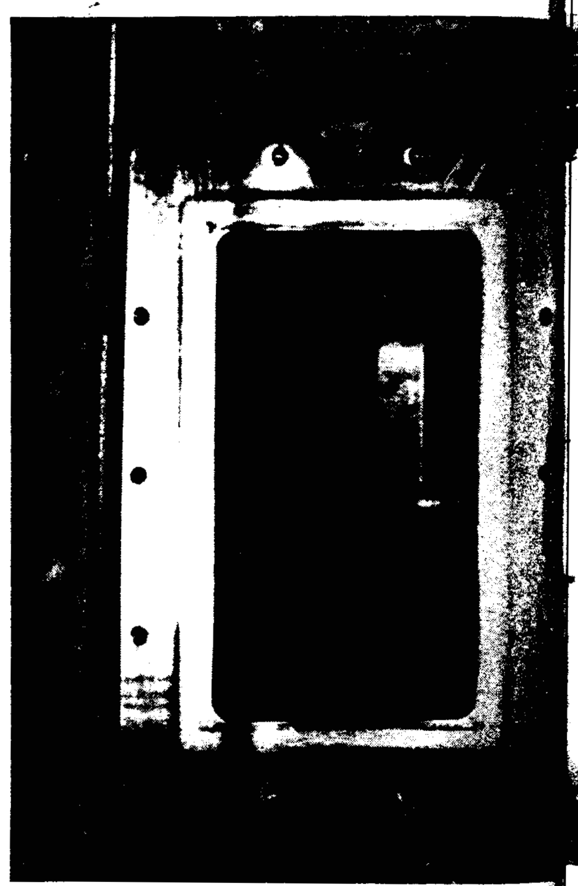
CESIUM BEAM PRINCIPLE is illustrated above. The beam emerging from the source (an electric furnace) contains atoms in two energy states. These are deflected by the first and second magnets in such a way that they miss the detector wire at right. When the atoms are excited by the radio field during their passage between the two magnets, they make transitions between the two energy states. The second magnet now deflects them in opposite direction so that they either land on detector wire or are refocused.

form of a radio wave of the right frequency is then added, the vibrations of the ammonia molecules will amplify the input signal. In this form the maser is an exquisitely selective and noiseless amplifier. It produces strong amplification when a weak signal at the proper frequency is fed into the cavity. Even if the input signal is contaminated with other frequencies, the ammonia responds only to its own vibration rate, so that its tuning is very selective.

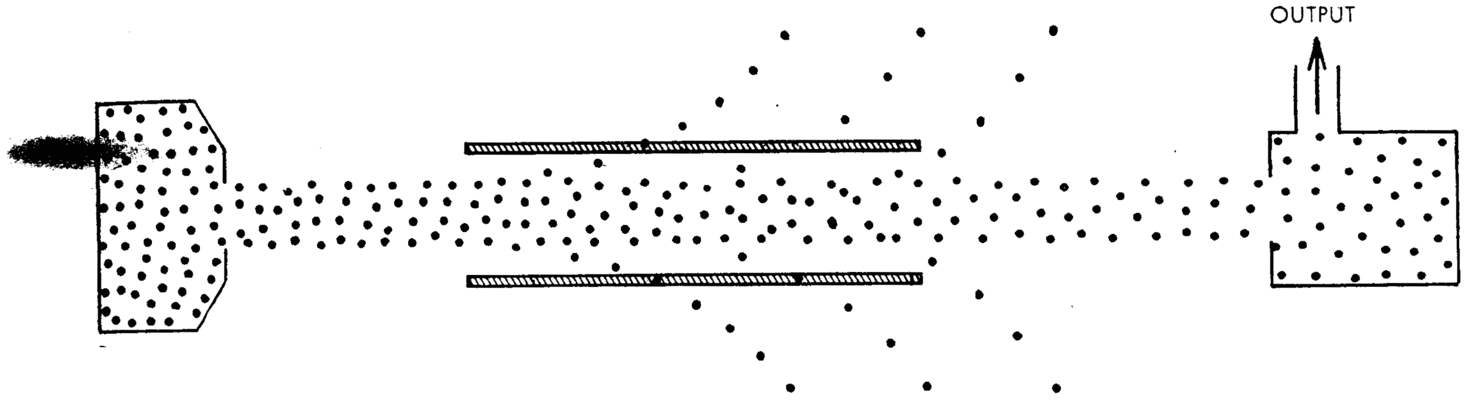
A number of laboratories are now building masers and applying them in many areas of research. Some experimenters are testing new designs which may give even higher degrees of accuracy. R. H. Dicke of Princeton University proposes to use rubidium atoms instead of ammonia molecules and to include argon gas as a buffer to insulate the rubidium atoms against collisions with one another. D. D. Babb, formerly of the Signal Corps Engineering Labora-



MASER FOCUSER seen end-on shows rods as hatched circles and the electric field as black curved lines. The colored dots are emitting molecules; black dots, absorbers.



MASER at Columbia University is seen with the front plate of the vacuum chamber removed. The



MASER PRINCIPLE is diagrammed above. Ammonia gas emerging from source (a high-pressure tank) contains high-energy molecules (*colored dots*) which emit radiation and low-energy molecules (*black dots*) which absorb it. The focuser is a ring of long electrodes. The electric field within the ring acts to disperse the low-energy molecules and concentrate the emitters. These find their way into the cavity, which is tuned to the frequency of the molecule. The oscillating energy is taken out through a wave guide.

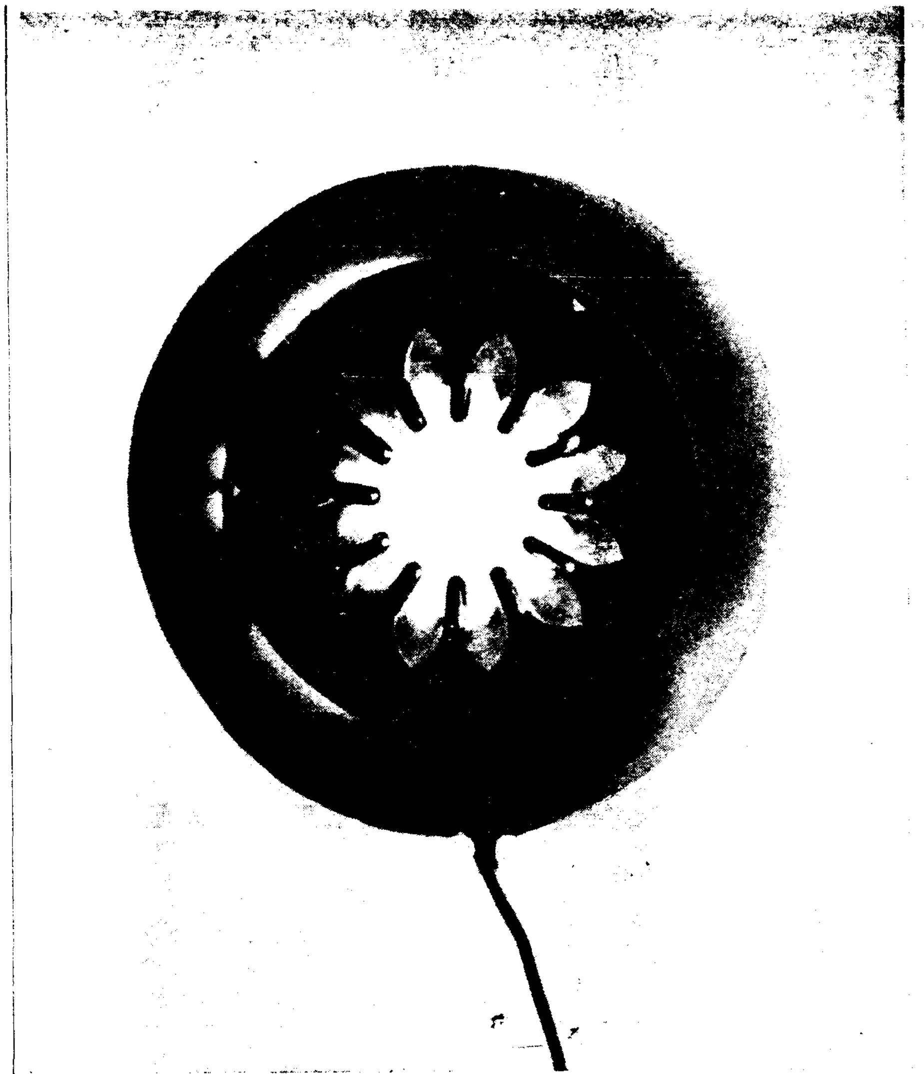
tories, hopes to build a maser with radiating cesium atoms, and he estimates that this clock would be stable to one part in 10,000 billion for long periods.

Uses for Atomic Clocks

When these remarkable timepieces have been built, what will they be used for? The list of needs is long and varied.

To begin with, atomic clocks would establish a more precise and invariant standard for the length of time units (*e.g.*, the second) than the astronomical one. The right time could be checked instantaneously, without waiting days or years for correcting astronomical measurements. The standard for distance could be related to the standard for time by means of an atomic clock coupled to an interferometer using microwaves. This would give the system of scientific units greater coherence and logic, for

ammonia "gun" is at left. Its gas stream is injected into the focuser, which is the assembly of horizontal rods in the center of the picture. The pipe at right is the resonant cavity, from which oscillating energy is withdrawn through rectangular pipe at upper right.



FOCUSER OF THE MASER, explained in the diagram on page 80, is photographed from the end. This component is from an early model of the maser built at Columbia University.

length and time are now measured in independent ways.

The establishment of a really accurate terrestrial time scale will permit more precise measurements of the earth's rotation, which in turn will help geophysicists to chart motions of the earth's molten interior, believed to be responsible for some of the irregularities in rotation. Atomic clocks also will play a major role in basic atomic research, making possible easier and more accurate measurement of the vibrations and rotations of molecules, atoms and nuclei.

Another imminent application is to aircraft navigation. Some of the present radio navigation instruments could give accurate position fixes over at least 3,000 miles if the frequency of the radio signals could be held stable to one part in a billion. Only 30 stations would be required to cover the entire globe.

The maser would even be useful in astronomy and cosmology. As a noiseless amplifier it would eliminate the noise generated in the circuits of radio telescopes and thus permit the resolution of weak signals, extending our vistas into space. Further, atomic clocks should make possible a check of the question whether the world of the atom runs on the same time as the universe.

There is a possibility that atomic clocks could furnish a test of Albert Einstein's general theory of relativity. The theory predicts that a light (or radio) wave traveling away from the earth should be slowed, or reduced in frequency, because of the work it does against gravity. A pair of atomic clocks, one at the bottom and the other at the top of a mountain, should be able to settle the point. The experiment would be of enormous interest, because there are few ways to check relativity theory.

Thus the atomic clock may reveal stories yet untold about our universe. Time will tell.