DEPARTMENT OF COMMERCE

BUREAU OF STANDARDS

George K. Burgess, Director

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TESTING OF LINE STANDARDS OF LENGTH[1]

ABSTRACT

This circular outlines the methods used in the comparison and standardization of line standards of length and gives the basis of such measurements in the United States. The apparatus used and the precautions necessary for precise work are considered. Information regarding the testing of line standards and of metal tapes is given, including shipping directions.

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[1] Prepared by Lewis V. Judson, associate physicist.

I. INTRODUCTION

This circular describes apparatus and methods of length measurement, particularly those used at the National Bureau of Standards in the comparison of line standards.

The act establishing the Bureau of Standards provided "that the functions of the bureau shall consist in the custody of the standards; the comparison of the standards used in scientific investigations, engineering, manufacturing, commerce, and educational institutions with the standards adopted or recognized by the Government; the construction, when necessary, of standards, their multiples and subdivisions; the testing and calibration of standard measuring apparatus; the solution of problems which arise in connection with standards; the determination of physical constants and the properties of materials, when such data are of great importance to scientific or manufacturing interests and are not to be obtained of sufficient accuracy elsewhere."

The Bureau of Standards compares line standards of length submitted for test and certifies them in accordance with the regulations governing such tests.

II. FUNDAMENTAL STANDARDS

The primary standard of length in the United States is the national prototype meter No. 27, which is identical in form and material both with the international prototype meter deposited at the International Bureau of Weights and Measures at Sèvres, near Paris, and also with the other national prototype meters distributed to the contracting nations under the terms of the treaty known as the Convention of the Meter, dated May 20, 1875. These meter bars were made in 1880, and the comparison of the lengths was begun the following year. At the international general conference of weights and measures in 1889 the final results were reported and the meter bars were assigned to the several countries by lot.

These meter bars are composed of an alloy of 90 per cent platinum and 10 per cent iridium, and they have an X or Tresca shaped section, as shown in Figure 1. On each bar are three fine transverse lines at each end, ruled on well-polished areas in the neutral plane. Two parallel, longitudinal lines, about 0.2 mm apart, define the portion of the transverse lines to be used in any measurement. The transverse lines are about 0.006 mm wide and have sharp, smooth edges when viewed with a magnification of 50 diameters. Care was taken to have both the rulings and the polish of the surfaces so uniform that both ends appear alike when viewed under the microscope.

One meter, the unit of length, is defined as the distance between the two principal lines on the international prototype meter when that bar is at a temperature of 0° C. and supported at points 28.5 cm

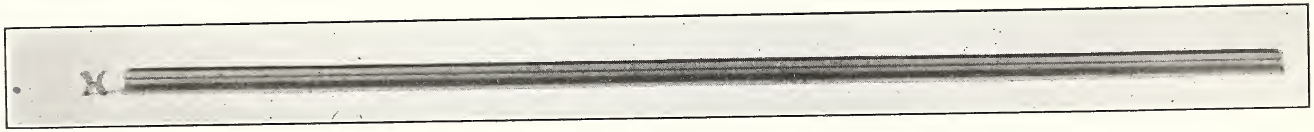

Fig. 1.—*The national prototype meter*

each side of the center. The lengths of all the national prototype meters have been certified in terms of the international prototype.

It is necessary to keep the distinction clearly in mind between the terms "units" and "standards," because the same words are used to express the idea of unit and also that of standard—as, for instance, "meter" or "yard." This has been clearly stated by H. W. Bearce, from whose paper, "A Fundamental Basis for Measurements of Length," the following is quoted:

> A unit, as applied to length measurements, is a nominal distance in space, fixed by definition. It is independent of temperature, pressure, or other physical condition.
>
> A standard is the physical embodiment of a defined unit. In general, a standard is not independent of temperature or other physical conditions. It is a true embodiment of the definition it purports to represent, only under definite standard conditions.

Thus, the meter as a unit is the distance defined by the bar known as the international prototype meter when that bar is under certain specified conditions. The length of that prototype is not 1 m at any other temperature than the specified temperature of 0° C.

All of the above bars are line standards; that is, standards in which the length is defined as the distance between lines or graduations on the surface. There is another type of length standard which is frequently used, especially in industrial work, namely, the end or contact standard in which the length is defined as the distance between two surfaces. This second type of length standard is not considered in this circular.

Besides the intercomparison of the national standards after the first comparison an entirely different method of determining the invariability of the meter and of detecting changes in the lengths of meter bars is employed by using the methods of interferometry with the wave length of homogeneous light as the unit. Measurements of the wave length of light with reference to the international prototype meter were made in 1892 and 1893 by Michelson and in 1906 by Benoit, Fabry, and Perot. The two sets of measurements are in substantial agreement, and the relation obtained by the latter workers has been quite generally accepted as standard. The relation for red cadmium light under specified conditions of temperature, pressure, and humidity is

$$1 \text{ m} = 1{,}553{,}164.13 \text{ wave lengths}$$

Previous to the year 1893 two different bars were used as the basis of length standardization in the United States. From 1836 to 1856 the interval from the twenty-seventh to the sixty-third inch on the 82-inch brass Troughton scale was used; from 1856 to 1893 the bronze yard No. 11 was accepted as the standard. In 1893 meter No. 27 was adopted as the primary standard of length in the United States because it was superior to either of the two previous standards in shape, sharpness of lines, and permanency of length. This bar has been twice verified at the International Bureau of Weights and Measures since its original standardization, and there is no evidence of any change in length with respect to the international prototype. What was first supposed to be a change detected in 1904 has since been traced to errors in the laboratory standards with which it was compared at Sèvres. Its equation of length is as follows:

$$\text{No. } 27 = 1 \text{ m} - 1.6\ \mu + 8.657\ \mu\ t + 0.00100\ \mu\ t^2$$

where 1 micron (μ) + = 0.000,001 meter (m) and t is temperature in centigrade degrees of the international hydrogen thermometer. This bar is used only for the verification of other platinum-iridium bars.

In addition to the national prototype meter No. 27 the Bureau of Standards possesses Meter No. 21 which is a bar in the same series as No. 27. This bar is used in the verification of the bureau's secondary or working standards and other meter bars where high accuracy is desired. The bureau also possesses two platinum-iridium standards known as the alloy of 1874 made of an alloy prepared the year before the signing of the Convention of the Meter. These are No. 4 and No. 12 (of the 1874 series). The former is graduated to millimeters for its entire length and, in addition, is ruled with a special line which is approximately 1 yard from the zero line. These bars are sometimes used in special work of high precision.

III. SECONDARY STANDARDS

For the routine work of testing, secondary or working standards are used whose values have been carefully determined by comparison with prototype meter No. 21 from time to time to detect any possible changes. These working standards include multiples and submultiples of the meter and of the yard.

IV. MULTIPLES AND SUBMULTIPLES OF THE METER

The secondary units of length in the metric system are multiples and submultiples of the meter based on powers of 10, and their equivalents in meters are shown in the following table:

Table of metric length units

1 kilometer	= 1,000	meters = 10^3	meters.
1 hectometer	= 100	meters = 10^2	meters.
1 dekameter	= 10	meters = 10	meters.
1 decimeter	= 0.1	meters = 10^{-1}	meters.
1 centimeter	= .01	meters = 10^{-2}	meters.
1 millimeter	= .001	meters = 10^{-3}	meters.
1 micron	= .000,001	meters = 10^{-6}	meters.
1 millimicron	= .000,000,001	meters = 10^{-9}	meters.

V. CUSTOMARY UNITS AND STANDARDS OF LENGTH

The United States yard is defined by the relation:

$$1 \text{ yard} = \frac{3,600}{3,937} \text{ meter}$$

The legal equivalent of the meter for commercial purposes was fixed as 39.37 inches by the law of July 28, 1866, and experience having shown that this value was exact within the error of observation the United States Office of Standard Weights and Measures was authorized, in 1893, by Executive order, to derive the yard from the meter by the use of this relation.

VI. COMPOSITION, FORM, AND USE OF LENGTH STANDARDS

The primary requisite of a length standard is that its length be a definite quantity under definite specified conditions. Platinum and iridium alloyed in the ratio of 90 to 10 has been found more nearly to fulfill this condition than any other known metal or alloy. While brass and bronze are much used for standards, they are known to be much less stable than platinum-iridium. Platinum-iridium, the material of which the prototype meters are made, is especially suitable for length standards of highest rank, not only because of its permanence but also because it does not rust, corrode, or tarnish, and because it takes an excellent polish. These properties insure at all times lines which, if properly made in the first place, will always be sharp and clear and not liable to slight alterations, because repolishing of the surface is not necessary. This alloy does not have the defect of the pure platinum of being too soft but is harder and stiffer and yet can be drawn and machined. Further information regarding material for standards will be found in Section XI.

The form used for the prototypes is that of a modified X shape. For other precision standards an H shape is generally used. Short bars and yard and meter bars of less precision are rectangular in shape with the lines on the upper surface.

The exact conditions under which a bar is standardized or used should always be definitely specified—whether in the air or in a liquid, whether supported throughout or at two specified points, etc.

The effect of temperature upon a standard is taken into account by specifying both the temperature at which the standard has its assigned value and the relation that connects changes of length with changes of temperature. The most common way of expressing this relation is by means of such an equation as

$$L_t = L_0 \ (1 + at + bt^2 + ct^3 + \ - \ - \ - \ -)$$

where L_t is the length at $t°$ C. and L_0 is the length at 0°. As many coefficients a, b, c, etc., may be used as are sufficient to give the required accuracy. Two are sufficient in most cases; often only one is needed. It is to be noted that the coefficients of expansion are pure numbers and that, in the case where only one is used, this is essentially a ratio—the change in length per unit length for a unit change in temperature.

The determination of the temperature of a standard when in use and the shielding of it from sudden changes of temperature are as important as the actual measurements of length. For accurate work the standard should be insulated as thoroughly as possible from the heat of the observer's body and from the heat of the illuminating system; its temperature should preferably be controlled by some constant-temperature bath. A constant-temperature room is very desirable for precision length measurements. When it is not possible to insulate the bars sufficiently, more frequent temperature readings must be taken and care exercised to insure that the thermometric device indicates the temperature of the standard. If the temperature of the air surrounding a bar is changing rapidly, the actual temperature of the bar may be quite different from the temperature indicated by the thermometer in contact with or near it.

The X, or Tresca, and the H types of cross section are designed to lessen differences between the temperature of the bar and the temperature indicated by a thermometer lying in the bar, to secure the maximum rigidity, and to bring the graduated scale into the plane of the neutral axis in order that changes in length with bending will be a minimum.

The use of a mercury-in-glass thermometer is the common and most economical method of determining the temperature, although the resistance thermometer and the thermocouple are being applied in the highest grade of precise measurements when accuracy and sensitiveness are desired. For most work at the ordinary room temperatures thermometers having a zero mark (for frequent determination of the variation of the ice point) and graduated from 10° to 30° or 35° C., in tenths of a degree, with a Jena-glass bulb, have been found very satisfactory. The corrections of the thermometer should be known for the horizontal position, and the thermometer laid in the bar in such a position as to give the best average temperature of the interval of the standard in use. When the bar is in air, a felt covering placed over the bulb and bar will often cause the thermometer to register more nearly the temperature of the bar than it otherwise would. Satisfactory thermal contact between the thermometer and the bar can be obtained by wrapping the thermometer bulb in metal foil free from paper and placing this in good mechanical contact with the bar.

When the temperature of a standard bar is obtained by packing it in ice, only the purest ice should be used, preferably manufactured from distilled water. The ice should be ground or cracked into pieces not over half an inch in length. Shaved ice may be packed over the graduation to be observed, and a hole made in the ice through which to sight on the line. Some distilled water should be mixed with the ice if the melting of the ice is not sufficient to provide water, as it is essential that the length standard be at the actual temperature of melting ice. When the melting is too rapid, the water should be drained off occasionally and the ice frequently packed to insure contact with the bar.

The apparent lengths of intervals on line standards may also be affected by the condition in which the graduations are maintained inasmuch as foreign matter in a line may change the apparent width and position of the line. The appearance of a line under a microscope may be quite different where a change in either the intensity or direction of the illumination is made. Satisfactory illumination is usually secured from a small lamp with frosted bulb placed a few centimeters away from the microscope, the light being reflected into a vertical direction by means of a small 45° prism or reflector. Excellent results may also be obtained by projecting the light from a large concentrated filament frosted lamp placed some distance away.

Since cleaning the surface to secure better illumination and consequently better definition of a line under a microscope is likely to wear down the edges of a line irregularly and change its position, the surface of precise standards should be of a metal not likely to tarnish easily. It is also desirable that the lines should be narrow, but as deep as possible, and that the bar should at all times be kept as free as possible from dust or other foreign matter. No attempt should be made to polish or smooth up the surfaces on which the lines have been ruled in any case where a possible change in length of the bar would be undesirable.

In case it is necessary to clean the surface of a ruled scale, the cleaning process should be carried out with extreme care. Whenever possible, it is preferable to allow all foreign matter to flow off the scale by the liberal use of benzol or alcohol. Then, with clean alcohol and a swab of absorbent cotton the process of cleaning may be continued, taking care to avoid any rubbing. It is often desirable to use a fairly forceful stream of alcohol from a chemist's wash bottle as a means of cleaning a ruled surface.

Where the construction of the bar permits, as in the case of H bars, it is frequently an advantage to keep the bar upside down when not in use. Dirt does not then collect in the graduations nor is the ruled surface so liable to accidental damage.

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VII. LENGTH COMPARATORS

In the comparisons of the lengths of line standards, the comparators used in all laboratories of the present day, while differing in design, have one common feature; namely, micrometer microscopes. Micrometer microscopes are ordinary compound microscopes with a measuring device consisting of a system of cross wires movable across the field of the ocular by a micrometer screw having a divided head. Micrometer microscopes are indispensable in precision-length measurements. For the complete classification of a length comparator for line standards at least three features of design must be stated: (1) Whether it is transverse or longitudinal or depending upon which direction there is motion of the movable parts, (2) whether it is fixed length or variable length, and (3) whether it is one with movable microscopes or one with movable standards. They may be classified according to purpose as those adapted for measurments at constant temperature, those for determinations of coefficient of expansion, for calibration of the subintervals of a standard, or those for permitting the measurements of end as well as line standards. Other features of the design of a comparator may also serve to differentiate it from others. Among these features are the use of electrical control of adjustments or of an electrically heated and thermostated water bath. The comparators are of various sizes, including those of especially large proportions, such as small comparators for calibrating scales less than a decimeter in length and 4 m geodetic bar comparators.

In the design of a length comparator for line standards many things must be carefully considered. The apparatus must be rigid; the distance between the two microscopes must remain constant during a set of observations; all motions must be smooth, definite, and regular; there must be a minimum of adjusting during the observations; everything must be so that the observer works under the most favorable conditions. Much attention must be paid to mechanical and optical perfection of the comparator and to its erection in a suitable room. Naturally the refinement in these various details will depend upon the accuracy required. The bureau will be glad to be of service in giving such further detailed information as it may have or may be able to obtain.

VIII. COMPARISON OF TOTAL LENGTH OF STANDARDS

The direct comparison of one length standard with another, especially in comparison with a fundamental standard, is of first importance. Although the comparison with the national standards can be done only at the Bureau of Standards in Washington where these standards are kept, the principles can be applied elsewhere in making comparisons of bars with calibrated scales.