Fundamental Measures and Constants for Science and Technology

Author
Frederick D. Rossini
Professor of Chemistry
Rice University
Houston, Texas

Published by
CRC PRESS

THE AUTHOR

Frederick D. Rossini is professor of chemistry at Rice University, Houston.

Dr. Rossini received his B.S. in Chemical Engineering and M.S. in Science from Carnegie Institute of Technology, and his Ph.D. in Physical Chemistry from the University of California, Berkeley. He is the recipient of seven honorary degrees.

Dr. Rossini is an authority in the fields of thermodynamics and thermochemistry, numerical data for science and technology, and physical chemistry of petroleum and hydrocarbons. Dr. Rossini joined the staff of the National Bureau of Standards in 1928, and from 1936 to 1950 served as chief of the Section on Thermochemistry and Hydrocarbons. He was Silliman Professor, head of the department of chemistry, and Chemical and Petroleum Research Laboratory director at Carnegie Institute of Technology from 1950 to 1960. From 1960 to 1967, Dr. Rossini was dean of the College of Science and associate dean of the Graduate School at the University of Notre Dame. He served as vice president for research at Notre Dame from 1967 to 1971, when he went to Rice University.

Dr. Rossini is the author of over 240 publications, including 10 books.

Library of Congress Cataloging in Publication Data

Rossini, Frederick Dominic, 1899-
Fundamental measures and constants for science and technology.

Includes bibliographies.
1. Units. 2. Physical measurements. I. Title.
QC39.R66 389 74-14759
ISBN 0-87819-051-1

International Standard Book Number 0-87819-051-1

Library of Congress Card Number 74-14759
Printed in the United States

PREFACE

This book on the fundamental measures and constants of science is based on my experiences of nearly 50 years devoted to researches and writings related to accurate measurements of thermodynamic and physical properties of chemical substances, particularly hydrocarbons and related compounds, and to the problems of numerical data for science and technology. It has been my privilege to have firsthand contact with some of the world's experts on the fundamental units of measurement, the scale of temperature, the scale of pressure, the scale of atomic masses, and the fundamental physical constants. The need to present the results of experimental measurements in a form and manner that will maximize their usefulness to scientists and engineers has been for me a continuing challenge, requiring adequate knowledge of and familiarity with the foregoing topics. Such matters are normally touched upon only casually and peripherally in regular courses of study, so that one is expected to develop knowledge of them on his own.

In 1972 and 1973, I gave detailed lectures on the above topics at Rice University, and in 1973 as the Strosacker Visiting Professor of Science at Baldwin-Wallace College. Having done this, it appeared desirable that the material presented in these lectures be put down in written form for the benefit of the many persons interested whom I cannot reach in the classroom. Each topic is presented in a simple, clear, and straightforward manner, including a brief history along with the present status.

It is my hope that this collection of information on the fundamental measures and constants of science will be really useful to working scientists and engineers as well as to undergraduate and graduate students in science and engineering. In particular, I hope that this book will provide for them, in convenient form, information that will ensure the reliability and maximize the effectiveness of their work in the area of measurements.

For the latest up-to-date information on the several topics, beyond material available in the open literature, I am greatly indebted to my friends in the several areas, whose names are indicated at the appropriate places in the text. I would greatly appreciate being informed of any errors of commission or omission in this book.

Frederick D. Rossini
April, 1974.

TABLE OF CONTENTS

Chapter 1

INTRODUCTION

Science is based upon observation and measurement. One of the most important capabilities possessed by man is the ability to measure. The better and more accurately we can observe and measure, the better and more accurately we can describe the phenomena of nature, develop theories to explain the natural state of things, and guide ourselves to more fruitful observations and measurements. The advance of science is proportional to the extent to which we have quantitative knowledge of the dimensions of material things, of the rates at which phenomena occur, of the forces that hold entities together, and of the changes in energy accompanying natural or man-made processes. With more knowledge, we are able to devise theories to correlate hitherto unrelated observations. In time, as theories become established, mountains of observational data can be replaced by a few simple formulas.

In the early beginnings of science, simple words and simple measures were adequate. Then, as science developed, with need for higher precision and accuracy, more precise words and measures became necessary to record observations and communicate the results. Today, the communication of scientific observations has become a highly complex and very important operation. One of the big problems that we have in science today is to communicate the results of observations and measurements in a manner that will be fully understood by other scientists.

Not infrequently, the full value of the measurements arising from a given investigation is not recovered because the Principal Investigator has not been sufficiently aware of the relation between his measurements and similar ones of others, and of the connection of such measurements with related other quantities. The resulting report or publication may be written in a manner that leads to less than full understanding by others in the same discipline. Communication without understanding can lead to misinterpretation and unnecessary and costly repetition of measurements. It is the obligation of each investigator to place his observations and measurements on a solid foundation by appropriate linkage with the fundamental units of measurement and proper use of appropriate values of the fundamental units of measurement involved. The scientific and technical literature contains many examples of reports of investigations that are woefully inadequate in such matters, as well as others that are prime examples of excellence.

We have the problem of communicating among scientists of the same country and then among scientists of different countries. Whether the communication is among scientists of the same discipline in the same country, among scientists of different disciplines in the same country, among scientists of the same discipline in different countries, or among scientists of different disciplines in different countries, it is important that the words, terms, and symbols used have the same meaning at both ends of the chain of communication. This means appropriate coordination of such matters by a national body in a given country and by an international body for all countries.

Within the past 150 years the speed of communication in the world has increased about several million times, and the speed of travel about several thousand times. This has brought all peoples of the world, including scientists and engineers, much closer together. This proximity in terms of time of communication and travel brings with it the need to communicate across national boundaries with adequate understanding.

Each of us can do his part in the scientific-technological endeavor by observing carefully, measuring with proper instruments of appropriate precision and accuracy, and then communicating the results in terms, units, and symbols that have international acceptance in the given disciplines of science and engineering.

Another very important reason for the spread of knowledge of the fundamental measures and constants of science is that the advance of science and technology in the service of mankind is dependent upon continued improvement in the precision and accuracy of the measurement and control of the variables of length, mass, time, temperature, pressure, and combinations of them. Our manufacturing industries require increasingly more efficient and finer control of their processes in order to compete successfully in the world markets. Similarly, many industries are now controlling new variables, representing complex combinations of the fundamental measures, that permit the production of new products hitherto undreamed of.

In the last century, Lord Kelvin wrote the following:

> I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be.

Chapter 2

THE FUNDAMENTAL UNITS OF MEASUREMENT

A. INTRODUCTORY COMMENTS

In this chapter, we discuss the units of length, mass, and time, giving a brief history of them, describing the present standards for them, showing how they are maintained at the international and national levels, and indicating how they are carried down to the working and living levels. These standards are related to the measuring instruments used in laboratories, industry, commerce, business, sports, recreation, and the home.

Our yardsticks, our meter sticks, our balances and weighing machines, and our watches and clocks are tied through a chain of connections, some short and some long, to the basic units of length, mass, and time as defined by international agreement. The fundamental units of measurement are really of concern to everyone, not only in science, engineering, industry, and business, but also in our everyday experiences as individuals, in the market place and in the home. Even the housewife has a big stake in the matter of weights and measures.

B. THE UNIT OF LENGTH

Early records on units of length in the various countries of the world are most interesting and replete with native customs.

The cubit (of somewhat varying sizes) appears to be the name most frequently used in ancient history for the unit of length. The cubit is related to the length of the arm from the tip of the middle finger to the elbow. In Egypt, the cubit (52.4 cm) was used beginning with the time of the predynastic royal tombs. Variations of this cubit were found in Babylon (53.1 cm), in Asia Minor (52.2 to 53.2 cm), in Jerusalem (52.2 cm), in early Britain (52.2 cm), and in early stone buildings in what is now New Mexico, U.S. (52.5 cm).

Another early unit was about 3/5 of a cubit, found in Athens (31.6 cm), in Aigina (31.5 cm), in Miletos (31.8 cm), in Olympia (32.1 cm), in Etruria (31.6 cm), and in medieval Britain (31.7 cm). Another unit was about 2/3 of a cubit, used in Pergamon (35.1 cm). The short cubit (about 6/7 of a regular cubit) was used also in Egypt (45.0 cm) and in Jerusalem (44.7 cm). The Greek cubit has a special value (46.3 cm).

The digit was taken as 1/40 of the diagonal of a square, one cubit (52.4 cm) on a side, making the digit 1.85 cm.

Taking 2/3 of the Greek cubit (46.3 cm) produced the Greek foot (30.9 cm). The Greek foot in greater use was found to be shorter (29.5 cm). Similar units were Italic (29.6 cm), Rome (29.5 to 30.0 cm), Etrusca (29.4 cm), Stonehenge (29.7 cm), and other stone circles and hill figures (29.5 cm).

Another widespread measure found has a different unit: in early Egypt (33.8 cm), in Asia Minor (33.9 cm), in Greece (33.9 cm), at Lachish (900 B.C.) (33.5 cm), in Syria (620 A.D.) (33.6 cm), in medieval Britain as the commonest building unit (33.5 cm), and in some early French architecture (33.1 cm).

Another unit was used in Persepolis (48.8 cm), in the tower of Babylon (49.5 cm), in Asia Minor (49.0 cm), in early Assyria (50.7 cm), in Khorsabad (54.9 cm), in Phrygia (55.4 cm), in Lucania, Italy (55.5 cm), in late Egypt (53.6 to 54.2 cm), and in Persia (54.4 cm). Another important unit was used in Phoenicia (56.4 cm) and in Carthage and Sardinia (56.3 to 56.7 cm).

Measures of volume in the ancient systems developed independently of the units of length. Examples are the Egyptian "hen" (477 cm^3), the Syrian "kotyle" (341 to 354 cm^3), the Syrian "log" (544 cm^3), the Phoenician "log" (508 cm^3), the Babylonian "log" (541 cm^3), the Jewish "log" (544 cm^3), the Attic "kotyle" in Egypt (285 cm^3), the Persian "kapetis" (1,221 cm^3), and the Roman "amphora" (25.7 to 29.9 x 10^3 cm^3).

In Britain, the inch was originally taken as the length covered by three barleycorns, round and dry, laid end to end; the fathom was taken as the length from tip to tip of the fingers, with hands and arms outstretched; the yard was one half of the fathom.

In Germany, there is a record in the 16th Century showing the establishment of the German "rute" or "rod" as the length covered by the feet of 16 men, standing together in a line, toe to heel, selected as the men issued from church on a Sunday morning.

The early units of measure used in the United States were, of course, inherited from the British system, which had been used throughout the 13 colonies in America.

Following are some early notes on units of length and capacity in Britain. In 1439, the "yard and handful," or the "40-inch ell," was abolished. The "yard of Henry VII" (35.963 in.) was abolished in 1527. In 1553, the "yard and inch," or the "37-inch ell," was abolished. A "cloth ell" (45 in.) was used until 1600. Early measures of capacity included the "Winchester bushel" of Henry VII, the "ale gallon" of Henry VII, and the old Queen Anne "wine gallon" of 1707 (231 in.^{3}), which became the U.S. gallon

Some of the units of length used in Britain at various times include the following (the number following the name is the nominal equivalent in inches): mil, 0.001; point, 1/72; line, 1/12; barleycorn, 1/3; palm, 3; hand, 4; span, 9; cubit, 18; pace, 30. Similarly, we have for longer units the following (the number is the nominal equivalent in feet): fathom, 6; rod, 16.5; rope, 20; chain, 66; skein, 360; furlong, 660; cable, 720; mile, 5,280; knot (nautical mile), 6,080; league, 15,840 (3 mi). Most of these units were also used in the American colonies and later in the U.S.

In 1758–60, a new British standard yard was constructed by direction of the Houses of Parliament in London. By the Weights and Measures Act of Parliament in 1878, the imperial yard was defined as the distance at 62°F between the axes of two lines traced on gold plugs set in a bronze bar preserved at the Standards Department of the Board of Trade in London. The legal equivalent of this was specified then as 0.9143992 m. However, later measurements by the British National Physical Laboratory showed that the yard as defined above was actually 0.9143987 m. The foot and the inch were taken as 1/3 and 1/36, respectively, of the imperial yard.

In 1790 in the U.S. President Washington suggested to the Congress that the United States should set up its own system of weights and measures. A report by the then Secretary of State, Thomas Jefferson, recommending a basic unit of length from which units of area, volume, etc., could be derived was accepted by the Congress, but, in spite of prodding by President Washington, the report was never implemented.

Nothing significant was done until 1816 when President James Madison reminded Congress that it was important that a uniform system of weights and measures be established. The U.S. Senate responded in the following year by passing a resolution requesting the Secretary of State to reinvestigate the problem. Four years later, in 1821, came the "Report upon Weights and Measures" submitted by Secretary of State John Quincy Adams. Adams' report included the following message:

> Weights and Measures may be ranked among the necessaries of life to every individual of human society. They enter into the economical arrangements and daily concerns of every family. They are necessary to every occupation of human industry; to the distribution and security of every species of property; to every transaction of trade and commerce; to the labors of the husbandman; to the ingenuity of the artificer; to the studies of the philosopher; to the researches of the antiquarian; to the navigation of the mariner, and the marches of the soldier; to all exchanges of peace, and all the operations of war. The knowledge of them, as in established use, is among the first elements of education, and is often learned by those who learn nothing else, not even to read and write. This knowledge is riveted in the memory by the habitual application of it to the employment of men throughout life.

Adams' report gave the following possible lines of action: (1) to adopt, in all its essential parts, the then-new French (metric) system; (2) to restore and perfect the old English system; (3) to devise and establish a new combined system by adapting parts of each system; (4) to adhere, without any innovation whatever, to the existing system – merely fixing the standards.

Adams himself preferred a two-stage approach: (1) standardization and approval of the customary familiar English units followed by (2) negotiations with France, Britain, and Spain to establish a uniform international system of measurement.

Adams' recommendations were practical in the sense of having some chance of approval, in view of the fact that by 1821 most states had already enacted laws specifying the English units of measure, and a sudden contrary national law might involve the problem of State's Rights. Further, it was a fact that the preponderance of United States trade in 1821 was still with Britain and that the U.S. was bounded by Canada and then-Spanish possessions. Congress took no action on Adams' report.

In 1832, the U.S. Department of the Treasury adopted the English standards of length and mass to meet the needs of customs houses.

In 1863, President Lincoln formed the National Academy of Sciences to advise the government on all technical matters. The Secretary of the Treasury appointed a committee, chaired by the eminent physicist, Joseph Henry, to reconsider the matter of weights, measures, and coinage. The committee issued its report 2 years later, favoring adoption of the French metric system.

In 1866 the newly appointed Committee on Coinage, Weights, and Measures of the U.S. House of Representatives, under the chairmanship of Congressman John A. Kasson, reported favorably on three bills dealing with the metric system. These were eventually passed by the Congress. One of the bills specified the metric equivalents of the English units used in the United States and made legal, though not compulsory, the use of metric weights and measures. Another bill directed the Postmaster General to distribute metric postal scales to all post offices handling foreign mail. The third bill directed the Secretary of the Treasury to provide each state with one set of metric standards. The following is quoted from the first of these bills:

> It shall be lawful throughout the United States of America to employ the weights and measures of the metric system; and no contract or dealing, or pleading in any court, shall be deemed invalid or liable to objection because the weights and measures expressed or referred to therein are weights and measures of the metric system.

In 1875, after 5 years of meetings in Paris, 17 nations signed the Treaty of the Meter. This treaty and convention accomplished several objectives: (a) the description of the metric system was clarified and reformulated to make the standards of the metric system more accurate; (b) provision was made for the construction of new standards of measurement; (c) provision was made for the distribution of accurate copies of these standards to the participating countries; (d) the International Bureau of Weights and Measures was created to serve as a world repository and laboratory, located at Sevres, near Paris, on a piece of international territory donated by France; (e) provision was made for continuing international conferences and action on weights and measures.

The present arrangements for international collaboration on weights and measures has the following pattern. The International Bureau of Weights and Measures, which aims to ensure worldwide uniformity of measurements by maintaining the international standards and carrying on comparisons of national and international standards, is under the cognizance of the International Committee on Weights and Measures which develops recommendations to be placed before the International General Conference on Weights and Measures, the top body in the enterprise. The General Conference consists of delegates from each member country of the Convention of the Meter and meets at least once every 6 years. The International Committee on Weights and Measures consists of 18 members, each from a different country, and meets at least once every 2 years. This International Committee has "consultative committees" for Electricity, Photometry, Thermometry, Definition of the Meter, Definition of the Second, and Standards for Measuring Ionizing Radiations and Units.

In 1889 the prototype copies of the international standard meter bar and international standard kilogram were completed and the U.S. received its copies. In 1893 the U.S. Secretary of the Treasury issued an administrative order declaring these new metric standards to be the fundamental standards of length and mass for the U.S. This meant that the customary units of length (inch, foot, yard, etc.) and of mass (pound) were defined in terms of the metric units:

1 yd	=	3,600/3,937 m	=	0.91440183 m
1 ft	=	1/3 yd	=	30.480061 cm
1 in.	=	1/36 yd	=	2.5400508 cm

This placed the U.S. on the basis of the metric system, although no effort was made towards a practical conversion of the day-to-day activities of the people to the units of the metric system. (The problem of the practical conversion to the metric system of the government, commercial, industrial, engineering, and personal measurement activities in the U.S. is discussed in the following chapter.)

In 1959 the U.S. in concert with the United Kingdom, Canada, Australia, New Zealand, and South Africa, agreed on precisely uniform definitions of the yard and the pound in terms of the metric equivalents. In the U.S. this was accomplished by a joint communique of the National Bureau of Standards and the U.S. Coast and

Geodetic Survey, with the approval of the Secretary of Commerce. The equivalent of the unit of length was given as:

1 yd = 0.9144 (exactly) m, so that
1 in. = 2.54 (exactly) cm, and
1 ft = 30.48 (exactly) cm

This changed the 1893 equivalent by two parts per million.*

Previous to 1889 the international meter bar was an "end standard," made of a platinum rod. An "end standard" is one where the given length is determined by the distance between the two parallel plane ends of the rod. (It should be noted that the size of the meter was originally selected so as to be one ten-millionth part of the quadrant of the earth's meridian passing through the poles and intersecting the equator at the earth's surface.)

In 1890, when the U.S. received its prototypes of the international standards, the international meter bar had been changed to a "line standard," made of an alloy consisting of platinum with 10% iridium by weight. A "line standard" is one where the given length is determined by the distance between the centers of two fine lines, cut parallel to each other, transversely on the rod. This rod had a "Tresca," or modified X, cross section, for resistance against deflection, with overall dimensions of 2 X 2 cm, as shown in Figure 2.1.

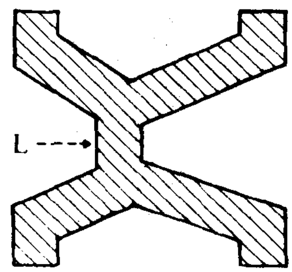

FIGURE 2.1. Cross section (Tresca) of the national standard meter bar of 1897. Two microscope lines were engraved on the measuring axis of the bar, one at each end, as indicated by L. (From Weights and Measures, in *Encyclopaedia Britannica*, Vol. 15, 14th ed., Encyclopaedia Britannica, New York, 1929, 135. With permission.)

In 1927 the Seventh International General Conference on Weights and Measures made the specifications for the international standard meter bar much more definite, as follows:

> The unit of length is the meter, defined by the distance, at the temperature of melting ice, between the centers of two lines traced on the platinum-iridium bar deposited at the International Bureau of Weights and Measures, and declared prototype of the meter by the First General Conference on Weights and Measures, this bar being subjected to normal atmospheric pressure and supported by two rollers, at least one centimeter in diameter, situated symmetrically in the same horizontal plane and at a distance of 572 millimeters from each other.

In discharging its obligations as the custodian and monitor of the unit of length, the National Bureau of Standards has maintained in its vaults the following units of length (obtained from appropriate government agencies which had received them before the establishment of the National Bureau of Standards): "Arago Platinum Meter," purchased from France in 1821; "Low Moor Iron Yard No. 57," copy of the British Imperial Yard, obtained as a gift from Britain in 1856; "Bronze Yard No. 11," copy of the British Imperial Yard, which was obtained as a gift from Britain in 1856 and served as the United States standard until 1893; "Committee Meter-Iron," copy of the first metric standard brought to the United States in 1905 and used by the U.S. Coast Survey from 1817 to 1890; "Prototype Meter No. 12," obtained from the International Bureau of Weights and Measures in 1890; "Prototype Meter No. 27," which was the reference standard of length for the U.S. from 1890 to 1960.

Beginning in the early part of this century, Michelson, in the U.S., had shown that it would be possible to base the international unit of length on the wavelength of selected monochromatic radiation. Work along these lines was also carried out by Fabry and Perot in France. The preferred radiation for this purpose then was principally the red line of cadmium. These investigators showed that, by comparison with the red line of cadmium, the international standard meter bar was unchanged, over a period of 15 years, to 0.1 ppm.

In 1927 the International General Conference adopted as an alternative and provisional defini-

*It should be noted that the geodetic survey records of the U.S. Coast and Geodetic Survey, maintained in terms of the equivalent of 1893, are exempted from this change until the time is propitious to readjust the basic geodetic survey networks to the new system.

tion of the meter the following: the meter is equivalent to 1,553,164.13 wavelengths of the red light emitted by a cadmium vapor lamp excited under certain specified conditions. It was taken that the uncertainty in this definition was 0.1 ppm.

But it was felt that much more experimentation was needed before the international standard meter bar could be abandoned completely. By about 1955, much of the needed experimental work was done, using principally the orange-red monochromatic radiation from the pure nuclide, Krypton-86

In October, 1969, the International General Conference on Weights and Measures made a new definition of the unit of length, in terms of the wavelength of monochromatic radiation from isotopically pure Kr-86, and gave up the international meter bar as the standard. They stated, "The unit of length is the meter, m, which is equal exactly to 1,650,763.73 wavelengths of light in vacuo produced by the unperturbed transition $2p_{10} - 5d_5$ in the pure nuclide, Krypton-86." (This is the orange-red radiation of Krypton.) Assuming an uncertainty of one half unit in the last figure written, this definition corresponds to an uncertainty of 0.003 ppm. This is to be compared with the corresponding uncertainty of 0.1 ppm attainable with the line-standard international meter bar.

The foregoing is the present international metric standard for the unit of length and is the legal basis of the system in the U.S. even before practical conversion to the metric system.

The new definition of the unit of length in terms of the wavelength of the monochromatic radiation from pure Krypton-86 eliminates world dependence on the security and validity of the international standard Pt-Ir bar maintained in the vaults of the International Bureau of Weights and Measures at Sevres. Also, the new definition eliminates the basic need for intercomparisons between national working standard meter bars, the national prototype bars, and, eventually, the international meter bar at Sevres.

At this point we can clear up a problem relating to the liter. The liter had originally been defined as the volume occupied by 1,000 g of water at its temperature of maximum density, near 4°C, at a pressure of 1 atm. When first defined, and confirmed by the Convention of the Meter in 1875, the liter was believed to be almost exactly 1,000 cm^3. Following an extensive investigation, the International Bureau of Weights and Measures reported, in 1910, the following:

1 liter = 1,000.027 cm^3.

In the International Critical Tables[1] in 1926, the relation was changed slightly to

1 liter = 1,000.028 cm^3.

This difference of 28 ppm between the milliliter and the cubic centimeter is small and can be neglected in many investigations. But there are many cases where this difference is very significant. Values of densities given to 1 to 10 ppm were required to be carefully and explicitly expressed as grams per milliliter or grams per cubic centimeter, depending upon the unit selected.

In 1964 the International General Conference on Weights and Measures eliminated this problem in the future by redefining the liter, independently of the properties of water, simply as the equivalent of one cubic decimeter:

1 liter = 1,000 (exactly) cm^3.

This means that values of density of high precision appearing in the literature prior to 1965, when expressed in grams per milliliter, require conversion to grams per cubic centimeter by dividing by 1.000028. Henceforth, values of density should normally be expressed in grams per cubic centimeter or a directly related quantity.

C. THE UNIT OF MASS

As in the case of units of length, units of mass in ancient times were many and varied and coupled with local customs. Examples are: in Palestine, the "shekel" or "peyem" (7.5 to 8.1 g), in Syria, the "manek" (408 g), in Persia, the "karasha" (834 g), in Egypt, the "gedet" (9.33 g), in Rome, the "libra" (327 g), and in Alexandria, the "sela" (14.3 g).

As in the case of units of length, the units of weight in the American colonies were those of Britain, where three different "English" systems were used:

Avoirdupois for general use
Apothecary for drugs
Troy for precious metals

In the British avoirdupois system, the various units used included the following (the number following the name gives the equivalent in pounds): dram, 1/256; ounce, 1/16; stone, customary, 8; stone, legal, 14, quarter, 28; cental, 100; hundred-weight, 112; ton, 2,240.

In the avoirdupois system in the U. S., similar units were used, as follows (with the number following the name being the equivalent in pounds): dram, 1/256; ounce, 1/16; hundred-weight, 112; ton, 2,000; long ton, 2,240. The troy and apothecary systems of the U.S. were the same as those of Britain. Following are the names and equivalents of these, in grains: for the troy system: pennyweight, 24; ounce, 480; pound, 5,760. For the apothecary system: scruple, 20; dram, 60; ounce, 480; pound, 5,760. In converting the foregoing, 1 lb avoirdupois is taken equivalent to 7,000 grains.

As previously reported in the preceding section on the discussions of the unit of length, the U.S. signed the Treaty or Convention of the Meter in 1875, along with 16 other countries. This Convention covered the unit of mass as well as the unit of length, and was an important step following the legalization (but not compulsory use) of the metric system by the U.S. Congress in 1866 and the accompanying definition of the yard and pound in terms of metric equivalents. It was in 1890 that the U.S. received its prototype of the international kilogram along with the international meter.

Earlier, the legal basis in the U.S. had been a prototype of the British imperial pound, which was a cylinder of pure platinum about 1.35 in. high and 1.15 in. in diameter. One grain was defined as 1/7,000 part of this pound.

Then, as similarly reported for the unit of length, in 1893 the U.S. Secretary of the Treasury issued an administrative order defining the pound in terms of the international kilogram:

1 lb = 453.592428 g.

As reported for the unit of length, in 1959 the U.S., in concert with the U.K., Canada, Australia, New Zealand, and Africa, agreed on a uniform equivalent for the pound in terms of the kilogram:

1 lb (avoirdupois) = 453.59237 g

In the U.S., this agreement came from the National Bureau of Standards and the U.S. Coast and Geodetic Survey, with the approval of the Secretary of Commerce. The new relation changed the U.S. equivalent of the pound, in terms of the international kilogram, by 0.1 ppm over what it had been previously.

The international metric unit of mass is the kilogram, kg, which is equal to the mass of the international kilogram maintained at the International Bureau of Weights and Measures at Sevres. The international kilogram is made of a special alloy of platinum with 10% by weight of iridium, and is cylindrical in shape, with approximately the same height and diameter.

Originally, the kilogram was intended to be the mass of 1,000 cm^3 of water at its temperature of maximum density (near 4°C), but, as we have already seen in discussing the liter, there was a difference of 28 ppm.

The United States National Bureau of Standards has two prototypes of the international kilogram, along with several working standard kilograms. It appears that comparisons between two platinum-iridium copies of the international kilogram can be made with an uncertainty of about 0.01 ppm. The international prototype kilograms maintained for the U.S. at the National Bureau of Standards are "Kilogram 4" and Kilogram 20," which were obtained from the International Bureau of Weights and Measures in 1890. Also at the National Bureau of Standards is the "Arago Kilogram" purchased from France in 1821.

D. THE UNIT OF TIME

Of all the natural phenomena observable by man, those occurring in the heavens are the most striking, the most readily observed, and the most regular. It was only natural, then, that in early historical times this regularity was connected with the measurement of time. In the 6th Century B.C., the Ionian Greek philosopher, Thales of Miletus, correctly predicted the time of an eclipse of the sun.

In more modern days, into the 19th Century, the keeping of time for living and working purposes at different locations on the earth's surface has been complicated, with cities and towns maintaining their own individual local or "sun" times. Less than 100 years ago, the railways in Britain ran on London-Greenwich time, while the railways in France ran on Paris time. But in the U.S., then, the great distance from one coast to the other made a difference of several hours in local or "sun" time, so that all the railways in the U.S. needed more than a single time system. Actually, each of the railroads that ran principally north and south, with not much east-west trackage, had its own time. And the long east-west lines, particularly those running from the middle west to the Pacific coast, had several different time zones. This created much confusion at the points where the time systems overlapped.

In 1878, Sandford Fleming, a Scotch-Canadian, proposed the plan of having 24 equal time zones around the earth, each of 1 hr, and each covering 15° of longitude, with London-Greenwich taken as the zero starting point. Railways in the U.S. and Canada adopted the plan, making four time zones in the then continental United States. However, now nearly a century later, a new suggestion is being seriously proposed, arising from the enormous increase in speed of communication and of travel, and the necessity for industry, business, government, and other components of our society to communicate rapidly and freely and transact business at reasonable times. This suggestion is that the continental United States return to one time system. But our existing system of 24 zones around the world is likely to remain with us a long time.

For centuries, the length of the day had been reckoned as the mean time of rotation of the earth on its own axis, with the day split into 24 hr, each hour into 60 min, and each minute into 60 sec, making 1 day equal to 86,400 sec.

Up to 1956, the international unit of time was the second, defined as 1/86,400 part (exactly) of the time required, on the average during a given year, for one complete rotation of the earth on its own axis. But astronomers found that the time of rotation of the earth on its own axis was not quite constant, there being small periodic fluctuations during a given year and small unpredictable changes from one year to another.

It appears that these variations in the time of rotation of the earth on its own axis may be categorized in three ways: secular changes; caused by tidal friction; irregular changes, probably caused by turbulent motion in the liquid core of the earth; and periodic changes, occurring in periods of ½ year caused chiefly by the tidal action of the sun, which slightly distorts the shape of the earth, and in periods of 1 year, caused principally by the seasonal change in the wind patterns of the Northern and Southern Hemispheres.

The secular changes consist of a slow, more or less regular, increase of about 0.0015 sec in a century. The irregular changes come in relatively short periods of time, say 5 to 10 years, with an increase in one period followed by a decrease in the next period. The maximum difference from the mean time for one rotation of the earth on its own axis has been found to be about 0.005 sec during a century. Since 1900 the algebraic accumulation of these irregular differences has amounted to about 40 sec. The periodic changes result in the cumulative effect of the earth being slow in its time of rotation near June 1 of about 0.030 sec and fast in its time of rotation near October 1 of about the same amount. The maximum variation in the length of the day, from one season to another, appears to be about 0.0005 sec.

The secular and irregular variations referred to were discovered by comparing the time of rotation of the earth on its own axis with the time of rotation of the earth and other planets around the sun. The periodic variation was discovered with the aid of quartz crystal clocks. The precision of observation of the periodic and irregular variations given in the foregoing results from the development of the new unit of time discussed later in this section.

Because of the variations described above, the International Committee on Weights and Measures, in 1956, changed the definition of the unit of time from that based on the rotation of the earth on its own axis to one based on the rotation of the earth about the sun. The second was then defined as 1/31,556,925.9747 part of the time required for the earth to orbit the sun in the year 1900. Specifically, the second was taken as the foregoing fraction of the tropical year at 12h, ephemeris time, 0 January, 1900.

One of the difficulties of this definition is the lack of any direct comparison with the second itself. It appears that, while the apparent precision of the foregoing definition* is 1 in 300 billion, the relationship between the definition and the actual realization of the second is of the order of 0.001 per million. This relationship was obtained by a series of astronomical observations over a period of several years.

Meanwhile, spectacular events relating to the measurement of time were taking place, involving the development of atomic beams, masers, and absorption cells for measuring frequency and time. It was found that these newly developed devices could be compared with one another with a precision of better than 0.0001 per million during observations lasting only an hour. Later, the precision was increased significantly.

In 1967, the International General Conference on Weights and Measures approved the following definition of the unit of time, which had been recommended by the International Committee on Weights and Measures in 1964:

> The unit of time is based on the transition between two hyperfine levels ($F = 4$, $M_F = 0$; $F = 3$, $M_F = 0$) of the fundamental state, $2S_{1/2}$, of the atom of the pure nuclide, Cs-133, undisturbed by external fields, with the value 9,192,631,770 cycles (Hertz) taken as (exactly) one second.

Taking the uncertainty as ½ unit in the last figure, this becomes 0.00005 ppm, or the equivalent of 1 sec in 600 years. One of the great advantages of this new unit is that exact calibrations can now be made in a matter of minutes, whereas before enormously long times were required for definitive checks.

It should be noted that the new international unit of time, based on atomic transitions in pure Cesium-133, is uniform and quite independent of the secular, irregular, and periodic variations in the time of rotation of the earth on its own axis, referred to previously. The time registered by the "atomic" clock can be adjusted to accord with mean solar calendar time given by the rotation of the earth.

In the foregoing discussion, the word second has uniformly meant the "mean solar second," which is to be distinguished from the "sidereal second" of the astronomer. The relation between the two is as follows:

$$1 \text{ sidereal sec} = 0.9972696 \text{ sec.}$$

For the benefit of users everywhere, in the laboratory, in industry, in the marketplace, and in the home, the U.S. Government is providing time and frequency services 24 hr a day from several radio stations operated by the National Bureau of Standards and by the U.S. Department of the Navy.

The U.S. Navy has ten different radio stations (NBA, NSS, NLK, NAA, NPM, NWC, NPN, NPG, NDT, and Omega) which broadcast time and frequency.[10]

The National Bureau of Standards has two radio stations which broadcast continuously day and night, WWV at Fort Collins, Colorado, and WWVH at Mauai, Hawaii.[7] The services provided include the following: (a) standard radio frequencies of 2.5, 5, 10, 15, 20, and 25 MHz (10^6 cycles); (b) standard time voice announcements, each minute; (c) standard time intervals of 1 sec and 1 min; (d) corrections to adjust mean solar time to astronomical time; and (e) standard audio frequencies of 440, 500, and 600 Hz.

These radio signals of the National Bureau of Standards are controlled against the new international unit of time with an accuracy near 0.001 ppm. These transmissions of time and frequency are coordinated through the International Bureau of Time in Paris in accord with international agreements, and are based on the international time scale, Universal Coordinated Time (UTC), more commonly known as Greenwich Mean Time. Prior to January 1, 1972, the NBS time signals were kept in close agreement with "astronomical time," but beginning at that date this was discontinued. The UTC maintained by the National Bureau of Standards is no longer adjusted periodically to agree with the rate of rotation of the earth, and gains about 1 sec per year on "earth rotation time." Corrections to UTC are now made in step adjustments of exactly 1 sec as directed by the International Bureau of Time. These "leap" second adjustments ensure that UTC signals as

*As explained by McNish,[3] this "multidigited number was obtained from Simon Newcomb's equation for the celestial motion of the sun. The equation is quadratic in time, and gives, subject to correction for periodic effects, the longitude of the sun in the plane of the ecliptic with respect to the vernal equinox. The particular time in the definition reduces the quadratic term in the equation to zero. This is the ephemeris second, the unit of time in terms of which all planetary motions were most simply expressed."