ATOMIC SECOND ADOPTED AS INTERNATIONAL UNIT OF TIME

13th General Conference on Weights and Measures Also Agrees on Changes in Terminology

■ A new definition of the international unit of time, the *second,* was adopted Friday, October 13, 1967, in Paris by the 13th General Conference on Weights and Measures.[1] The second has now been defined in terms of a characteristic rate of electromagnetic oscillation of the cesium-133 atom. The Conference also made terminological decisions in regard to the "micron," the "degree Kelvin," and the "candela"; and it added several to its list of derived units in the International System.

The General Conference on Weights and Measures, convened every few years, is a meeting of delegates from the countries (now numbering 40) adhering to the Treaty of the Meter. It is the principal body concerned with working out international agreements on physical standards and measurements. The U.S. delegation to the 13th General Conference was led by A. V. Astin, Director of the National Bureau of Standards.

Speaking for the governments represented, which include those of all the leading scientific and industrial countries, the Conference agreed overwhelmingly that the moment had come to replace the existing definition, based on the earth's orbital motion around the sun, by an "atomic definition."

The Conference decided that:

> The unit of time of the International System of Units is the second, defined in the following terms:
> "The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the fundamental state of the atom of cesium–133."

and abrogated the resolutions giving the earlier definition.

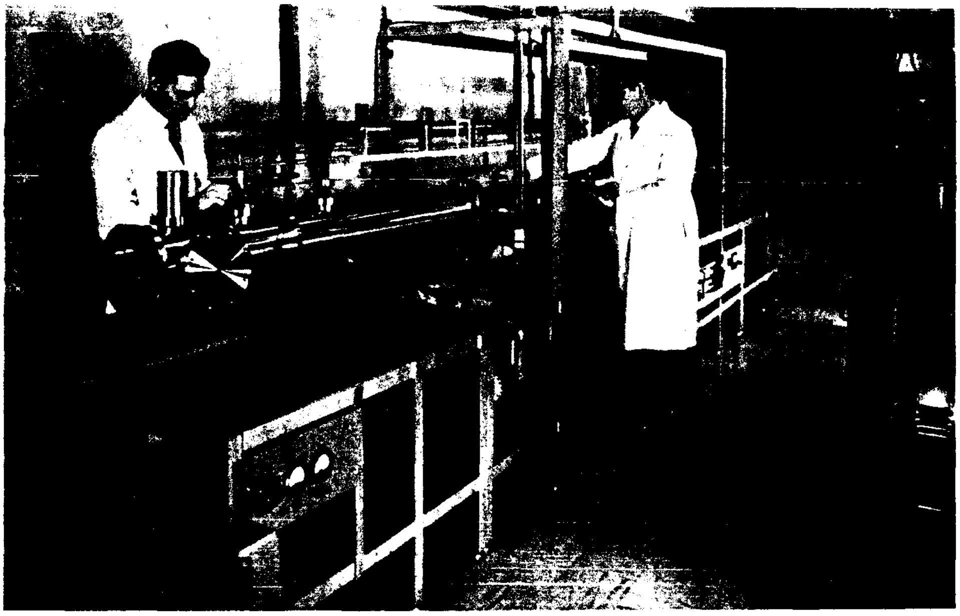
The frequency (9,192,631,770 Hz) which the definition assigns to the cesium radiation was carefully chosen to make it impossible, by any existing experimental evidence, to distinguish the new second from the "ephemeris second" based on the earth's motion. Therefore no changes need to be made in data stated in terms of the old standard in order to convert them to the new one.

On the other hand, the atomic definition has two important advantages over the preceding definition: (1) it can be realized (i.e., generated by a suitable clock) with sufficient precision, ±1 part in a hundred billion (10^{11}) or better, to meet the most exacting demands of current metrology; and (2) it is available to anyone who has access to or who can build an atomic clock controlled by the specified cesium radiation,[2] and one can compare other high-precision clocks directly with such a standard in a relatively short time—an hour or so as against years with the astronomical standard.

The development in the last few decades of atomic clocks, without which the new definition could not have been considered seriously, has laid the preliminary groundwork for an eventual experimental assault on a fundamental question: Are the time scales based respectively on gravitational, electrical, and nuclear forces compatible and consonant with each other? And if (as some think) they are not, then why not?

Laboratory-type atomic clocks are complex and expensive, so that most clocks and frequency generators will continue to be calibrated against a standard such as the NBS Frequency Standard, controlled by a cesium atomic beam, at the Radio Standards Laboratory in Boulder, Colo. In most cases the comparison will be by way of the standard-frequency and time-interval signals broadcast by NBS radio stations WWV, WWVH, WWVB, and WWVL.[3] Similar services are supplied by several radio stations of the U.S. Navy. NBS broadcasts have been monitored by an atomic frequency standard since 1957. The Radio Standards Laboratory has also developed a rubidium-vapor (instead of cesium), portable (39 lb), battery-operated frequency standard with a short-term stability of ±1 part in 10^{10}, which has proved useful for time comparisons at isolated facilities.[4] Similar atomic standards, weighing only about 20 lb, but at some cost in accuracy, have been developed for use in aircraft where they serve as components in precision navigation systems.

Cesium atomic clocks had already become so good by 1964 that the International Committee on Weights and Measures, acting under authority of the 12th General Conference held in that year, designated the present atomic definition for temporary use for measurements requiring maximum precision.[5] Continued improvements of the cesium clock are anticipated; and, in the not too distant future, clocks based on other than cesium radiations are expected to open the way to substantial further increases in precision. The present



The cesium atomic clock at the NBS Radio Standards Laboratory generates the second—the SI unit of time. A quartz-oscillator-controlled microwave signal is held at 9,192,631,770 Hz by continuous comparison with the cesium-133 resonance at that frequency. A beam of cesium-133 atoms passes left to right through the long metal cylinder (center) and interacts with microwaves brought in by waveguide components (above cylinder).

(13th) Conference adopted a resolution urging that research and development programs along these lines be pursued with all possible vigor.

The Path to the New Second[6]

The founders of the metric system (in its present-day version known as the International System) did not define a unit of time. But, by convention among scientists, time had long been measured in terms of the rotation of the earth, the scientific unit of time—the second—having once been defined as 1/86,400 of a mean solar day. But the rotation of the earth has proved too erratic to meet modern scientific needs for keeping time—it is subject to periodic fluctuations within a year and to unpredictable fluctuations from year to year—and, therefore, the mean solar second is continually changing. The inconsistencies created by this are small—of the order of a part in 10^8—yet enough so that the time scale kept by the rotation of the earth on its axis now lags behind that kept by the revolution of the earth about the sun by about 30 seconds, reckoning from the year 1900.

A partial remedy was achieved in 1956 when the International Committee on Weights and Measures redefined the second for scientific use as 1/31,556,925.9747 of the tropical year at 1200 hours, ephemeris time, 0 January 1900. This imposing number was obtained from Simon Newcomb's equation for the apparent motion of the sun across the celestial sphere. This so-called ephemeris second is made available in practice with the aid of atomic clocks, but only retrospectively, as an average value over several years, by means of continual observations of the position of the moon. It can be determined experimentally with an uncertainty of a few parts in 10^9, a large uncertainty compared with the exactness implied by the multidigitality of the definition.

This 1956 definition of the second—though a great improvement for astronomers—still had one serious fault. No one else could measure an unknown interval of time with it by direct comparison. But even as this redefinition of the second was being formulated, a spectacular revolution in the measurement of time was taking place in the laboratory, where experimental techniques in molecular and atomic physics had been advancing rapidly.

Physicists had been able to excite some of the lower energy states of atoms and molecules, the associated frequencies of which, in accordance with Planck's equation $E=h\nu$, fall within the microwave part of the spectrum. These frequencies could be measured by comparison with laboratory oscillators and expressed in terms of the germane time-inverse unit of frequency, the cycle-per-second (now called the hertz, abbreviated Hz). Even in the early experiments, frequencies could be compared

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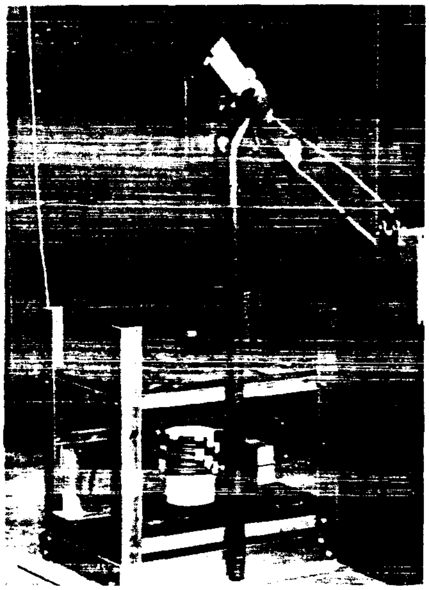


The SI unit of luminous intensity is the candela. The light-colored porcelain cylinder with black cable coiled around it has a relatively narrow and deep vertical cavity containing platinum. Rf current in the coil keeps the cavity at the freezing temperature of platinum (2042 K). The opening at top of the cavity then radiates 60 candelas per square centimeter in the direction perpendicular to the plane of the opening.

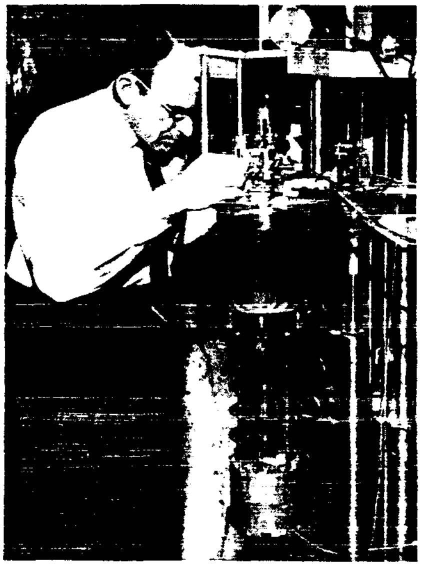
ATOMIC SECOND *continued*

repeatedly with an agreement to within parts in 10^8 or 10^9. Subsequently, atomic beams, masers, and absorption cells were developed which also proved to be very stable standards for frequency and time; not only could they be compared with each other with a precision of 1 part in 10^{10}, or better, during an observing time of an hour or so, but cesium-beam resonators, independently constructed in different laboratories, agreed in frequency to a few parts in 10^{11} (equivalent to a second of cumulative error in 3000 years). It was apparent that if the second were defined as the interval of time corresponding to x cycles of a suitably selected atomic resonance frequency, the second could be realized more easily and more exactly than by the ephemeris second.

Other Actions Taken by Conference

The 13th General Conference also made the several other decisions summarized below.

Length. The name "micron," for a unit of length equal to 10^{-6} meter, and the symbol "μ" which has been used for it, are dropped. The symbol "μ" is to be used solely as an abbreviation for the prefix "micro-," standing for multiplication by 10^{-6}. Thus the length previously designated as 1 micron should be designated 1 μm.



L. A. Guildner adjusts valves on the NBS gas thermometer which measures temperature in kelvins as a function of pressure changes of a constant volume of a nearly perfect gas.

Temperature. The Conference recognized the urgency of revising the International Practical Scale of Temperature of 1948. Noting that the laboratories competent in the area are agreed on the main lines of the changes required, it authorized the International Committee on Weights and Measures to take the steps necessary to put a new International Practical Scale of Temperature into effect as soon as possible.

The name of the unit of thermodynamic temperature was changed from *degree Kelvin* (symbol: °*K*) to *kelvin* (symbol: *K*). The definition of the unit of thermodynamic temperature now reads:

> The kelvin, the unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.

It was also decided that the same name (*kelvin*) and symbol (*K*) be used for expressing temperature intervals, dropping the former convention which expressed a temperature interval in *degrees Kelvin* or, abbreviated, *deg K*. However, the old designations are acceptable temporarily as alternatives to the new ones. One may also express temperature intervals in *degrees Celsius.*

Photometry. Recognizing that photometry must take into account the principles and techniques of colorimetry and radiometry, the Conference approved plans drawn up by the International Committee on Weights and Measures to expand the scope of its activities to include the fundamental metrological aspects of colorimetry and radiometry.

The definition of the unit of luminous intensity, the *candela,* was rephrased to meet the objections of critics who found a certain awkwardness in its wording. The meaning of the definition, which was never in doubt, remains the same. The reformulated definition follows:

> The candela is the luminous intensity, in the direction of the normal, of a blackbody surface 1/600,000 square meter in area, at the temperature of solidification of platinum under a pressure of 101,325 newtons per square meter.

Derived units. To the derived units and associated symbols that the 11th General Conference (1960) had included in its Resolution 12, which introduced the International System of Units (official abbreviation: SI, from the French designation, Système International d'Unités), the 13th General Conference added the following:

Wave number	1 per meter	m^{-1}
Entropy	joule per kelvin	J/K
Specific heat	joule per kilogram kelvin	J/kg K
Thermal conductivity	watt per meter kelvin	W/m K
Radiant intensity	watt per steradian	W/sr
Activity (of a radioactive source)	1 per second	s^{-1}

A proposal to have the *mole* defined by the 13th General Conference was deferred.

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[1] The Proceedings of the Conference will be published by Gauthier-Villars & Cie., Paris. A summary will appear in the journal, **Metrologia.**

[2] A description of such clocks is given in Atomic frequency standards, NBS Tech. News Bull. **45**, 8–11 (Jan. 1961). For more recent developments and technical details, see **Cesium beam atomic time and frequency standards,** by R. E. Beehler, R. C. Mockler, and J. M. Richardson, Metrologia **1**, 114–131 (July 1965).

[3] The services provided by these stations are described in NBS Misc. Publ. 236, 1967 edition, **NBS Standard Frequency and Time Services,** for sale at 15 cents per copy by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

[4] **Portable atomic frequency standard,** NBS Tech. News Bull. **49**, 4–5 (Jan. 1965).

[5] **The Twelfth General Conference on Weights and Measures,** by H. Moreau, Metrologia **1**, 27–29 (Jan. 1965).

[6] **This section is an excerpt, with minor changes, from Measurement standards,** by A. G. McNish, International Science and Technology, No. 47, 58–66 (Nov. 1965).