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THE ATOMIC CLOCK

An Atomic Standard of Frequency and Time

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National Bureau of Standards

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VOLUME 33 FEBRUARY 1949 NUMBER 2

New Helium Liquefier in Low-Temperature Research

An improved type of helium liquefier,[1] designed by R. B. Scott of the Bureau's cryogenics laboratory, is proving very useful in a program of basic research on the properties of matter at extremely low temperatures, where many remarkable phenomena occur. An important feature of the new liquefier, resulting in greatly increased versatility, is a transfer siphon for delivering the liquid helium to an external receiver that can be easily modified to accommodate the experiment at hand.

The production of temperatures in the region near absolute zero is becoming increasingly important in many fields of scientific investigation. At the temperature of liquid helium, metals such as lead and tin, ordinarily poor conductors of electricity, become superconductors with a complete loss of electrical resistance. The National Bureau of Standards, with the support of the Office of Naval Research, is now making studies to seek a more complete explanation of this and other low-temperature phenomena. Included in the program is an investigation of the extraordinary properties of helium II near absolute zero, which seems to constitute a fourth state of matter. It is expected that information of much basic scientific interest will result from this work.

The unique low boiling point of liquid helium (4.2 centigrade degrees above absolute zero under atmospheric pressure) makes it indispensable for low-temperature research, particularly in the region below 4.2° K. At ordinary temperatures, no pressure, however great, will liquefy helium, and free expansion through a throttle valve causes warming rather than cooling. However, if gaseous helium is first cooled to about 20° K, the expansion produced by continuous flow through a throttle valve will result in further cooling. This was the method used by H. Kamerlingh Onnes, who first liquefied helium in 1908 at the University of Leiden.

About 16 years ago, F. Simon devised a simpler method of liquefying helium, which is utilized in the present apparatus. He filled a strong, thermally insulated container with helium at 150 atmospheres pressure. After cooling with solid hydrogen to about 10° K, the compressed helium was allowed to escape through a throttling valve. When the pressure had reached atmospheric, the container was found to be more than half filled with liquid helium. This marked cooling effect may be explained in terms of the work done by the gas molecules remaining in the container as they push out the gas that escapes through the valve. The energy to produce this work is supplied from the internal energy of the helium, so that, as the expansion proceeds, the temperature of the gas left in the chamber falls. After the liquefaction temperature is reached, further expansion results in the liquefaction of a considerable fraction of the remaining gas.

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[1] For further technical details, see A Simon-type helium liquefier with transfer siphon, Russell B. Scott and J. Williamson Cook, Rev. Sci. Instr. 19, 889 (1948).

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TECHNICAL NEWS BULLETIN

U. S. Department of Commerce
Charles Sawyer, *Secretary*
National Bureau of Standards
E. U. Condon, *Director*

FEBRUARY 1949 Issued Monthly Vol. 33, No. 2

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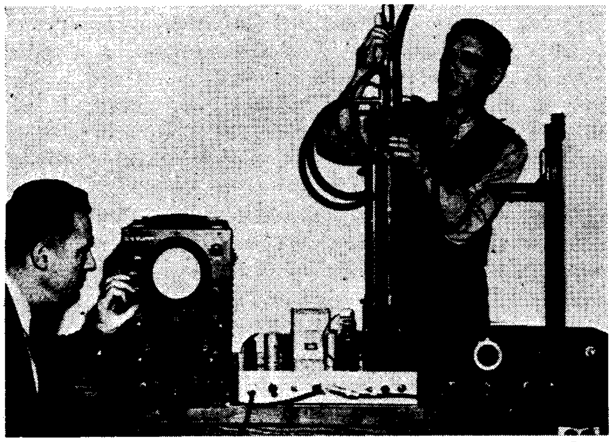
Contents

The helium liquefier constructed at the National Bureau of Standards operates on the Simon principle, but it differs from the usual type of Simon liquefier in that the liquid helium is delivered into an external receiver. In most earlier Simon-type instruments, on the other hand, the experimental chamber was a permanent part of the liquefier itself, and no provision was made for withdrawing the liquid helium. The new liquefier delivers about 310 cubic centimeters of liquid in a single expansion, sufficient for some experiments lasting as long as 24 hours.

The heart of the apparatus is a thick-walled monel chamber, designed to withstand a pressure of 4,100 pounds per square inch, within which the helium is liquefied. This chamber, together with an outer jacket containing pumped liquid hydrogen, is supported in an evacuated container by a tube of low conductivity, also used for filling and pumping the hydrogen jacket. The evacuated container is surrounded by liquid hydrogen in a sealed Dewar flask, which in turn is immersed in a Dewar of liquid air.

After all the inner parts of the apparatus have been cooled to liquid-air temperature by filling the hydrogen Dewar and the liquid-hydrogen compartment with liquid air, the liquid air is removed from them and replaced with hydrogen. Pure helium is then admitted slowly to the high-pressure chamber and the pressure rise observed. When the pressure in the chamber reaches about 80 atmospheres, the hydrogen container is refilled and pumping is started to reduce the pressure over this hydrogen. As the temperature is thus lowered, the helium pressure is brought to a maximum, about 150 atmospheres. When the temperature has been lowered to about 10° K, the helium is allowed to escape from the liquefier by expansion through a throttle valve at the end of a transfer siphon. This valve is adjusted so that the pressure falls at a moderate rate, reaching atmospheric pressure in 5 to 15 minutes. When condensation conditions are reached slightly below the critical temperature (5.2° K), liquid helium forms in the high-pressure chamber and flows over through the siphon as the expansion proceeds. After the expansion is complete, any liquid remaining in the chamber is forced over by the introduction of more helium gas. The cold helium gas that is first released serves to precool the external receiver, so that very little liquid helium is lost during the transfer.



In the Bureau's study of second sound, thermal pulses generated in liquid helium II (Dewar flask, background) travel through the helium as second sound and are detected by a temperature-sensitive element, amplified, and placed on the screen of the oscilloscope.

Temperatures are followed during operation of the liquefier by means of a gas thermometer having high sensitivity at low temperatures. The thermometer bulb is attached within the liquid-hydrogen jacket. The cryostat into which the liquid helium is usually transferred consists of a soda-glass helium Dewar surrounded by a Dewar of liquid hydrogen, which in turn is protected with liquid air.

The new helium liquefier promises to aid materially in several lines of low-temperature research now being pursued at the Bureau. Among these are the study of superconductivity and an experimental determination of the properties of He II.

The phenomenon of superconductivity, characterized by the complete disappearance of the electrical resistance of certain materials at very low temperatures, was discovered by H. Kamerlingh Onnes in 1911. Soon after this discovery, it was found that resistance reappears when a large electric current is sent through a superconductor or when a sufficiently strong magnetic field is applied. In 1918, F. B. Silsbee of the National Bureau of Standards postulated[2] that resistance is restored when the magnetic field reaches a critical value, regardless of whether the field is applied externally or is caused by the current in the conductor. This theory, known as the Silsbee hypothesis, has been verified for pure metals in numerous experiments; alloys, however,

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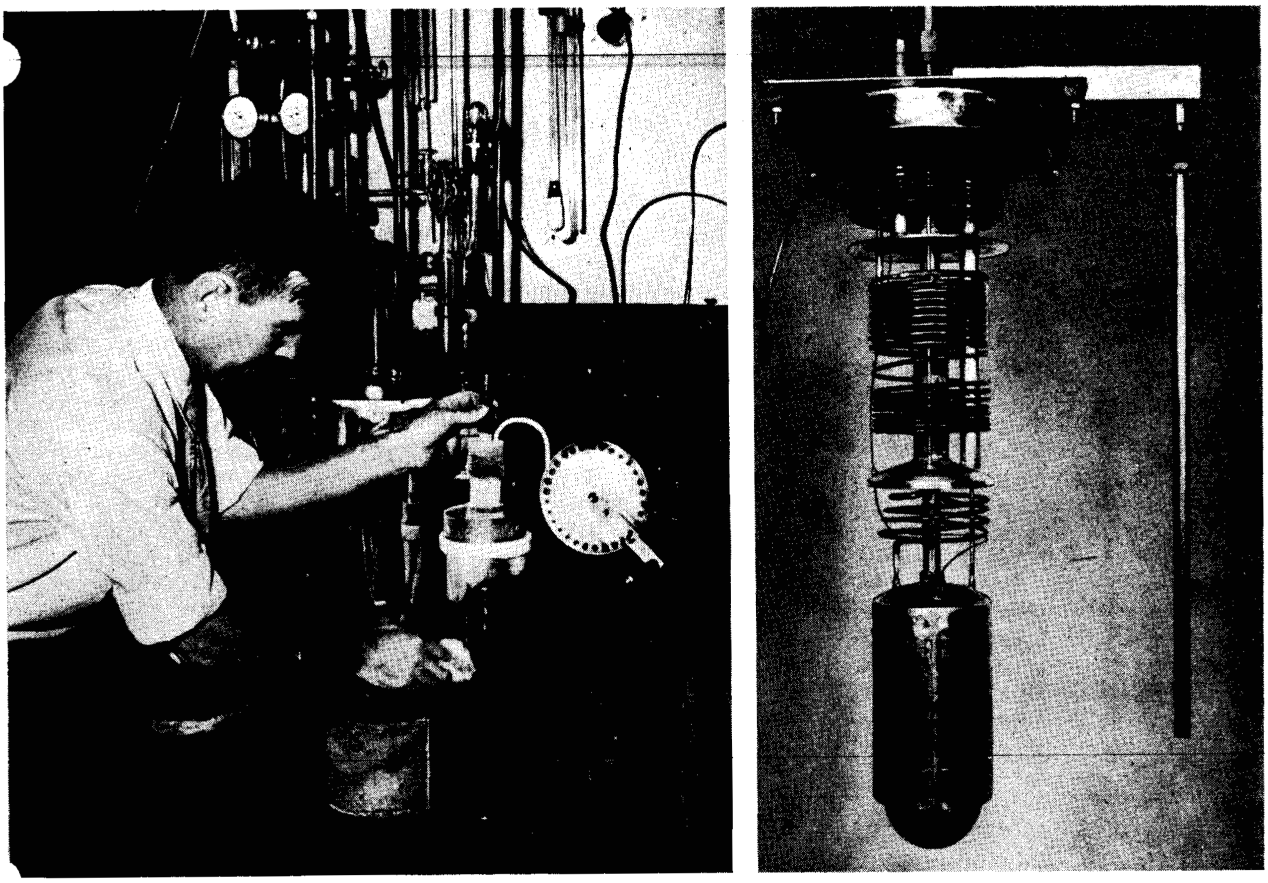
[2] Note on electrical conduction in metals at low temperatures, Francis B. Silsbee. Bul. BS 14, 301 (1918) S307.



eft: Helium liquefied in the new liquefier developed at the Bureau is collected for experimental use in a flask surrounded by liquid air. Right: The new liquefier, partially assembled. Helium gas at about 10° K is allowed to escape from the high-pressure liquefaction chamber (bottom) by expansion through a throttle valve at the end of the transfer siphon. The resultant cooling in the chamber produces liquid helium, which flows over through the siphon.

are an interesting exception. Dr. Silsbee also gave an analysis, based on electromagnetic theory, which described the resistance in a straight cylindrical superconducting wire as a function of the current as the current is increased up to, and beyond, the critical value. It was predicted that there would be no resistance until the current reached the critical value; the resistance would then rise suddenly to one-half the "normal value" (its value just above the superconducting transition temperature); and, upon further increase of current, the resistance would rise gradually to approach the normal resistance as the current was increased indefinitely.

As part of a comprehensive research program on superconductivity at the National Bureau of Standards, an experimental investigation [3] was recently made of the restoration of the resistance of superconducting wires with increase in current. Straight lengths of pure indium wires of three different diameters were immersed in a bath of liquid helium and cooled until they became superconducting. Resistance was obtained as a function of current for each specimen at several different temperatures. It was found that there was a sudden rise of resistance when the current reached a critical value, followed by a slower rise of resistance as the current was further increased. Moreover, the amount of resistance that appeared suddenly was independent of the temperature of the specimen, even though the current required to restore this resistance was temperature-dependent. To this extent the results described are in agreement with the theory. However, the magnitude of the sudden rise of resistance was 77 to 85 percent of the normal resistance, instead of one-half, as predicted. Also, the larger the diameter of the wire, the smaller was the fraction of the normal resistance that reappeared when the current reached the critical value, although the theory shows no dependence on specimen diameter.

This disagreement with theory adds interest to the experimental results. Recent theoretical investigations on the nature of the intermediate state of superconductors have pointed out in a qualitative way some of the shortcomings of the earlier theory, but as yet no quantitative theoretical treatment has explained the experimental results.

Another phase of superconductivity research at the Bureau concerns the behavior of superconductors at

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[3] The destruction of superconductivity by current. Russell B. Scott, J. Research NBS **41**, 581 (1948) RP1940.

microwave frequencies. In experiments using low-frequency or direct currents, superconductors show a complete loss of resistance below the transition temperature, whereas at optical and infrared frequencies the superconducting state does not occur. The microwave region remains as a kind of twilight zone; here the metals exhibit an intermediate type of behavior, losing only a portion of their resistance at low temperatures. Results of the present investigation may well contribute to a clearer conception of the fundamental nature of the phenomenon.

At 2.19° K, ordinary liquid helium (He I) undergoes a transition to He II with a radical alteration of many of its properties. In some ways He II acts as though it has no viscosity, flowing through virtually vacuum-tight openings and up the side of a containing vessel in apparent defiance of gravity. At the transition temperature the thermal conductivity of He I increases very abruptly to an apparent value for He II much greater than that of any other substance. This is because heat is propagated in He II as a kind of wave motion analogous to sound and known as "second sound," whereas in other materials heat flow is purely a diffusion phenomenon. All of these effects may be explained by the presence in He II of a superfluid. The atoms of the superfluid have had their energies reduced by cooling to the point where thermal motion has almost ceased, yet the intermolecular forces are not great enough to produce a rigid solid. As a result, viscosity practically disappears, and other remarkable properties ar observed.

Second sound has recently been obtained at the National Bureau of Standards through use of liquid helium produced in the new Simon-type liquefier, and a project is now well under way at the Bureau for the study of various aspects of second-sound propagation in He II. Unlike ordinary sound, second sound is generated thermally and can be detected only by temperature-sensitive devices, rather than by microphone. The present investigation employs a recently developed pulse method [4] so that signals that would otherwise be quite difficult to detect are presented on an oscilloscope screen for visual observation. Pulses of heat generated electrically within liquid He II travel through the helium and are detected upon arrival at a temperature-sensitive element; meanwhile, their transit time is measured accurately by electronic timing circuits. Several quantities, including the velocity and attenuation of second sound, result directly from these data. Various types of coupling with ordinary sound are also under study by this method. Investigation of the properties of liquid He II provides one of the most promising approaches toward a better understanding of the properties of matter. The work now in progress at the Bureau should eventually lead to a clearer picture of the liquid and solid states.

NBS Interim Computer

Design and development work supported by the Department of the Air Force is well under way at the National Bureau of Standards for the construction of a small-scale electronic computing machine to be used until the several large-scale machines now being built become available. The new high-speed machine, to be known as the NBS Interim Computer, will perform a substantial portion of the computation work of the Bureau's laboratories, solving many problems until recently considered impossible of solution. It will also aid in computing-machine development at the Bureau and will provide important training and operational experience for personnel of those agencies that plan to operate the more complex electronic computers when their construction is complete.

The National Bureau of Standards is now engaged in an extensive computer program, in cooperation with the Office of Naval Research, the Bureau of the Census, the Department of the Army, and the Department of the Air Force. This program involves the research, design, and development work necessary to produce electronic machines that will perform, upon instruction, predetermined sequences of calculation running into the thousands of operations without the intervention of human operators. The result will be the solution in a few hours of complex problems in atomic physics, ballistics, and aerodynamics that cannot now be solved except by simplifying assumptions and thousands of man-days of work. The rapidity with which numerical data can be handled, classified, and analyzed will also be cor respondingly increased.

These new large-scale electronic computing machines are being eagerly awaited. However, because of their complexity, their construction is a long-range project. Meanwhile, by scaling down certain features of a larger machine, such as the high-speed memory, the Bureau expects to assemble within a few months a machine capable of solving many of the less complicated problems that continually arise in scientific work. Such a small-scale computer will be quite adequate for routine computations similar to those now being performed in the Computation Laboratory of the Bureau's Applied Mathematics Division. Moreover, it is expected to increase present knowledge of maintenance and servicing problems related to electronic digital computers and will be invaluable in many other ways as a test model and research instrument.

In its essential elements, the new Interim Computer will be similar to the EDVAC (Electronic Discrete Variable Automatic Computer), an electronic digital computer now under construction for the Army at the Moore School of Electrical Engineering, University of Pennsylvania. The NBS machine will have a memory capacity of 500 "words", or series of numbers, in contrast to the 1,000-word memory to be built into the EDVAC. Initially the input and output equipment will be punched paper tape instead of magnetic recording

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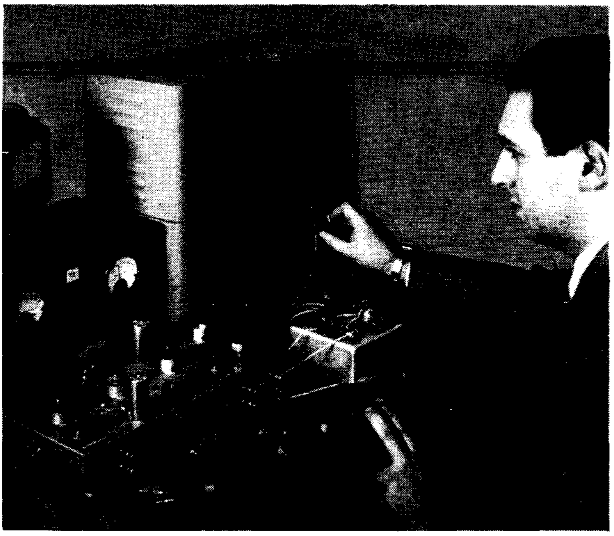
[4] J. R. Pellam, Phys. Rev. 70, 841 (1948).



The performance of miniature tubes and pulse transformers (foreground), specially designed for use as ssential elements of the NBS Interim Computer, is valuated in NBS electronics laboratories. A tube and transformer under study appear just beneath the operator's hand.

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wire. Although the number of commands the calculator can obey is substantially reduced, its computing power should be of the same order of magnitude as that of the EDVAC. It will accept numbers in binary form, which are the equivalent of more than 12 decimal digits, together with algebraic sign. The average time for addition of two such numbers will be 864 microseconds; for multiplication, 2,880 microseconds. Operating at this high speed, the NBS Interim Computer will be an extremely powerful computing system, capable of solving many of the problems—considered insolvable only a few years ago—that are now handled by the famous ENIAC (Electronic Digital Numerical Integrator and Computer), located at Aberdeen Proving Ground. It is hoped that the Interim Computer will be assembled and ready for testing by summer.

Plans are also being made by the Bureau for the design and construction of another automatic computing machine for its West Coast mathematics laboratory, the Institute for Numerical Analysis. Present indications are that the high-speed memory for the machine will be of the electrostatic type based on the standard cathode-ray-tube memory device developed at Manchester University in England. This project will not only provide a more powerful computing facility at the Institute for Numerical Analysis, but should also furnish an excellent opportunity for the study of the parallel type of computer.

The Atomic Clock

An Atomic Standard of Frequency and Time

A basically new, primary standard of frequency and time, invariant with age, has been developed at the National Bureau of Standards; an atomic clock based on a constant natural frequency associated with the vibration of the atoms in the ammonia molecule. Derived from a principle developed by Dr. Harold Lyons of the Bureau's microwave research laboratory, the new clock promises to surpass by one or two orders of magnitude the accuracy of the present primary standard, the rotating earth. Dr. Lyons was assisted in the design and construction of the clock by B. F. Husten, E. D. Heberling, and other members of his staff.

This is the first atomic clock ever built and is controlled by a constant frequency derived from a microwave absorption line of ammonia gas, providing a time constancy of 1 part in 10 million. Theoretical considerations indicate a potential accuracy of 1 part in a billion or even 10 billion, depending on the type of atomic system and spectrum line used.

The present crowding of the radio-frequency spectrum has imposed severe limitations, both nationally and internationally, on the expanding use of radio for industry and communications. The atomic clock may be expected to benefit greatly the communications industries and the military services, for it will, in effect, provide additional room in the radio-frequency range for more communication stations of all types. The present "radio space" allows for a drifting of each station's frequency, so that a broad radio space is required if interference with other stations is to be avoided. The maximum utilization of available space in the radio spectrum depends on the accuracy with which the frequency of an individual station can be controlled, especially at the higher frequencies where quartz crystals cannot be used as frequency-controlling elements. These frequencies, used by radar, television relays, and microwave equipment in general, could be controlled by atomic elements. Such control would also make possible the permanent establishment of radio channels on such an exact basis that tuning could be made as automatic as the dialing of a telephone number.

The improvements in frequency and time measurement offered by the atomic clock are also of fundamental importance in many fields of science. An absolute time standard will be of special importance in astronomy, where present time standards leave much to be desired. The atomic clock and the method represent important tools of research and development in every technical field where precise measurements of time and frequency are crucial—for example, in long-range radio navigation systems, in the upper range of the microwave region where atomic systems can serve as electronic components, and in basic research in microwave spectroscopy and molecular structure.

The present time and frequency standards are based on astronomical determinations of the period of rotation of the earth. However, the earth is very gradually slowing down in response to the forces of tidal friction in shallow seas. In addition, there are irregular variations, some of them rather sudden, in the period of rotation, the reasons for which are unknown. These two causes are responsible for changes in mean solar time and therefore in the frequency of any periodic or vibrating systems measured in terms of such time standards.

In recent years, vibrations of atoms in molecules, or what are more specifically termed spectrum lines originating in transitions between energy levels of these atomic systems, have been found in the microwave region of the radio spectrum. It has been possible to make very precise measurements of these lines by radio methods using all-electronic equipment of unprecedented sensitivity and resolution. When it became evident that such spectrum lines might eventually provide new primary frequency standards, scientists at the Bureau began seeking a means of utilizing one of these lines to control an oscillator which in turn could be used to drive a clock. Because the resulting equipment, the atomic clock, is controlled by the invariable molecular system of ammonia gas, it is independent of astronomical determinations of time.

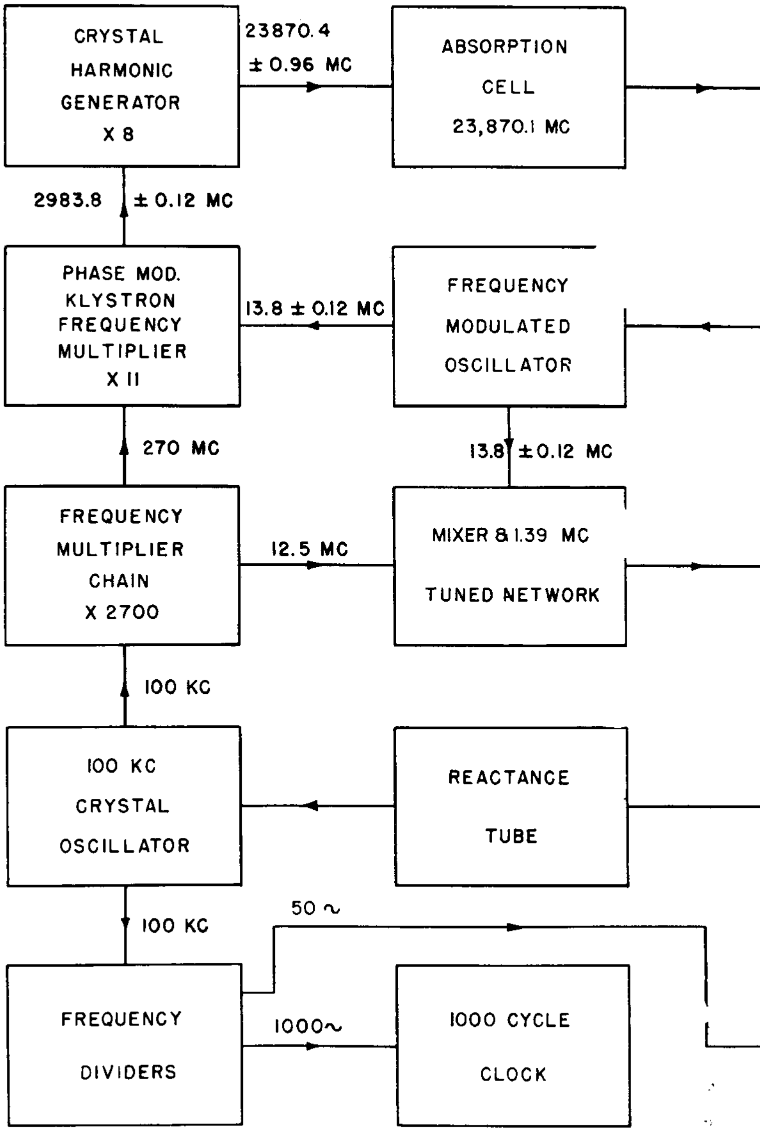
Principles and Operation

The National Bureau of Standards atomic clock consists essentially of a crystal oscillator, a frequency multiplier, a frequency discriminator, and a frequency divider, all housed in two vertical-type cabinet racks; on the top of the cabinet are mounted a special 50-cycle clock and a waveguide absorption cell. Ammonia gas under a pressure of 10 or 15 microns is maintained in this cell, a rectangular ½- by ¼-inch copper tube wound in a compact 30-foot spiral about the clock.

The new development uses an absorption frequency of ammonia to hold a microwave signal fixed. If the microwave signal output of a generator differs in frequency from the ammonia absorption line, then the control circuits generate an "error signal" which brings the microwave signal back to the frequency of the spectrum line. The oscillator generating the microwave signal is thus controlled, and the setting of the clock which it drives can be compared with an astronomical clock.

The microwave signal is initiated by a 100-kilocycle quartz-crystal oscillator or any other oscillator which, for purposes of convenience and accuracy, is designed for a high degree of stability. By means of vacuum-tube circuits and silicon-crystal diodes, this frequency is multiplied to provide output signals throughout the microwave range. These signals are compared with the frequency of a microwave spectrum line, in this case of ammonia gas, by suitable control circuits, often called frequency discriminator or "servo" circuits. If the quartz-crystal oscillator drifts after the microwave signal at the upper end of the multiplier chain has been exactly tuned to the frequency of the spectrum line, the discriminator circuit generates an output signal which, through the proper control circuits, can be applied to the oscillator at the bottom of the multiplier chain to bring it back to the proper frequency. By means of a frequency divider, the 100 kilocycles may be reduced to any desired frequency for driving a clock; for example, one thousand cycles or 50 cycles.

Frequency-discriminator or servo-mechanism control circuits for atomic clocks might be developed in many different forms. The electronic control circuit in the present atomic clock [5] is one successful form of several being developed by the National Bureau of



The NBS atomic clock, which is controlled by a constant frequency de
rives its fundamental driving signal from a 100-kilocycle quartz-crysta
monic generator multiply this signal up to microwave frequencies an
The frequency of these signals is then compared with the ammonia f
control link. After the microwave signal is exactly tuned to the freq
oscillator will cause the discriminator to send an "error signal" back
The crystal oscillator is thus locked to the invariant frequency of the
synchronous-motor clock, first reducing the stabilized 100-kilocycle sig

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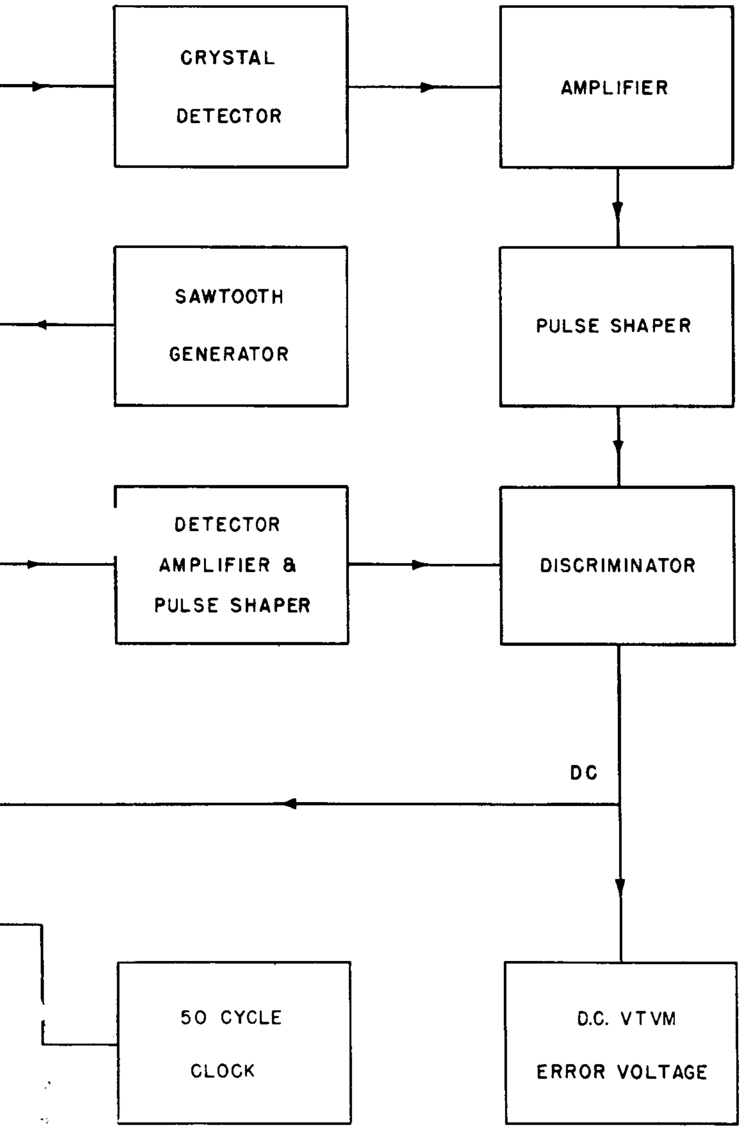
[5] Microwave frequency standards, Harold Lyons, Phys. Rev. 74, 1203, (1948). This includes the first discussion of the atomic clock, presented at the meeting of the American Physical Society in Washington, D. C., on April 30, 1948.

Standards. It is now being refined to give even greater timekeeping accuracy.

The fundamental frequency signal generated by the 100-kilocycle oscillator is first multiplied up to 270 megacycles per second (abbreviated Mc) by a frequency-multiplying chain using standard low-frequency tubes. In the next step, the multiplying chain is continued up to 2,970 Mc by means of a frequency-multiplying klystron, which is also modulated by an FM oscillator generating a signal at 13.8±0.12 Mc. This makes the frequency-modulated output of the klystron 2983.8±0.12 Mc. After further amplification, the frequency-modulated signal is multiplied in a silicon crystal rectifier to 23,870.4±0.96 Mc, and fed to the ammonia absorption cell. As the frequency of this modulated control signal sweeps across the absorption line frequency of the ammonia vapor, the signal reaching the silicon crystal detector at the end of the absorption cell dips because of the absorption, thus giving a negative output pulse.[6]



**uency derived from a microwave absorption line of ammonia gas, de-
rtz-crystal oscillator (lower left). Frequency multipliers and har-
encies and provide output signals throughout the microwave range.
monia frequency standard by frequency-discriminator circuits in the
the frequency of the spectrum line, any drift in the quartz-crystal
al" back to the oscillator, maintaining it at the proper frequency.
y of the ammonia line. A frequency divider chain then drives a
locycle signal to the clock frequency.**

A second pulse is generated when the output of the frequency-modulated oscillator at 13.8±0.12 Mc is fed to a mixer (or radio receiver) into which is also fed a 12.5-Mc signal from the quartz-crystal multiplying chain. When the signal sweeps across the proper frequency to be tuned in (12.5 Mc plus the 1.39-Mc intermediate frequency of the receiver, or 13.89 Mc), an output pulse is generated. The time interval between the two pulses—that from the absorption cell, caused by the absorption line, and that from the receiver or mixer—is a measure of the degree to which the frequency-multiplying chain is tuned to the absorption line. The two pulses can therefore be made to control a discriminator circuit that will give zero output when the time interval is right (that is, when the circuit is tuned to the absorption line) and will generate a control signal when the time interval is wrong. If the quartz-crystal oscillator drifts in frequency to higher values, the time interval between the two pulses increases; for frequencies that are too low, the interval decreases. The control signals thus generated are fed to a reactance tube, which then forces the quartz-crystal circuit to oscillate at the correct frequency to tune to the absorption line. The quartz-crystal oscillator is thus locked to the ammonia line. Frequency dividers then divide the precise 100-kilocycle signals down to 50 cycles to drive an ordinary synchronous-motor clock, and also down to 1,000 cycles to drive a special synchronous-motor clock, which is designed for exact adjustment and comparison with astronomical time to within 0.005 second.

Control of the quartz-crystal circuit depends on the relative duration of the positive and negative portions of a square-wave signal generated by the discriminator. In the discriminator, the two pulses between which the time interval is to be measured turn a trigger circuit or square-wave generator on and off. When the time interval is correct, the on-off cycle generates no output signal from the positive and negative peak detectors driven by the square-wave signal. The detectors or rectifiers draw current on the positive and negative peaks of the square wave, but when the positive and negative portions of the square wave are of equal duration, they balance and give no direct-current output. However, if the time interval between the two input driving pulses gets longer or shorter, the relative duration of the positive and negative parts of the square wave changes, so that a resultant direct-current output is generated. This output is positive or negative, depending on the change in the time interval. Thus, no con-

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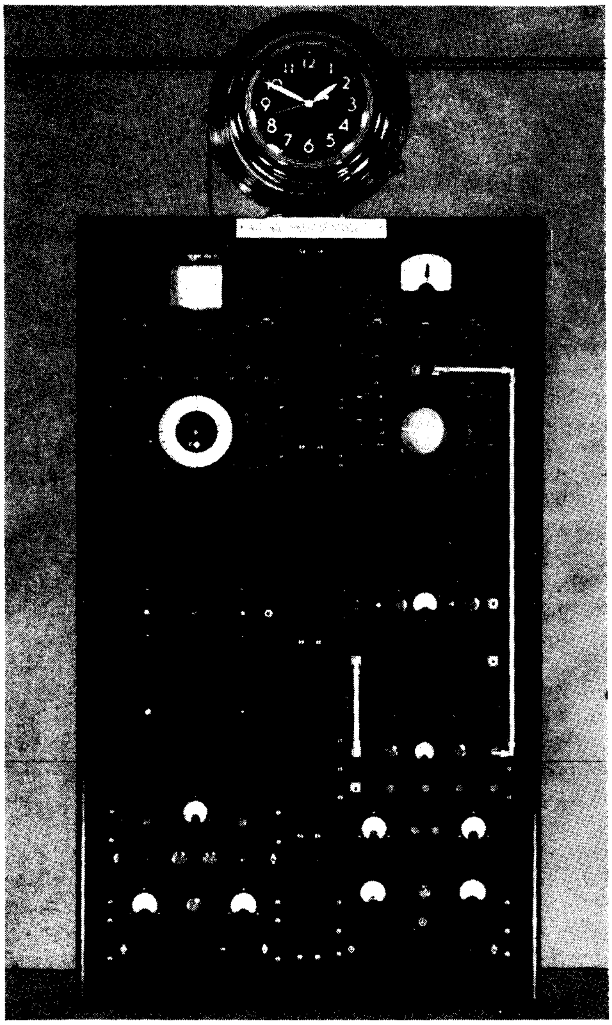
[6] Somewhat similar pulse circuits were first used in a stabilized klystron oscillator by Dr. W. D. Hershberger of the RCA Laboratories, Princeton. Such an application is fortunately simpler than the application to an atomic clock, which must work with much lower signal levels.



The new NBS atomic clock is completely contained in a single unit with the electronic equipment housed in a standard rack cabinet and the waveguide absorption cell wound in a spiral around a 50-cycle synchronous clock (top).

trol voltage is generated when the quartz-crystal oscillator is on the proper frequency to agree, through the frequency-multiplying chain, with the ammonia line; but a positive or negative control voltage is produced for correcting the oscillator circuit when it drifts one way or the other from its proper value.

Recording equipment and a frequency meter are used in checking the accuracy of the clock. For this purpose, the frequency of the clock's crystal oscillator is compared to the frequency of the Bureau's primary frequency standards, a group of precision, 100-kilocycle quartz-crystal oscillators calibrated in terms of the U. S. Naval Observatory time signals. These oscillators maintain constant frequency with respect to each other to an accuracy of 1 part in a billion for intervals up to 10 hours, and better than 1 part in 100 million per day. They can therefore be used to measure the constancy of the atomic clock to this accuracy. This is done by beating the signals from the two sources together at a frequency of 12.5 Mc to obtain greater measurement sensitivity. A change of 1 cycle per second in the frequency of the beat note, as recorded on the frequency meter or on an automatic recorder, indicates a frequency variation of 1 part in 12.5 million. In recent tests the clock maintained a constancy of one part in ten million for several hours. These tests show that the clock will lock accurately to the ammonia line even when a perturbing signal is applied to the reactance tube in the attempt to force the clock to change its rate.

Ultimate Accuracy

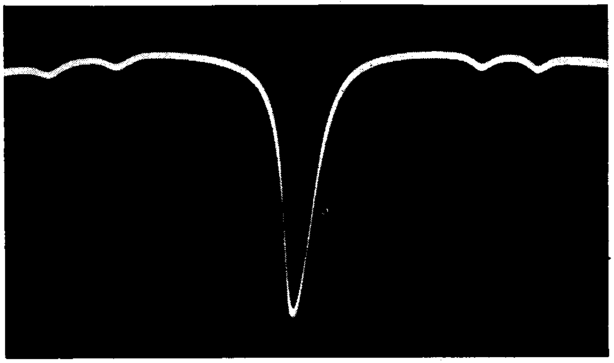
The ultimate accuracy of an atomic clock depends on many factors, of which the most important are those governing the width of the spectrum line. Spectrum lines are not infinitely narrow but have a finite width covering a considerable frequency range, since atoms or molecules do not emit or absorb radiation at only one frequency but rather over a narrow band of frequencies. The ratio of a line frequency to its width at the half-power points is called the Q of the line, in analogy to the Q (quality) factor of resonant circuits used in standard radio technique. The Q is a measure of the sharpness of the line and therefore determines its usefulness as an accurate frequency and time standard.

In the case of ammonia, the natural line width determined by the uncertainty principle of quantum mechanics gives a Q of about 10^{18} (a billion billion). If a line width were determined only by the natural life of an excited state in the ammonia molecule, giving a Q of 10^{18}, frequency and time could be determined to better than 1 part in a billion billion (1,000,000,000,000,000,000). However, the line is broadened by other factors that lower the Q to a value of from 50,000 to 500,000, depending on the temperature and pressure of the gas. This may be compared to Q values of roughly 50,000 for a good cavity resonator in a microwave circuit and values of 1,000,000 or so for the best quartz crystals. The ammonia spectrum line thus has a Q approximating that of the best quartz crystals, though much more constant and stable.

The ammonia molecules in the absorption cell are moving rapidly in random thermal motion at an average speed of almost 2,000 feet per second at room temperature. When a gas molecule in an absorption cell is approaching or receding from the source of an electromagnetic wave because of its heat motion, its absorption frequency is different from that which it would have if it were standing still. This gives rise to a "Doppler broadening" of the absorption line, analogous to the change in pitch of sound as its source approaches, passes, and leaves an observer. Thus, the line width can be reduced slightly by lowering the temperature of the gas (or by using a heavier molecule). Doppler broadening lowers the Q of the ammonia line to about 330,000 at room temperatures.

Molecular collisions also broaden the absorption line. This broadening occurs because the collisions abruptly terminate the absorption process, causing the molecules

While the NBS atomic clock is in operation, the monitoring oscilloscope continuously displays a trace of the 3,3-absorption line of ammonia. The symmetric output pulse is produced by absorption of the FM control signal as it sweeps across the natural absorption-line frequency of the ammonia gas.



to absorb wave trains whose lengths vary in a random way determined by the distribution of time intervals between collisions. A frequency analysis of these wave trains shows a corresponding random distribution of absorbed frequencies, all centering about a mean value determined by the number of collisions per second. In ammonia gas at a pressure of 10 microns there are about 120,000 collisions per second, giving an experimentally measured Q of 45,000 for the absorption line used. (This is the line known to spectroscopists as the 3,3 line, for which the quantum numbers J and K are each equal to 3.)

Actually, there are more collisions effectively interrupting the absorption process in ammonia than the kinetic theory of gases would indicate. Further broadening of the line results from collisions of the molecules with the walls, and even near misses between molecules cause interaction strong enough to interrupt absorption. The number of collisions per second, and thus the collision broadening, can be reduced by lowering the gas pressure. This process, if not carried too far, does not reduce absorption in the gas, because the decrease in number of molecules absorbing energy is offset by the increase in absorption per molecule resulting from the increase in Q. However, when the pressure is reduced too much, a phenomenon known as saturation of the line sets in, caused by an excess of radiation. Too few molecules are then left in the proper energy states to absorb the microwave radiation coming into the cell. Many molecules, which normally would be in the proper energy state to absorb the incoming radiation, are in an excited state as a result of previous absorption. Eventually these molecules will emit the quanta that they have absorbed, returning to the normal level where absorption is again possible. However, as this process is slow, the molecule usually returns to the ground level in a collision with another molecule, converting the absorbed radiation into heat. As the gas pressure is lowered, the number of collisions is greatly reduced, and not enough molecules return to ground levels. The excessive incoming radiation then weakens and broadens the absorption line through saturation.

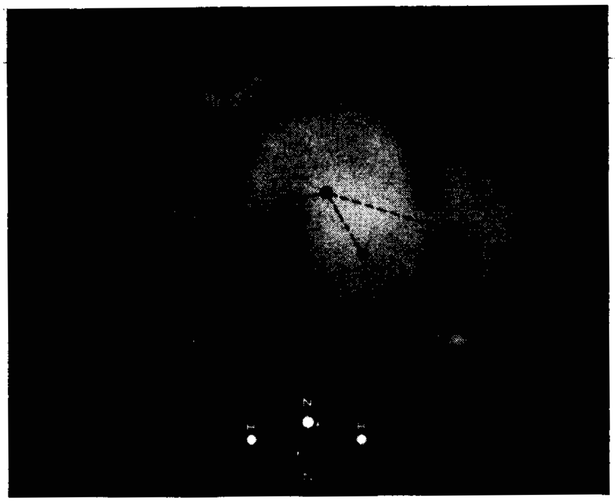
Saturation can be eliminated by reducing the strength of the incoming radiation. However, as the gas pressure and radiation intensity are both lowered, a condition will finally be met for which the signal strength will be down in the natural electrical noise level of the circuits used to detect the signal. Circuit noise then sets the ultimate limitation on the reduction of collision and saturation broadening. It is estimated that a Q of 300,000 to 400,000 can be attained at pressures of about 1 micron, still a long way from the Q of the natural line width. Assuming that effective Q values of 400,000 can be obtained with ammonia, an accuracy of 1 part in 100 million or better should be possible, since a measurement of the center of the absorption line to within 1/250 of the width of the line could be made.

Applications and Significance

Improvement of the accuracy of the atomic clock will make it useful in several fields of pure and applied science. The lengths of the mean solar day, used in astronomical measurements, fluctuate as much as 1 part in 20 to 30 million, because of variations in the rate of rotation of the earth on its axis. The variation in present time standards, due to these fluctuations, causes errors in the location of heavenly bodies and in studies of their orbits and motions. The atomic clock offers the possibility of an invariant master clock against which the variation in the earth's time-keeping could be measured. An absorption cell on an atomic clock could, for some purposes, take the place of an astronomical observatory.

Broadcasts of standard frequency are of importance in keeping all kinds of radio, radar, and electronic equipment properly tuned throughout the world. This service is required in international transportation and communications so that, for example, an airplane with radio-navigational equipment will be using the right frequency wherever it is in the world and whatever airport it is using. At present, the Bureau's radio station, WWV, broadcasts standard frequency and time signals on several transmitter frequencies to all the world. The Navy Department also uses quartz-crystal clocks to broadcast time signals for navigational purposes. These quartz-crystal clocks drift slightly in frequency and have to be adjusted to keep them in agreement with the basic astronomical time signals. Clocks of this type could be kept constant automatically by means of absorption lines.

Maintenance of transmitter frequency to within close limits is also necessary to utilize the available radio spectrum efficiently. The use of long-distance standard frequency broadcasts is complicated by a large reduction in accuracy due to ionospheric effects. A long distance, short-wave signal travels around the earth by reflection from the upper ionized regions of the atmosphere, known as the ionosphere. Every morning at sunrise the ionosphere moves downward, and every evening at sunset it rises. This daily variation in height causes a Doppler shift of the frequency of the



The quantum transition by which the ammonia molecule (top), absorbing energy at one sharply defined frequency, can turn itself inside out is illustrated in classical terms by the schematic diagram (below). An absorption line produced by such a transition serves as the frequency control for the NBS atomic clock.

reflected wave and, together with other as yet unknown causes, is responsible for a reduction by a factor of 25 or more in the accuracy of the frequency of the received signal. Thus, the Bureau's standard-frequency broadcast agrees with astronomical time signals to 1 part in 100 million at the transmitter but may be known to only 1 part in 4 million after transmission over long distances. This difficulty can be partly overcome in several ways. One is the provision of a local, precise frequency standard calibrated by means of received standard time signals also transmitted by radio. However, this process, which requires a day or more, complicates the equivalent problem and introduces additional errors, making impractical the use of standard-frequency broadcasts for instantaneous or continuous frequency calibrations of the highest precision.

At the most recent International Radio Conference held in Atlantic City in 1947, plans were formulated to provide standard-frequency and time broadcasts from many stations located to render good service throughout the word. These services may be improved or simplified by means of atomic clocks and frequency standards. Such clocks could control the standard-frequency emissions of the various stations without checking and monitoring by astronomical time signals. The Doppler frequency shifts could then be eliminated by limiting transmission distances to short ranges. Also, equipment anywhere in the world could be checked against an absorption line with the certainty of obtaining a precision calibration against an absolute standard and without depending on a standard-frequency broadcast.

One advantage of the rotating earth as the basic timekeeper is that it never stops rotating or breaks down. Likewise, any man-made clock must not break down but must be kept running forever if it is to keep track of time from some arbitrary instant chosen as a starting point. With the present quartz-crystal clocks, this difficulty is met by using a large number of similar clocks constantly intercompared so that breakdown of one does not mean a loss of timekeeping records. Although this procedure could also be used with atomic clocks, it would not be necessary for use of the clock as a frequency standard or for defining a standard of time intervals, since these applications do not require continuous operation of the atomic clock.

The atomic clock should permit improvement in astronomical time standards in a way impossible with electric-pendulum or quartz-crystal clocks. It thus opens the possibility of improving the precision of knowledge of the length of the year, that is, the time it takes the earth to revolve once in its orbit around the sun. This is independent of the time it takes the earth to rotate once on its axis, the mean solar day. Measurements could then determine whether the mean sidereal year is more constant than the mean solar day, as some astronomers believe may be the case.

Although the use of atomic time presents advantages in many fields of science, it will always be necessary for some purposes to have astronomical time standards. This is because the pointing of a telescope depends on the orientation of the earth at the instant of observation, in other words, on astronomical time measurements that derive from the motion of the earth.

The NBS Program and Microwave Spectroscopy

The atomic clock program is being carried on at the Bureau along several different lines. Among these is a project being developed with the cooperation of the atomic beam laboratory of Columbia University, which may result in greatly improved accuracy. In this method, quantum transitions in beams of atoms such as cesium will be used to establish frequency and time standards. The broadening of the lines by collisions and Doppler effect is largely eliminated in this method so that the potential accuracy is increased by a factor of 10 to 100 or more. Calculations show that an ultimate accuracy of 1 part in 10 billion may be reached. The atomic beam is again used in conjunction with a quartz-crystal oscillator and frequency-multiplier system, just as in the present method using an absorption cell.

The chemical analysis of many heavy molecules by means of a microwave spectroscope has been carried out by many investigators. This makes it highly desirable to place frequency standards on an atomic basis at an early date, in order that better precision can be obtained in the measurement of molecular constants. More and more chemicals will be analyzed as the technique is pushed to higher and higher frequencies in the microwave region. Spectroscopic analysis has hitherto been dependent on infrared, optical, and ultraviolet methods, which for the most part are limited to work on atoms and the simpler molecules. However, a large part of medical and industrial chemistry requires analysis of large, complicated molecules. The heavy molecules, rotating at slower rates, usually have spectrum lines in the microwave region so that the recent advances in microwave measurement technique now provide highly accurate methods for the study of molecular constitution. Such large molecules are principally involved in the fields of high polymers, plastics, rubber, textiles, oil, foods, drugs, and biological chemicals such as vitamins.

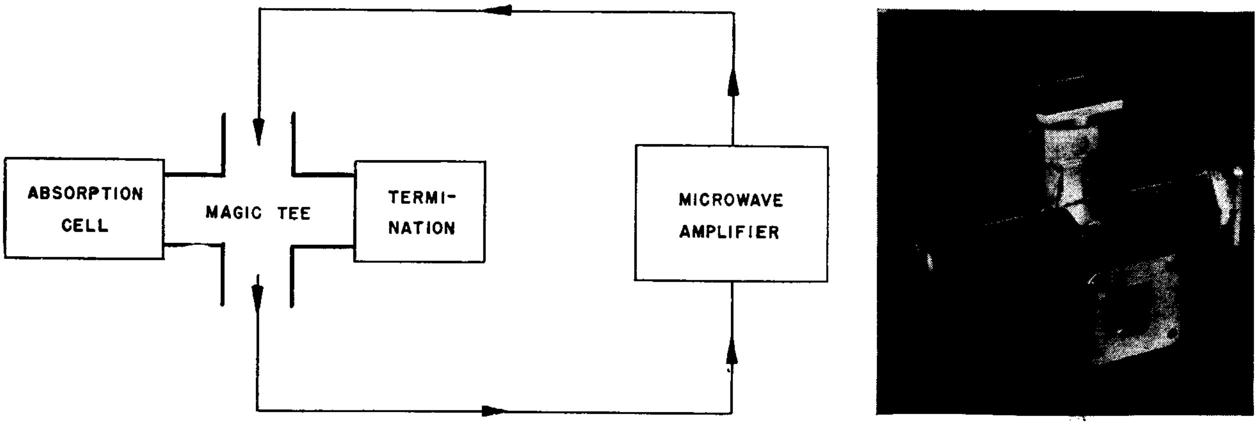
Stable isotopes that are now available from the Atomic Energy Commission are being widely applied in industry and medicine, and it is becoming important to have quick, accurate instruments for measurements of the kind and quantity of isotopes present in a sample. Isotopic identification is not possible by ordinary chemical methods, which deal only with the outer parts of an atom or molecule and not with the nucleus. The microwave spectrometer, having a resolution up to 100,000 times greater than an infrared spectroscope, will be able to make measurements on minute isotopic samples, and it can be built to do this quickly and accurately with automatic, all-electronic components.

One of the most important applications of quartz crystals is to the frequency-control of transmitters and filters used in radio equipment, both military and civilian. If these transmitters varied in frequency, radio and television sets would constantly have to be retuned, and much interference between adjacent channel transmitters would also result. Telephone companies operate carrier telephone circuits in which large numbers of simultaneous messages are transmitted over the same cable and are separated by means of crystal filters. Similar needs are met in microwave relay networks used for simultaneous communications, television, and FM broadcasting. At the higher frequencies, which are inaccessible to crystal oscillators or filters, the need for frequency-control equipment is urgent. Here atomic oscillators and spectrum lines used as filters would give the necessary frequency control and stability. A filter would consist of a cell filled with a gas that would absorb many different frequencies. A band-pass rather than a band-stop filter can also be made by means of additional microwave components called magic tees. Such filters could be electrically tuned by making use of the Stark effect, in which an applied electric field can force a molecule to change its frequency.

Stable oscillators for controlling high-frequency transmitters can be made by using a method similar to that in the present atomic clock. Here a discriminator or servo circuit locks the transmitter to a spectrum line through a control signal generated by the servo whenever the frequency drifts. However, it would be advantageous to eliminate the servo or discriminator and develop an atomic oscillator in which the absorption line would directly determine the frequency of the oscillator or transmitter. This would be analogous to a low-frequency quartz-crystal oscillator and make possible many new applications to microwave radio systems.

Dr. Harold Lyons, in recent work at the Bureau, has designed circuits of this type for use in transmitter control and for making an atomic clock and frequency standard without using discriminator circuits. In this method, the atomic-oscillator frequency is reduced by means of frequency dividers, but no quartz-crystal-driven frequency-multiplying chain is used, as in the present clock, nor is any servo circuit required. The circuit is that of a feedback oscillator in which feedback is obtained for the amplifier through a magic tee only at the absorption-line frequency. The tee is balanced at other frequencies, but the absorption occurring at the resonance frequency of the line unbalances it and allows the signal to be passed through so that the amplifier oscillates. This circuit requires a microwave amplifier at the frequency of the absorption line. Such amplifiers have been built, but are not yet commercially available, at 24,000 Mc where the ammonia lines are found.

Meanwhile, an exact equivalent of this circuit has been set up at 3,000 Mc, where amplifiers are now available. This circuit uses a resonant cavity in an equivalent circuit of the absorption line. As the oscillator has functioned satisfactorily, an attempt is being made to find suitable absorption lines in the 3,000-Mc region. This involves a search for the lines of deuterated ammonia, in which some of the hydrogen atoms in the ammonia molecules have been replaced by heavy hydro-



Atomic oscillators for frequency-control applications in the microwave region, where quartz-crystal oscillators cannot be used, are now being developed in the Bureau's microwave standards laboratory. One such oscillator, for use in transmitter control and for making atomic clocks and frequency standards without using discriminator circuits, employs a waveguide assembly known as the magic tee, in which feedback to the microwave amplifier occurs only at the resonant frequency of the gas in the absorption cell.

gen (deuterium) atoms. The heavier deuterated ammonia will give lines at lower frequencies than ordinary ammonia. For example, when all three hydrogen atoms have deuterium atoms substituted for them, the frequency will go down to approximately 1,200 Mc. The Bureau plans to construct a magic-tee atomic oscillator using the lower-frequency ammonia lines. Another atomic oscillator to be constructed at the Bureau will be similar to the magic-tee type but will use a six-arm waveguide bridge to control the feedback of the amplifier. This circuit should largely eliminate possible effects of the external circuits on the frequency of the oscillator. Thus, the oscillator, controlled by the absorption line alone, should be especially suitable for primary atomic clocks and frequency standards. Analogous circuits at low frequencies, using quartz crystals in ordinary bridges, have become the most precise quartz-crystal oscillators so far constructed. The relative merits of the magic-tee and bridge circuits are being investigated.

The atomic clock may eventually be used to improve the standard frequency and time broadcasts of the National Bureau of Standards, both from Station WWV and the Bureau's new station in Hawaii, WWVH. This could be done by monitoring the present quartz-crystal clocks with an atomic clock and would be especially useful at the Hawaiian transmitter. A precise atomic clock would give the Bureau a time standard analogous to the Bureau's new atomic standard of length provided by the invariant wavelength of the light from a single mercury isotope (Hg^{198}).

The goal of using spectrum lines of individual, isolated atoms in a field-free space to establish time and frequency standards is most nearly attained in the method using quantum transitions in atomic beams. Both this method and the method using absorption cells stem from the application of atomic physics to practical problems. In fact, quantum mechanics must be used to calculate and design the necessary apparatus, and the absorption by ammonia gas is a typical quantum mechanical effect incapable of explanation by classical physics. The ammonia molecule, structurally like a pyramid with the three hydrogen atoms forming the triangular base and the nitrogen atom at the apex, continually turns itself inside-out, giving rise to a quantum-mechanical resonance absorption. The atomic clock is thus another example of the importance of atomic physics to engineering. The overlapping of the fields of electronics and microwave physics may well provide a new technique for opening up the millimeter-wave-length bands above the region where ordinary microwave methods are applicable and below the region of optical methods.

NBS Publications

Periodicals [7]

Journal of Research of the National Bureau of Standards, volume **42,** number 1, January 1949. (RP1946 to RP1952 inclusive.)

Technical News Bulletin, volume **33,** number 1, January 1949. 10 cents.

CRPL–D53. Basic Radio Propagation Predictions for April 1949. Three months in advance. Issued January 1949. 10 cents.

Nonperiodical

RESEARCH PAPERS [7, 8]

RP1938. Effect of boron on the hardenability of high-purity alloys and commercial steels. Thomas G. Digges, Carolyn R. Irish, and Nesbit L. Carwile. 15 cents.

RP1939. Absorption of radio waves reflected at vertical incidence as a function of the sun's zenith angle. Eloise W. Taylor. 10 cents.

RP1940. Destruction of superconductivity by current. Russell B. Scott. 10 cents.

RP1941. Study of the modifications of manganese dioxide. Howard F. McMurdie and Esther Golovato. 10 cents.

RP1942. Laboratory evaluation of a method proposed by Gnam for measuring the temperature of rotating parts. Andrew I. Dahl and Paul D. Freeze. 10 cents.

RP1943. Amides of glucuronic, galacturonic, and mannuronic acids. Harriet L. Frush and Horace S. Isbell. 10 cents.

RP1944. Absorption spectra of methane in the near infrared. Richard C. Nelson, Earle K. Plyler, and William S. Benedict. 10 cents.

RP1945. Transmittance of near infrared energy by binary glasses. Jack M. Florence, Francis W. Glaze, Clarence H. Hahner, and Ralph Stair. 10 cents.

COMMERCIAL STANDARDS [7]

CS12–48. Fuel oils. (Sixth Edition. Supersedes CS12–40) 10 cents.

LETTER CIRCULARS [9]

LC930. Standards of length, mass, and time. (Supersedes LC449).

Articles by Bureau Staff Members in Outside Publications [10]

Note on a theorem in n-dimensional geometry. O. Taussky and L. A. Wigglesworth. Am. Math. Monthly (C. V. Newsom, Editor, State Education Bldg., Albany, N. Y.) **55,** 492 (1948).

Basis of standardization of electrical instruments and meters. F. B. Silsbee. Electrical World (330 West Forty-second Street, New York 18, N. Y.) **130,** No. 21, 90 (Nov. 20, 1948).

Laboratory corrosion tests of iron and steel pipes. G. A. Ellinger L. J. Waldron, and S. B. Marzolf. Paper Trade J. (15 West Forty-seventh Street, New York 19, N. Y.) **127,** No. 10, 27 (Sept. 2, 1948).

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Effect of temperature and time on the weight loss of leather. Joseph R. Kanagy and Arbelia M. Charles. J. Am. Leather Chem. Assoc. (Easton, Pa.) **43,** 274 (1948).

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