CONFIDENTIAL

THE ROYAL SOCIETY
BURLINGTON HOUSE
LONDON W.1

9 March 1942

IN pursuance of Statutes 6 to 9, we forward herewith the list of candidates recommended by the Council for election into the Royal Society; and we are to inform you that THURSDAY, 19 MARCH 1942 at 4.25 o'clock, has been appointed for the election, which will be held in the Apartments of the Society at Burlington House.

A. V. HILL
A. C. G. EGERTON } *Secretaries*

SELECTED CANDIDATES

BURN, Joshua Harold	Prof of Pharmacology, Oxford
BURNET, Frank Macfarlane	Medical Melbourne
DIXON, Malcolm	Biochemist Cambridge
DODDS, Edward Charles	Biochemistry London
FAGE, Arthur	Aerodynamics: Nat. Phys. Lab
FAIRLEY, Neil Hamilton	Tropical diseases: London
HALL, Phillip	Pure Mathematics = Groups: Camb.
HANES, Charles Samuel	Biochemist: low temp. Camb.
HENDERSON, George H.	Physics: Pleochroic holes Nova Scotia
HILDITCH, Thomas Percy	Industrial Chemistry
HINDLE, Edward	Zoology Glasgow
HOLMES, Arthur	Geology: Appln of radioactivity (Dur. to geological purposes)
NEWITT, Dudley Maurice	Chem. Technology, London
PATERSON, Clifford Copland	Lighting industry: Nat. Phys. Lab
ROBERTS, John Keith	Colloid Sc. Camb. (Heat + Thermodyn)
SKINNER, Herbert Wakefield Banks	Physics Soft-X-rays Bristol
THODAY, David	Botany Bangor
TODD, Alexander Robertus	Org. + bio chemist: Manchester
TRUEMAN, Arthur Elijah	Geology Glasgow
WILSON, Alan Herries	Elec. Theory metals Camb.

Ind Physics 1
Pure Physics 3
Medicine 3
Bioch. 3
Org. chem. 1
Ind. chem. 2
Phys chem. 1
Math 1
Aerodynamics 1
Geology 2

Zoology 1
Botany 1
20.

MORNING SUBJECT (*h*)

THE ROYAL SOCIETY EMPIRE SCIENTIFIC CONFERENCE

JUNE–JULY
1946

COMMUNICATIONS FROM
THE NATIONAL PHYSICAL LABORATORY

A Discussion on Units and Standards

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A discussion on Units and Standards

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Introduction

By Sir Charles Darwin, F.R.S.

The sequence of papers following, contributed by members of the staff of the National Physical Laboratory, gives an account of most of the units and standards which are studied at the Laboratory. Each paper explains briefly the principal technical points involved, together with a short history. Of necessity a standard is to some extent a convention, and it may therefore be well to introduce the subject by a short review of the legal and conventional authorities on which they depend.

For the metric system the main international authority is the Conférence Générale des Poids et Mesures, at which duly accredited delegates of each of the thirty-two nations subscribing to the 1875 Treaty, the Convention du Mètre, are present, and which, in normal circumstances, meets every six years. The Comité International des Poids et Mesures is the Executive body appointed by the Conférence Générale to manage the affairs of the Bureau International des Poids et Mesures between meetings of the Conférence Générale. It consists of eighteen members, elected by the Conference, each of whom must belong to a different State, but who, as members of the Committee, are no longer representatives only of their individual countries, but of all subscribing countries. The International Committee meets every two years, makes recommendations to the General Conference, or acts on authority delegated to it by the Conference.

There are also three Advisory Committees which deal respectively with electricity, photometry and temperature. These Committees meet whenever necessary and make their recommendations to the International Committee which, if it approves them, offers them to the General Conference for ratification. The original Convention covered length and mass, and matters incidental thereto, such as thermometry and barometry; it was amended in 1921 to bring in the electrical and

photometric units. The headquarters of the organization are at the Bureau International at Sèvres.

Although the countries subscribing to the Convention du Mètre look to the Bureau International as the central authority for all measures relating to the metric system, this body has no direct legal authority in any individual country. It may be well, therefore, to touch on the legal situation in Britain. Our standards go back a long way—there are still in existence standards authorized by Henry VII, Henry VIII and Elizabeth—and due regard was paid by successive administrations to the need of properly legalized standards for purposes of trade and industry. From the scientific angle, however, it must be admitted that the legislation has not been at all systematic. The present legal standards of length and mass, the yard and pound (avoirdupois) were remade after the destruction of the old standards, when the Houses of Parliament were burnt down in 1834, and they were equated as nearly as could be ascertained to the old standards. The provisions for their use were embodied in the Act of 1856, but the specifications were incomplete in some respects, and in others they prescribed methods of measurement which were subsequently shown to be capable of improvement. Similar defects are to be found in the legal definition of the unit of cubic capacity.

For the electrical standards, on the other hand, a better policy was adopted, and the relevant Act made no quantitative specifications, but provided that they should be determined by Order in Council. The legal standard of the volt is at present embodied in an instrument at Teddington, which later experience has shown to be somewhat defective; however, when a certification is demanded it is always for the international and not for the legal volt, so that there have been no serious consequences of the defects.

Though many Acts of Parliament refer to temperature 'on Fahrenheit's scale', there is no enactment that prescribes what this scale is; it is now conventionally taken to be the absolute thermodynamic scale with 32° and 212° F exactly equal to 0° and 100° C. This certainly differs appreciably from the Fahrenheit scale as realized by the mercury-in-glass thermometers which were actually employed at the time the standards were laid down. Similarly, in calorimetry various enactments refer to the British thermal unit, but never specify it, and there are no less than three equally good authorities who might be quoted, all giving slightly different values for it. In photometry, candle-power was defined in 1860 in terms of a sperm candle, but it has been changed since then without formal authority, first to a flame lamp and later to electric lamps.

The general outcome of the papers following is summarized in table 1, which calls for some explanation. Apart from the need that it should keep constant in time, the important character of a fundamental standard is its accuracy of comparison, that is to say the degree of precision with which copies can be compared with their prototype. For derived standards there are two differing qualities of this type, accuracy of comparison and accuracy of realization. The first is the relative accuracy with which two examples of the same unit can be compared,

the second the evaluation of an example of the unit in terms of the fundamental standards of length, mass and time, and it will be noted that in many cases the second is distinctly inferior in accuracy to the first.

TABLE 1. TABLE OF ACCURACIES

Unit	Physical Dimensions	Standard or Reference	Nature	Accuracy of Realization parts per million	Accuracy of Comparison parts per million
length	L	international metre	material	—	0·2
		wave-length of light	natural	0·02	0·01 (1)
mass	M	international kilogram	material	—	0·002 (2)
time	T	mean solar second	natural	—	0·01
temperature	—	thermodynamic scale	theoretical	— (3)	1 (4)
volume	L^3	litre	derived (5)	1	—
gravity	LT^{-2}	earth's attraction	natural	2	1 (6)
pressure	$ML^{-1}T^{-2}$	standard barometer	—	10	—
electric resistance	LT^{-1}	ohm	theoretical	10	1
electric current	$M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}$	ampere	theoretical	10	1 (7)
quantity of heat	ML^2T^{-2}	calorie	—	100 (8)	—
luminous intensity	ML^2T^{-3}	candle (9)	material	2,000	1,000
sound pressure	$ML^{-1}T^{-2}$	—	derived	10,000	— (10)

(1) Comparison of derived end-standards (metre or yard).
(2) Comparison of kilograms.
(3) The absolute zero is accepted as $-273{\cdot}15 \pm 0{\cdot}02°$ C.
(4) Reproducibility of the ice-point on the absolute scale.
(5) Derived from the kilogram of water; 1000·027 cm.^{3} = 1 l.
(6) Accuracy of relative comparisons between different stations.
(7) The relative comparison is not of amperes but of volts.
(8) Electrical determination of the mechanical equivalent for the 15° C cal.
(9) The dimensions are those of power, but there is an additional factor representing the response of the eye to energy at any wave-length.
(10) The acoustic unit selected is the most generally useful; the accuracy of comparison varies with the experimental conditions but would generally be better than the accuracy of realization.

The succeeding papers deal with all the items in the table with two exceptions. One of these is time, and though much work is done on the subject at the laboratory, it is primarily the responsibility of the Astronomer Royal. We owe to him the information entered in the table, which is roughly speaking the accuracy of behaviour of the best crystal clocks; already these clocks are so good that they can show up small irregularities in the earth's rotation. Time, of course, plays a part in many of the derived standards, but the accuracy of realization of these is for the most part much lower, so that time-keeping is not usually the most serious difficulty in their attainment.

There is also no paper on calorimetry. In modern times precise calorimetry is always done electrically, since the measurement of electrical energy is much easier than that of any other form. Indeed, it has been proposed that when the absolute system of electrical units is adopted in place of the present International System, the calorie shall be redefined as a definite quantity of electric energy by the

equation 1 cal. = 3600/860 joules or 1/860 watt-hour. The effect of this reform will be to remove the question of the specific heat of water from the place of importance which it now occupies, and which it does not deserve.

One entry in the table is the value of gravity, which is not strictly speaking a standard at all. Its presence here is justified because it is an essential intermediary in the evaluation of several of the other standards, in particular those of pressure and of electric current.

The very different natures of all these physical quantities impose some strain in forcing them into a single table. In each case there is some range of values where the measurement is easiest and most precise: for example, absolute temperature is very much more precisely known at ordinary temperatures than at a red-heat. In the table the most favourable case has been taken, and the choice is partly explained by footnotes, but for full appreciation the succeeding papers must be studied.

The standards of length

By J. E. Sears

The fundamental standards

The units of length, on both the British and metric systems, are at present defined by material standards known respectively as the Imperial Standard Yard, and the International Prototype Metre.

The Imperial Standard Yard is a bar of Baily's metal (16 parts copper, $2\frac{1}{2}$ parts tin and 1 part zinc) 1 in. square in section and 38 in. long. It is one of a number of similar bars, cast in 1845, and was given legal status as the Imperial Standard by the Weights and Measures Act of 1856. It replaced the former standard—the 'Bird' Yard—which had been destroyed in the fire at the Houses of Parliament in 1834. At 1 in. from either end there is a hole $\frac{1}{2}$ in. diameter and $\frac{1}{2}$ in. deep, the bottom of which therefore lies in the neutral plane of the bar. At the centre of the bottom surface of each hole a polished gold stud is inserted on which three lines are ruled, at right angles to the length of the bar. The length of the yard is defined, in the Weights and Measures Act, 1878, as the distance between the central lines at the two ends when the bar is at the temperature of 62° 'of Fahrenheit's thermometer'.

The International Prototype Metre is a bar of platinum-iridium alloy (90 % platinum, 10 % iridium) of a special winged X-form section devised by G. Tresca to give maximum rigidity in relation to the weight of metal used; the neutral plane of the section is exposed throughout the length of the bar, and the metre is defined as the distance between two transverse graduations on the neutral plane, near the ends of the bar, when the latter is at the temperature of 0° C. This bar is one of a number prepared in pursuance of the International Treaty of 1875, known as the Convention du Mètre, and received sanction as the International Prototype,

replacing the old Mètre des Archives, at the first General Conference of Weights and Measures held in pursuance of the Treaty, in 1889.*

The reason for putting the graduations on the neutral plane is that the material of the bar in this plane is neither extended nor compressed by the elastic distortion of the bar due to its own weight when resting on its supports. It is still necessary, however, to specify the manner in which the bar shall be supported. If supported at its two ends, for example, it would droop in the middle, and the distance between the graduation marks would be slightly shorter than the 'free' distance between them. The Weights and Measures Act, 1878, specifies that the Imperial Standard Yard shall be supported on a system of eight rollers connected by pivoted levers in such a manner that the weight of the bar is equally distributed between them, thus minimizing the flexure of the bar, and providing freedom for expansion or contraction according to temperature conditions. The International Prototype Metre is supported for measurement on two rollers symmetrically arranged at a separation of 571 mm., this distance being calculated so that the separation of the graduations is a maximum and therefore, to the first order, independent of slight errors in positioning of the rollers. Actually the difference in the length of the yard as supported on eight rollers, or alternatively as supported on two rollers suitably placed to give maximum length, is quite negligible in relation to the accuracy of measurement, and it is found preferable in practice to make comparisons on two supports only, since there is less risk in this way of accidental movements of the bar during measurement.

Comparisons of line-standards

It will be noted that both the Imperial Standard Yard and the International Prototype Metre bars are 'line' standards, adapted to be compared with other measures by means of micrometer microscopes on a comparator. On the comparator two microscopes are used, set at a fixed distance apart, to read the lines at the two ends of the bar, and the two bars to be compared are carried on two parallel girders on the carriage of the comparator, with independent adjustments for aligning the bars and focusing the graduations in the microscopes. The carriage can be moved so as to bring either bar at will into view in the microscopes. In the eyepiece of each microscope a pair of parallel cross-wires is adjusted by means of the micrometer so as to appear symmetrically disposed in relation to the image of the graduation on the bar, and the reading recorded.

In this way the lengths of two bars can be compared. But owing to the effects of possible asymmetry in the graduations and in the cross-wires of the microscopes, and of the 'personal equations' of setting of the observers, it is necessary to repeat the readings with the bars reversed in direction, and for each observer to take an equal number of readings with each microscope under each condition. Finally, in order to achieve the greatest possible accuracy it is usual to compare not merely

* 1889, *C.R. Première Conférence Générale des Poids et Mesures.* Paris: Gauthier-Villars.

two bars, but a series of bars, each with each, and to evaluate from the totality of the measurements, by the method of least squares, the most probable values of the differences between the individual bars.

It should be remarked that the graduation marks on a line-standard are, in the last resort, in the nature of furrows, with more or less ragged edges, whose appearance will differ according to the magnifying power of the microscopes employed, and according to the manner in which they are illuminated. Both these factors will affect the observer's estimate of the mean position of the line. The complete specification of a line-standard should therefore, strictly speaking, include instructions on these two points. Generally speaking it is undesirable to employ a magnification exceeding $\times 100$; $\times 50$ is more usual. The exact reproduction of illumination conditions is in any case a matter of some difficulty. The actual nature and quality of the graduations has, of course, a marked bearing on this question, and the metric standards have the advantage over the older British standards in this respect.

Temperature effects

It is necessary, of course, to maintain a close control and make accurate measurements of the temperature of the bars during comparison. For this reason the comparator is arranged so that the bars can be immersed, during measurement, in the inner compartment of a double water-bath, provided with stirring devices to maintain a uniform temperature. In the case of the metric standards it is permissible to immerse the bars in distilled water, together with suitable thermometers, during measurement, but the construction of the British standards makes this procedure undesirable in their case, and the comparisons have to be made in air, so that the control of temperature presents greater difficulty, though the outer water-bath can still be used. In any case measurements cannot readily be made exactly at 62° F, and still less can they conveniently be made at 0° C. Since different bars will have different coefficients of thermal expansion, it is necessary to determine these and make allowances for them in computing the results of comparisons actually made at other temperatures.

The process of determining coefficients of expansions is similar to that of comparing two bars, except that the bars being compared are kept in separate compartments on the comparator (or dilatometer as this variant of the apparatus is named), one of which is kept at a constant temperature while the temperature of the other is varied by known amounts between successive comparisons.

It is important to note that the *units* are absolute measures of spatial extension, and entirely independent of any temperature considerations, once their values have been ascertained in terms of the defining standards under the prescribed conditions. There has in the past been a certain confusion of ideas on this point, with the result, for example, that it was at one time considered that a metre of any material must have the length of a metre at the temperature of definition, 0° C, and that, in consequence, metres of varying materials would be of varying

lengths at ordinary temperatures. It has now been agreed internationally that industrial standards of length, whether British or metric, shall be adjusted to be correct—i.e. to agree in value with the units—at 20° C (68° F). So long as such standards are made of materials having a similar coefficient of expansion to the articles they are used to measure, and the standards and the articles are at the *same* temperature at the time of measurement, the comparison will then give directly the true size of the article at 20° C, whatever the actual temperature of measurement.

Materials of construction for length standards

This brings us to a consideration of the kinds of materials used for the construction of standards for various purposes, other than the primary standards. The principal materials so employed are steel, brass and invar, together with fused silica and crystal quartz. Steel and brass are used for industrial standards for the measurement of articles made of materials with corresponding coefficients of expansion. In some cases brass, or gun-metal, gauges are used in preference to steel in explosives factories simply for safety reasons.

Invar, an alloy steel containing 36 % nickel, has the remarkable property of having a very low coefficient of thermal expansion, varying according to the size and shape of the piece and the thermal and mechanical treatment to which it has been subjected, from about $1{\cdot}5 \times 10^{-6}$ to $-0{\cdot}5 \times 10^{-6}/1°$ C. It is, however, subject to a marked secular growth which renders it unsuitable for use as a reference standard, and its low coefficient makes it also unsuitable as a standard of comparison for use in most industrial measurements. Apart from its special applications in the construction of such articles as thermostats, pendulum rods for clocks and the like, it serves two very useful purposes in metrology, namely, it provides a convenient comparison standard for the determination of coefficients of expansion, and is very valuable as a material of construction for the tapes and wires which are used for the measurement of bases in geodetic surveys where errors due to uncertainty of temperature measurements in the field, with materials of higher coefficients, might be of serious consequence.

Fused silica, with a coefficient of expansion of about $0{\cdot}4 \times 10^{-6}/1°$ C, was considered likely to be a stable material, and therefore as possibly helping to provide a control on the constancy of units of length defined by material standards made of alloy metals. Two standards of fused silica have been made, one of which is at the N.P.L. (Kaye 1911) and one with the Indian Ordnance Survey. Comparisons of the silica metre at the N.P.L. since 1911 with other copies of the metre linked back to the platinum-iridium standard have exhibited no systematic change.

Crystal quartz is another material which, by virtue both of its structure and its antiquity, might be expected to have a high degree of stability. Standards of crystal quartz are necessarily limited to a fraction of the length of the normal unit. End-standards of quartz of 1 dm. length have, however, been made and measured

with high precision by optical interference methods. This work has not yet been repeated systematically over a long enough period to draw any definite conclusions from it.

Constancy of units

Control on the reproducibility of the units in the event of loss or damage is maintained by the provision of copies, in the case of the Imperial Standards the Parliamentary Copies, which are held in the custody of the Board of Trade, the Royal Observatory, the Royal Mint and the Royal Society, and in the case of the Metric Prototype Standards the 'Témoins', which are held at the Bureau International des Poids et Mesures, and the various national copies distributed to all the countries subscribing to the Convention du Mètre. Periodical intercomparisons between these copies suffice to show whether any one of them has changed relative to the others, and very occasional checks between the principal copies and the fundamental standards maintain the connexion with the latter. Should one of the fundamental standards be found at any time to have changed relative to the copies by an amount appreciably exceeding the experimental error of the comparisons, steps would need to be taken to replace it, or to substitute for it one of the copies presumed not to have changed. It must be remarked, however, that continued agreement between a number of standards all of the same material does not, by itself, suffice to establish the absolute constancy of any of them.

With regard to the continuity of the units and the stability of the standards the following may be stated. There are still in existence, at the South Kensington Museum, the old standard yards of Henry VII and Elizabeth. Both these are end-standards, with roughly incised subdivisions representing fractions of the yard. The former has been found to agree with our present yard within $\frac{1}{32}$ in., and the latter, though broken and roughly mended, within 0·01 in.* This bar, which has since been more carefully repaired, remained the standard of the country until 1824, when it was superseded by a yard known as the Bird Yard, whereon the unit length was defined as the distance between two dots on inserted gold plugs, which had been placed in the custody of the Clerk of the House of Commons in 1760, following the Reports of Lord Carysfort's Committee,† but which did not receive legal sanction till 64 years later (Weights and Measures Act, 1824). Unfortunately, its legal existence was all too short, for it was destroyed, as mentioned above, in 1834.

The Weights and Measures Act, 1824, prescribed that if the Imperial Standard Yard were ever lost or destroyed it should be restored by reference to the length of the pendulum beating seconds in London. In a certain sense, then, the unit of that day was theoretically a 'natural' unit, of which the standard was no more than the material representation. The Committee entrusted with the duty of

* 1873, *Report of the Warden of the Standards on the Proceedings of the Standard Department of the Board of Trade.*

† 1738–65, *Reports from Committees of the House of Commons, Miscellaneous Subjects*, **2**, 434.

producing a new standard soon found, however, that the difficulty of reproducing with accuracy the length of the seconds pendulum was greater than that of reproducing the length of the old bar through the agency of other standards which were known to have been compared with it, and this procedure was that which, in fact, was employed for the establishment of the new (and present) standard. It is estimated that the new standard represented the current values of the best scientific standards of the time (which were susceptible of intercomparison with higher accuracy than the Imperial Standard itself) within 0·0002 in. and was in agreement with the standard it replaced within the limit of accuracy to which the latter could be measured.

Evidence for the constancy of the yard in recent times is fairly satisfactory. The results of the comparisons of the Imperial Standard Yard with its three contemporary Parliamentary Copies, Nos. 2, 3 and 5, in 1912, 1922 and 1932,* show that each of the four bars has remained in the same relationship to the mean of the group as when first determined in 1852, within 0·00005 in. In particular P.C. 2 has remained constant in relation to the mean within 0·000004 in., and P.C. 5 within 0·000016 in. for the last three comparisons. It should be mentioned, however, that a new Parliamentary Copy authorized to be made by the Weights and Measures Act, 1878, was constructed as nearly similar as possible to the original series in 1879. Since its first determination, in 1886, this bar has shown a systematic shortening in relation to the rest of the group, successive comparisons, when plotted, falling very closely on a smooth curve, with an asymptotic value of -228×10^{-6} in. which had very nearly been reached 40 years after its construction. If it is assumed that the original bars behaved similarly during the first 40 years of their existence dating from 1845, then at the date of the first comparison of P.C. VI, in 1886, they would have reached an effectively steady condition, but they would, in the meantime, have shortened by just over 0·0002 in. since their own original determinations in 1852.

With regard to the metre, the present international standard, when given legal status in 1889, was declared equal, within the limits of accuracy of measurement estimated at the order of 0·001 mm., with the old Mètre des Archives which it superseded. Evidence of subsequent consistency is available from the results of recomparisons of twenty national copies since 1919 with the working standards of the Bureau International.† After making due allowance for changes known to have occurred in the values of the working standards, and for certain adjustments in the accepted values of the coefficients of expansion of the various bars, the results of all these individual comparisons were in agreement within $\pm 0{\cdot}001$ mm. with the original determinations made prior to 1889, the average change being $\pm 0{\cdot}0003$ mm., and the mean of all the results was in agreement with the original

* 1936, *Report by the Board of Trade on the comparison of the Parliamentary Copies of the Imperial Standards.*

† 1927, *La Création du Bureau International et son Œuvre*, p. 125, Ch. Ed. Guillaume. Paris: Gauthier-Villars.

mean within 0·0001 mm. As regards the secular constancy of the metre, there have been a series of determinations of its length in terms of the wave-length of the red radiation of cadmium, commencing in 1893 with that of Michelson & Benoît (1895), which, while they exhibit variations amounting to $\pm 0{\cdot}0003$ mm. from the mean, give no indication of any progressive change. There is therefore good reason for confidence in the constancy of this unit.

The current accuracy of measurement of the yard is estimated at about 0·00002 in., or 0·5 part in 10^6, that of the metre, which has more perfect graduations, at about half this amount. Recently a number of the copies of the metre at the Bureau International have been regraduated, with still better lines, and an accuracy of the order of 1 part in 10^7 is now claimed. Fortunately, the prototype metre itself has particularly good lines.

Types of standard

It will be noticed that the standard yard, originally an end-bar, passed through the phases of the 'dot' standard, and the 'natural' standard defined by reference to the 'seconds' pendulum, and finished as a line-standard. The history of the metre is remarkably similar, though the order is somewhat different. Originally a 'natural' standard, defined as the ten-millionth part of the earth's polar quadrant passing through Paris, and represented for practical purposes by the Mètre des Archives, a platinum end-standard 25×4 mm. in section, it was fairly soon found that the difficulty of repeating the determination of the value of the standard by reference to the definition was so great that it was necessary to legalize the length of the Mètre des Archives itself as defining the unit. Later, when the new international standard of the metre was established, the principle of defining the unit by means of a material standard was maintained, but preference was given to a line-standard, graduated on the neutral plane, as had already been adopted by British scientists for the yard.

The parallelism between the histories of the British and metric standards of length is worthy of some comment. It is evident that British scientists have not been behind their Continental colleagues in the initiation of improvements. The common change from end- to line-standards, and the common abandonment of natural standards, is clearly indicative of the stage of technical development reached at the epochs concerned. When the earliest standards were constructed end-standards offered greater advantage in accuracy than line-standards. Later, with the application of the ruling engine and microscope, this position was reversed. But the story is not yet complete. There are now very good prospects of being able in the near future to propound a natural standard, in the form of a selected wave-length of monochromatic light, which is capable of definition and reproduction with an accuracy of the order of 1 or 2 parts in 10^8—appreciably higher than can be attained even with the best line-standards. Further, there are now technical means available to produce end-standards (which are those most readily and

directly measurable in terms of wave-lengths) of sufficient perfection to take advantage of this accuracy.

It may be of interest to remark here that the pendulum experiment, regarded as a means of ascertaining the value of gravity in terms of the units of length and time, still remains one of the essential operations of metrology, since a knowledge of the local value of gravity is necessary, for example, to the establishment of the electrical unit of the ampere by weighings on a current balance, and of the standard atmospheric pressure in determining the boiling-point of water for fixing the temperature scale. Mr Clark's note in the present series of papers summarizes the position with regard to the accuracy with which the value of g has been determined.

Ratio of yard to metre

It might be supposed that further evidence as to the constancy of the yard would be available from successive determinations of its relationship to the metre. Unfortunately, however, early determinations of this ratio, by Kater (1818) and Clarke (1867 & 1873) were made with standards about which adequate knowledge is now lacking, so they are not very reliable for this purpose. Three determinations have, however, been made of the ratio of the present Imperial Standard Yard and International Prototype Metre, the results being as follows:

1 m. = 39·370113 in. (Benoît & Chaney 1895),
1 m. = 39·370147 in. (Sears, Johnson & Jolly 1928),
1 m. = 39·370138 in. (Sears & Barrell 1934),

the last of these being an indirect value obtained from independent determinations of the yard and metre in terms of the wave-length of light. With regard to these it can be said that although they suggest a possibility that the yard has shortened slightly in relation to the metre during the past 40 years, the whole range of the variations exhibited does not exceed the possible range of experimental error in the comparisons, so that the previous conclusion as to the present stability of the yard may still be regarded as justified.

While on the subject of the relationship between the yard and the metre it may be of interest to mention that, by an Act of Congress of 1866, legal sanction was given in America for the use of the relationship

1 m. = 39·370000 in.,

and that by a subsequent order of the United States Treasury, known as the Mendenhall Order, this ratio is now accepted as defining the American inch in terms of the International Metre, instead of vice versa. It follows that there is at present a small difference between the U.S. and U.K. inches, the former being equivalent to 1 in. = 25·400051 mm., and the latter (taking the mean of the three determinations above mentioned) to 1 in. = 25·399965 mm. These two values are both so

near to the convenient round value 1 in. = 25·4 mm. that it would be very advantageous if adjustment could be made in both countries to agree on this common ratio for the future by redefining the yard as equal to 0·9144 m. exactly.

It may be remarked that if the conclusion suggested above as to the shortening of the Imperial Standard Yard be correct, then the ratio of the Imperial Yard to the International Metre (had the latter been already in existence at the dates mentioned) would have passed through the value 1 m. = 39·370000 in. about the year 1858 (very soon after the legalization of the British standard) and, curiously enough, through the value 1 m. = 39·370079 in., corresponding to 1 in. = 25·400000 mm., about 1865, just before the former value was adopted in America.

Until comparatively recently the difference has been of no practical significance, but it is now just appreciable in relation to the accuracy guaranteed by the makers of the most accurate end-gauges used in industry. The round figure has the further practical advantage of facilitating mechanical conversion by means, for example, of a 127-tooth gear wheel on a lathe or measuring instrument, between the units of the two systems.

Comparison of line- and end-standards

Whether the primary material representation of the unit of length takes the form of a line-standard or of an end-standard, the operation of transferring from the one to the other is an inevitable necessity, since both types are needed for practical applications in different fields of measurement. Probably the best method of carrying out this comparison which has so far been devised is the following.

Taking, for example, the case of the yard, it is necessary to provide an auxiliary end-bar of say 35 in. in length, with ends highly finished and accurately plane and parallel. In addition, two small end-blocks each 1 in. in length are required, similarly finished as regards their ends, with graduation marks on plugs inserted in holes at the level of their neutral planes, similar to those on the standard yard. The perfection of the surfaces will enable these end-blocks to be adhered to the ends of the 35 in. bar by the process known as 'wringing'. If both the end-blocks are so attached the combination constitutes a built-up line bar which can be compared with a 36 in. line-standard in the comparator in the usual manner. If only one of the end-blocks at a time is attached to the 35 in. bar the combination can be compared with a 36 in. end-standard on an end-measuring machine. Let the length of the 35 in. bar be B, that of the line-standard L, and that of the end-standard E. And let the distances of the graduation lines from the surfaces of the two end-blocks be a_1, b_1, a_2, b_2 respectively. Finally, let the thickness of a 'wringing film' be t. If the observed differences are x_1, x_2 and y_1, y_2, the results of the measurements may then be written as follows:

$$B+a_1+a_2+2t = L+x_1, \quad B+b_1+b_2+2t = L+x_2,$$

whence

$$B+\tfrac{1}{2}(a_1+b_1+a_2+b_2)+2t = L+\tfrac{1}{2}(x_1+x_2),$$

and

$$B+a_1+b_1+t = E+y_1, \quad B+a_2+b_2+t = E+y_2,$$

whence $$B+\tfrac{1}{2}(a_1+b_1+a_2+b_2)+t=E+\tfrac{1}{2}(y_1+y_2).$$

Thus, finally, $$E+t=L+\tfrac{1}{2}(x_1+x_2)-\tfrac{1}{2}(y_1+y_2),$$

whence it will be seen that the lengths of both the 35 in. bar and of the end-blocks have been eliminated.

Actually, of course, a number of variations can be made in the wringings which are not included above. In practice all possible variations would be employed, and the mean result taken. But the principle of the comparison should be clear. The fact that the thickness of one wringing film is associated with the length of the end-standard as the result of this comparison corresponds to the fact that, in practical use, precision end-gauges are habitually combined together, by the process of wringing, so as to make up composite standards of any desired size. The calibrated mechanical size of each gauge must therefore always include the thickness of one wringing film, which may be regarded as distributed half over each end of the gauge, so that when wrung together in groups the thickness of one wringing film is automatically provided for at each interface. In addition, the composite gauge, just as a single gauge representing the same size, will be associated with one film thickness divided between its terminal faces, and allowance may need to be made for this in some circumstances, e.g. when deriving the 'mechanical' length of an end-standard from its 'optical' length under certain conditions. The actual thickness of an individual wringing film is, however, very small, amounting only to about 0·0000002 in. (Rolt & Barrell 1927).

Determination of submultiple end-standards

Now follows the process of determining the values of end-standards representing subdivisions of the fundamental unit, which are of great importance in practical applications. This can be done by comparing together, in a suitable end-measuring machine, combinations of gauges of equal nominal size. It is convenient, though not essential, that a duplicate series should be available. As a typical case consider the entries in table 2, which refers to the determination of the values of a series of end-gauges 7, 8, 9, 10 and 11 in., in relation to those of 6 and 12 in. supposed already known. Duplicate gauges are indicated by a dash (′).

TABLE 2

12+10	11+11′	...	...	...	...
12+ 9	11+10	10+11′	...	...	...
12+ 8	11+ 9	10+10′	9+11′	...	...
12+ 7	11+ 8	10+ 9	9+10′	8+11′	...
12+ 6′	11+ 7	10+ 8	9+ 9′	8+10′	7+11′
6+11′	11+ 6′	10+ 7	9+ 8	8+ 9′	7+10′
6+10′	...	10+ 6′	9+ 7	8+ 8′	7+ 9′
6+ 9′	...	...	9+ 6′	8+ 7	7+ 8′
6+ 8′	...	...	...	8+ 6′	7+ 7′
6+ 7′	...	...	...	...	7+ 6′

It will be noted that all the combinations in any row of this table have the same nominal length. Suppose each combination in any column is compared with the corresponding combination in column 1, and let the observed differences be x_1, x_2, etc. Adding all the results relating to any particular column it is seen that the sum of the right-hand members in the combinations compared cancels out, and there remains a series of equations of the form, taking, for example, column 3,

$$10 \times 6 = 12 \times 4 + 6 \times 2 + \Sigma x \quad \text{or} \quad 10 = 12 \times 4/6 + 6 \times 2/6 + \Sigma x \times 1/6.$$

This case has been selected as exhibiting in a simple form the general procedure involved. It is easy to follow the modifications involved, say, in deriving a series such as 30, 24, 18, 12 and 6 in. from a yard end-standard, or a series such as 0·100, 0·101, 0·102, ..., 0·110 in. which is found in a normal set of slip gauges. Reference gauges of the smaller sizes are, however, more readily measured, provided the flatness and parallelism of their surfaces is sufficiently high, by interference methods in terms of the wave-length of light, other gauges being then compared directly with reference gauges of similar size in a suitable end-measuring machine.

By one or other of the above processes the lengths of reference end-gauges can be established to an accuracy of 1 part in 10^6 for sizes above 1 in., or to 0·000001 in. for sizes below. It may be worth while to point out that this accuracy is actually necessary to meet industrial demands at the present time. Grouped combinations which may include as many as five such gauges are required to be correct to the nearest 0·0001 in., that is, to within 0·00005 in., and their users expect to be able to rely on this without making use of corrections for known errors. Each individual gauge must therefore be correct within 0·00001 in., and the makers guarantee this, and in some cases even higher, accuracy. Reference gauges used in verifying that such guarantees have been fulfilled must therefore be known at least to 0·000001 in. It follows that the present difference of nearly 4 parts in 10^6 between the British and American inches is, as already stated, no longer negligible in relation to the highest grade of current commercial accuracy.

Subdivision of line-standards

To complete the present survey reference must be made to the operations of calibrating the subdivisions of a divided scale, and of building up from the yard or metre to the longer standards which are required, for example, in field-survey work.

For the first of these processes the bar to be examined is mounted, under two micrometer microscopes, on the girder of a comparator in which the carriage, instead of moving transversely, is arranged to move in the direction of the length of the bar. The separation of the microscopes can be varied to suit the successive stages of the comparisons. Suppose, for example, one wishes to determine the decimetre subdivisions of a 1 m. bar. The microscopes are set first 1 dm. apart and direct comparisons are made between the 0/1 interval and the 1/2, 2/3, etc., intervals up to 9/10. The results of these measurements give a series of values, $a_1, a_2, a_3, \ldots, a_9$ for the differences 0/1–1/2, 1/2–2/3, ..., 8/9–9/10 between the

successive adjacent decimetre intervals on the bar. The microscopes are then placed 2 dm. apart, and similar comparisons made of the intervals 0/2, 1/3, etc., up to 8/10. The results of these measurements, subtracting the parts common to the two adjacent intervals compared, give a series of values $b_1, b_2, \ldots, b_8$ for the differences 0/1–2/3, 1/2–3/4, etc., up to 7/8–9/10 and so on, with successively increasing distances between the microscopes, up to 9 dm. The results of all these measurements can then be tabulated as follows:

	0/1	1/2	2/3	3/4	4/5	5/6	6/7	7/8	8/9	9/10
0/1	0	$-a_1$	$-b_1$	$-c_1$	$-d_1$	$-e_1$	$-f_1$	$-g_1$	$-h_1$	$-k$
1/2	a_1	0	$-a_2$	$-b_2$	$-c_2$	$-d_2$	$-e_2$	$-f_2$	$-g_2$	$-h_2$
2/3	b_1	a_2	0	$-a_3$	$-b_3$	$-c_3$	$-d_3$	$-e_3$	$-f_3$	$-g_3$
3/4	c_1	b_2	a_3	0	$-a_4$	$-b_4$	$-c_4$	$-d_4$	$-e_4$	$-f_4$
4/5	d_1	c_2	b_3	a_4	0	$-a_5$	$-b_5$	$-c_5$	$-d_5$	$-e_5$
5/6	e_1	d_2	c_3	b_4	a_5	0	$-a_6$	$-b_6$	$-c_6$	$-d_6$
6/7	f_1	e_2	d_3	c_4	b_5	a_6	0	$-a_7$	$-b_7$	$-c_7$
7/8	g_1	f_2	e_3	d_4	c_5	b_6	a_7	0	$-a_8$	$-b_8$
8/9	h_1	g_2	f_3	e_4	d_5	c_6	b_7	a_8	0	$-a_9$
9/10	k	h_2	g_3	f_4	e_5	d_6	c_7	b_8	a_9	0

It will be noted that in this table each entry is repeated, above the left to right diagonal, with reversed sign. Taking any particular column of the table, for instance the fourth, and adding up all the entries, it is seen that the total of all the observations relevant to the interval 3/4 leads to the result

$$10 \times 3/4 - \Sigma(0/1 + 1/2 + \ldots + 9/10) = -(c_1 + b_2 + a_3) + (a_4 + b_4 + \ldots + f_4),$$

or

$$3/4 = \tfrac{1}{10} \times 0/10 - \tfrac{1}{10}(c_1 + b_2 + a_3) + \tfrac{1}{10}(a_4 + b_4 + \ldots + f_4),$$

and similarly for any other interval.

With slight modification the same process can be applied to determining the values of every centimetre of two particular decimetres in terms of the whole length of the other. In this case each space in the square will be occupied by an independent observational result. The millimetres of two particular centimetres can then be determined in the same way.

The accuracy of this process, given good conditions, is remarkably high, since the bar may be assumed to have the same coefficient of thermal expansion throughout its length, and errors due to temperature variations, if kept within reasonable limits, should be negligible. With good lines it is considered that a final accuracy of the order of 0·0002 mm. in the placing of any intermediate subdivision in relation to the terminal graduations can be readily attained.

Longer standards

Turning to the converse process, of building up to larger lengths, the first step is the comparison of a long bar, say of 4 m. length, 1 m. at a time with a reference standard metre, in a transverse comparator of suitable capacity. As this bar will

subsequently be used in air, under less favourable conditions for temperature control, it is nowadays usually made of invar. When standardized it is used either as a basis of comparison for 4 m. intervals on a mural base or, alternatively, the bar may be directly compared with 4 m. intervals graduated on the surface of a standard invar tape. These normally have a total length of 24 m.

Tapes intended for use in the field in setting out bases for geodetic surveys are compared either with the appropriate interval on the mural base, or directly with a standard tape of similar length. In the case of English measures the most usual length is 100 ft., built up in eight steps from a bar 12 ft. 6 in. in length. The operation of standardizing this bar in terms of the yard consists (*a*) of determining each 6 in. length in terms of the whole length by the method of subdivision, and (*b*) determining the lengths of the 0 to 12 ft. and 6 in. to 12 ft. 6 in. lengths in four steps against a reference standard yard.

It is considered that under the best conditions an accuracy of the order of 1 part in 10^6 can be attained in the standardization of the field tapes in either the British or the metric systems. Field surveyors find that, even in the adverse conditions of open-air working, they are often able to repeat their measurements of a long base to appreciably higher accuracy than this, and are sometimes inclined to criticize the accuracy offered them as the result of calibration under laboratory conditions. The explanation is, of course, that so many observations are taken in the field that casual errors are averaged out, and the probable error of determination of the whole length of, say, a 20 km. base in terms of the length of a particular tape, becomes very small. In the laboratory, on the other hand, we are concerned, not merely with the repeatability of observations, but with their relationship to the absolute value of the unit. Some countries have already experimented with the possibility of determining the length of a mural base in terms of the wave-length of light, and it is intended to do so also at the National Physical Laboratory when opportunity affords. So far, however, we have no experience of the method in this special application.

It may be of interest, finally, to record that the 50 m. mural base at the National Physical Laboratory has gradually grown, since it was first built in 1908, by something over a centimetre, due presumably to progressive chemical action in the cement with which the bricks are bonded.

The standards of length in wave-lengths of light

By H. Barrell

Historical survey

The first direct measurement of the metre in terms of wave-lengths of the red radiation of cadmium was made by Michelson & Benoît (1895) in 1892–3 at the Bureau International des Poids et Mesures (B.I.P.M.). In 1905–6, Benoît, Fabry & Perot (1913) repeated the determination of the metre, using improved methods and apparatus. The International Solar Union (now the International Astronomical

Union) adopted, in 1907,* the wave-length of the red line of cadmium as the reference basis for all spectroscopic measurements of wave-lengths of light, and defined its value in terms of the International Ångström. Using the relationship between the wave-length of the red line of cadmium originally quoted by Benoît *et al.* namely, $\lambda_R = 6438{\cdot}4696 \times 10^{-10}$ m. in normal† air, the Ångström was defined by assigning the value of 6438·4696 A to the wave-length of the red line of cadmium in normal air, and hence can differ only to the extent of the error in the above determination from 1×10^{-10} m.

In 1923, the International Committee of Weights and Measures‡ accepted in principle the possibility of the eventual adoption of a definition of the metre in terms of wave-lengths of light, subject to the formulation of satisfactory conditions for practical realization of such a definition, and urged national standards laboratories to undertake investigations for this purpose. Four years later, the International Conference on Weights and Measures§ (1927) gave formal sanction, as an interim measure, to determinations of length being made by reference to the wave-length of the cadmium red radiation, determined by Benoît *et al.*, as an alternative to direct reference to material standards.

Reports of the Board of Trade (1930, 1936)‖ have expressed the need for replacing the present Imperial Standard Yard by a standard more in accordance with modern requirements, and also suggest the possibility of defining the yard in terms of wave-lengths.

Following the International Committee's recommendation of 1923, the first result to be announced was that of Watanabe & Imaizumi (1928); it was the outcome of work carried out by means of apparatus, constructed in this country for the Japanese Government, which was almost identical with that of Benoît *et al.*

Each determination so far mentioned made use of purely line-standard technique by relating the position of a line or lines engraved on an interferometer standard (or étalon) to the graduations on a copy of the metre by microscope observations. With the introduction of modern types of end-standard constructed in the form of steel blocks or bars in lengths up to a metre or more and having flat, parallel, terminal faces with a mirror-like finish of optical perfection, it became possible to apply interferometric methods, as devised by Michelson and others, directly to the measurement of a practical standard of length.

Determinations of the metre and the yard made by Sears & Barrell (1932, 1934) at the National Physical Laboratory (N.P.L.) and of the metre by Kösters &

* 1907, *Trans. int. Un. Sol. Res.* (2), **20**, 28.

† The modern specification of normal air for spectroscopy and metrology is: dry air at 15° C under a pressure of 760 mm. of mercury at 0° C ($g = 980{\cdot}665$ cm./sec./sec.) and containing a normal proportion of 0·03 % by volume of carbon dioxide usually found in the open air and in well-ventilated rooms.

‡ 1923, *P.V. Com. int. Poids Mes.* p. 67.

§ 1927, *P.V. Com. int. Poids Mes.* p. 67.

‖ 1930 and 1936, *Report of the Board of Trade on the comparisons of the Parliamentary Copies of the Imperial Standards.* H.M.S.O.

Lampe* at the Physikalisch-Technische Reichsanstalt (P.T.R.) in 1933 produced evidence of this trend, for the interferometry at both institutions was concerned with the measurement of an end-gauge approximately equal to one of the fundamental units. Correlation of the optically measured end-gauges with the fundamental line standards was effected by the already well-established metrological procedure for transferring from line- to end-measures,† to which reference is made in Mr Sears's paper in the present series.

Other important changes were introduced in both the new methods. With the N.P.L. apparatus it was possible to measure the end-gauge either in air under known and controlled conditions or *in vacuo*; with the P.T.R. apparatus the end-gauge was measured in air and a concurrent determination made of refractive index over an optical path equivalent to that of the gauge length. Thus the results obtained from both methods can be expressed, if desired, in terms of wave-lengths *in vacuo*, rather than in air for which the temperature, pressure and composition must also be specified in order to define the refractive index. Platinum resistance thermometry was used in both determinations for the measurement of temperature of the end-gauge. In the neighbourhood of 20° C it is probable that the temperature scale defined by a platinum resistance thermometer conforming with international specification does not differ by much more than 0·001° C from the thermodynamic Centigrade scale, corresponding to an uncertainty of only about 0·01 μ in the length of a 1 m. end-gauge constructed of steel.

Owing to the disappointingly large discrepancy between the originally announced N.P.L. and P.T.R. results, the determinations were repeated in 1934–5 (Kösters & Sears 1935), but the mean discrepancy remained equivalent to 0·54 μ in the metre. At the same time, however, direct optical comparisons of the N.P.L. and P.T.R. metre end-standards, both independently established in terms of light waves *in vacuo*, were made at both institutions, and the results of all the optical measurements were found to be mutually consistent to $\pm$ 1 part in 36 millions, equivalent to 0·028 μ in the metre.

Results of subsequent P.T.R. work have recently been noticed (Kösters 1938) which indicate that the former P.T.R. results have been modified in a sense which considerably reduces the original divergence, and this change is substantiated by a new determination made in 1937, the result of which differs from the more recent of the two N.P.L. results by an amount equivalent to only 0·14 μ in the metre.

In 1940, a preliminary determination of the metre was made in Russia (Barinov 1941) by methods which appear to be similar to those used in Germany.

Values of the yard have been determined by Tutton (1931) and from the N.P.L. work mentioned above.

It should be mentioned that Williams (1933) has proposed a novel method of measuring an end-gauge by comparison with a reflexion echelon grating constructed of fused silica and of length approximately equal to the metre or the yard.

* 1934, *C.R. Conf. Gén. Poids Mes.* p. 79. Paris: Gauthier-Villars.

† 1919, *Ann. Rep. Nat. Phys. Lab. Lond.* p. 90.

Wave-length measurements of length made under generally practicable conditions in air effectively involve, for their reduction to comparable terms, concurrent observations of refractive index of the air. Such observations may be made either directly, as in the P.T.R. apparatus, or indirectly from a knowledge of the temperature, barometric pressure, humidity and possibly the CO_2 content of the air and of how these variable factors influence the refractive index. For spectroscopic purposes use is made of the experimental data obtained in 1918 by Meggers & Peters (1918–19) on the refraction and dispersion of air. At the 1931 meeting of the International Committee of Weights and Measures it was decided that further precise measurements of the refractive index of air were required. Concordant results for the refraction and dispersion of air in the visible region have since been announced from the B.I.P.M. (Pérard 1934), the P.T.R. (Kösters & Lampe 1934) and the N.P.L. (Barrell & Sears 1939), which appreciably disagree with the hitherto accepted tables of Meggers & Peters for the same spectral region. Suggestions have been made (Sears & Barrell 1934; Kösters 1938) for defining the reference standard of wave-length in the vacuum condition and so eliminating the refractive index entirely from the fundamental definition.

With one exception, all wave-length determinations of the metre have been made directly in terms of the red radiation of cadmium, which was selected by Michelson as the most suitable for the purpose. Certain radiations of krypton have since been proposed as better alternatives, notably the yellow-green line (λ5651 A) by Kösters* which was used during the actual P.T.R. determinations of the metre. The P.T.R. results were finally expressed, for comparison with other work, in terms of the cadmium red radiation by use of an experimentally determined relation between the two wave-lengths.

Discussion of results obtained on the metre and the yard

(*a*) *The metre.* The original results of all the determinations mentioned in the previous section are not strictly comparable, as the experimental conditions were not identical, nor in all cases fully specified. But, reducing them as far as possible from the data available to a common basis, the following table has been prepared.

The values originally quoted by the observers are corrected in the fourth column of the table below to take account of subsequent conclusions regarding the values to be attributed to the standards of length employed and adjusted, so far as the information available permits, to uniform conditions of normal air (see footnote, p. 165). It is to be noted that no evidence of any systematic change in the length of the metre is shown, over a period of nearly 50 years, compared with the wave-length of light; also the greatest departure of any individual result from the mean is less than 0·3 in 10^6, which is of the same order of accuracy as that generally associated by experienced metrologists (Sears 1936; Kösters 1938) with the measurement of length in terms of the existing national copies of the metre.

* 1927, *P.V. Com. int. Poids Mes.* p. 67.

Furthermore, the mean value of the wave-length is almost identical with that originally quoted by Benoît *et al.* which has been accepted as the basis of spectroscopic measurements of wave-lengths and involves the definition of the Ångström.

The mean of the two N.P.L. values of the wave-length of the red line *in vacuo*, determined respectively in 1933 and 1934–5, was $6440{\cdot}2513 \times 10^{-10}$ m.‡ (Kösters & Sears 1935). If the mean corrected and adjusted P.T.R. value of $6438{\cdot}4693 \times 10^{-10}$ m. for normal air, abstracted from the table, is reduced to vacuum condition by use of the P.T.R. value of 1·000,276,47 (Kösters & Sears 1935) for the refractive index of the red line in normal air, the mean P.T.R. value of the wave-length *in vacuo* becomes $6440{\cdot}2493 \times 10^{-10}$ m.

Values of the wave-length of the cadmium red radiation in terms of the International Metre (*unit* $= 1 \times 10^{-10}$ *m.*)

Date of Determination	Observers	Original Values	Corrected and adjusted Values in normal air	Differences from Mean	
				10^{-10} m.	parts per 10^6
1892–3	Michelson & Benoît	6438·4722	6438·4691*	−0·0004	−0·06
1905–6	Benoît, Fabry & Perot	6438·4696	6438·4703*	+0·0008	+0·12
1927	Watanabe & Imaizumi	6438·4685	6438·4682	−0·0013	−0·20
1933	Sears & Barrell	6438·4711	6438·4713	+0·0018	+0·28
1934–5	Sears & Barrell	6438·4709	6438·4709	+0·0014	+0·22
1933	Kösters & Lampe	6438·4672	6438·4689	−0·0006	−0·09
1934–5	Kösters & Lampe	6438·4685	6438·4690	−0·0005	−0·08
1937	Kösters & Lampe	6438·4700	6438·4700	+0·0005	+0·08
1940	Romanova, Varlich, Kartashev & Bartarchukova†	6438·4677	6438·4677	−0·0018	−0·28
		mean	6438·4695	±0·0010	±0·16

* See Guillaume (1927). † See Barinov (1941).

(*b*) *The yard.* The number of wave-lengths of the cadmium red radiation contained in the yard under normal air conditions, as determined by Tutton (1931), was 1,420,209·8.

The following N.P.L. results§ (Sears & Barrell 1934) were obtained in 1933, using the red radiation of cadmium:

1 yard = 1,419,818·24 wave-lengths *in vacuo*
= 1,420,210·74 wave-lengths in normal air.

‡ The corresponding number of wave-lengths in the metre is 1,552,734·44, which may be associated with the value of the yard in terms of wave-lengths *in vacuo* to determine the relationship between the yard and the metre, as quoted later.

§ These values are slightly lower than those originally published owing to a reduction of 0·07 wave-length in the value previously assigned to the correction applied to the optically measured end-gauge, in the N.P.L. method, to derive the practical mechanical length (Rolt & Barrell 1929). This small change has been made as the result of further work on determining the phase loss in light reflected at the lapped steel surfaces of the gauge.

The difference between the Tutton and N.P.L. values in normal air accords with the precision of measurement actually attainable with the present Imperial Standard Yard, which is assessed at about 0·5 part in 10^6 (Sears 1936).

The relationship of the yard to the metre, derived from the comparison of the N.P.L. wave-length determinations quoted above, is given by

$$1 \text{ m.} = 39{\cdot}370138 \text{ in. (or } 1 \text{ in.} = 25{\cdot}399962 \text{ mm.}).$$

Future definition of the units of length

From the foregoing, it is clear that it may soon be possible to supersede the present definitions of the fundamental units of length, based on the distances between lines engraved on certain metal bars, by a definition in terms of the natural standard provided by the wave-length of a monochromatic ray of light. The various national laboratories already employ interferometric methods in routine procedures (Kösters 1938; Barrell 1945) for directly calibrating the practical reference standards of measurement—such as, for instance, sets of slip or block gauges containing sizes up to 10 cm. or 4 in.—in terms of this natural, invariable and easily reproducible unit of length to an accuracy of 0·025μ or one-millionth of an inch. Experience in this use of a wave-length standard shows that it is capable of a higher precision and greater convenience in the measurement of such practical standards than the line-standard. The results of the British and German experiments on the calibration of end-gauges 1 m. in length demonstrate that it is possible to establish metre lengths independently in two countries on the basis of a wave-length standard of reference with a precision of $\pm 0{\cdot}03\mu$, which is approximately ten times better than is generally attainable with the present material standards. If the definitions of the units of length were established in terms of wave-lengths the end-standard would obviously become the first material representation of both units, rather than the line-standard.

The red radiation of cadmium, selected 50 years ago by Michelson as the best available, is still the approved standard for all measurements of wave-lengths of light, but it is not now considered to be quite as ideally monochromatic as is desirable for a universal standard of length. Cadmium is known to consist of a mixture of six isotopes, four being of even and two of odd atomic masses; krypton, the suggested alternative source of monochromatic radiation, also consists of six isotopes, five being of even atomic masses and one odd. It is found that the hyperfine structure of certain radiations emitted by cadmium and krypton may be accounted for by associating a nuclear spin of $I = \frac{1}{2}$ with each of the odd isotopes of cadmium and of $I \geqslant \frac{7}{2}$ with the odd isotope of krypton. Some evidence of hyperfine structure, due to the odd isotopes, has, indeed, been observed in the red line of cadmium, but none has so far been observed in the yellow-green line of krypton, possibly because of its rather low intensity. Although the even isotopes of both elements, by reason of their zero nuclear spin, are not expected to produce complexity, there may be some minute mass displacement effect between

the corresponding radiations emitted by the different even isotopes in each element.

The conditions under which excitation of an element takes place in the discharge lamp are also known to affect the monochromatic quality of the emitted radiations, and care must be taken to reduce, as far as possible, perturbative effects due to Doppler motions of the radiating atoms, electric and magnetic fields (Stark and Zeeman effects), collisions, pressure and reversal. As regards the Doppler effect of motions in a radiating gas or vapour, it is known, from kinetic theory, that the 'width' of a line is proportional to $\sqrt{(T/A)}$, where T is the absolute temperature and A the atomic mass, so that radiation tends to become more monochromatic when excited from heavy atoms at low temperature.

A new possibility now exists of finding a more suitable radiation from a single isotope of a heavy element with zero nuclear spin (and therefore with even mass number), owing to the recent advances in the technique of separating isotopes. If a single even-number isotope of mercury, for instance, could be isolated and caused to emit the well-known green radiation 5461 A, either in a Paschen and Schüler hollow-cathode type of discharge lamp at the temperature of liquid air or by very high-frequency excitation of a fine atomic beam of such mercury viewed normally to the direction of motion in the beam, it might provide an ideal source of monochromatic radiation. Information was received from America in 1941 that a suitable isotope of mercury had been obtained from a radioactive isotope of gold.

Although there may be some minor objections in practice to adopting a wave-length *in vacuo* as the basis of definition, it is considered that the weight of ultimate scientific advantage is greatly in its favour. Whatever radiation may be eventually selected for this purpose, the new definition of the metre should preferably be so adjusted as to yield a value of $6438{\cdot}4696 \times 10^{-10}$ m. for the wave-length of cadmium red radiation in normal air, which happens to be almost identical with the mean experimentally determined value (see table), thus preserving the definition of the Ångström which from thenceforth could be redefined simply as 10^{-10} m. The yard could then with advantage be defined in similar terms to the metre, on a basis which would make the yard exactly equal to

$$0{\cdot}9144 \text{ m. (or 1 in.} = 25{\cdot}4 \text{ mm.)}.$$

With the improvements that are now believed to be possible in producing pure monochromatic radiation, combined with new definitions based on wave-lengths *in vacuo*, it is considered that the units of length could be reproduced through the agency of end-standards with a precision approaching 1 part in 10^8. The best precision that could be expected from the existing definitions in terms of material line-standards, utilizing all modern resources for their production and observation, is unlikely to be superior to 1 part in 10^7.

The standards of mass

By F. A. Gould

In this review it is proposed to consider briefly the various standards of mass, including primary, secondary and also the more ordinary standards in everyday use in trade, industry and scientific work. Particular reference will be made to the principal standards, their comparisons, and the technique of this class of weighing. Consideration will also be given to air buoyancy in relation to the derivation of secondary and other standards from the primary standards, and to conventions for the adjustment of ordinary standards.

Primary standards

The fundamental standard in the British system of units is the Imperial Standard Pound (Weights and Measures Act, 1878). This was constructed in 1844 in the form of a cylindrical piece of platinum of diameter slightly smaller than its height, and with a shallow circular groove around its flank to take an ivory lifting fork. There are five Parliamentary Copies of this standard, four of which are of platinum and one of platinum-iridium alloy, which serve for the replacement of the Imperial Standard in the event of its being lost or damaged. It is to be noted that this standard is the avoirdupois pound containing 7000 gr. The troy pound, which was the sole standard from 1824 to 1834, is no longer legal and the troy ounce, defined as 480 gr. is now the basis of the troy system.

In the metric system it is of interest to refer to the original conception underlying the definition of the unit of mass. The kilogram was originally defined by reference to a 'natural' standard, i.e. the mass of the cubic decimetre of water. The material representation of this standard was the Kilogramme des Archives, a simple cylindrical piece of platinum which was constructed in the latter part of the eighteenth century. The practical realization of the definition of the kilogram proved to be insufficiently precise, and it was accordingly superseded by the material standard itself, viz. the Kilogramme des Archives. Though there may be natural standards of mass which might be employed, there is no prospect as yet that any of these could be realized with a precision approaching that with which material standards of mass can be compared.

The Kilogramme des Archives remained the standard until 1889, when, under the auspices of the Metric Convention, it was replaced by the International Prototype Kilogram, the present fundamental standard in the metric system. The latter takes the form of a simple cylinder, of height equal to its diameter, and is made of the same 10 % platinum-iridium alloy as the international metre. At the time of this replacement the new kilogram was declared* to be equal to the earlier standard, to within the limits imposed by the uncertainty of the volume of the older standard, which had not been established so closely as that of the later one.

* 1889, *C.R. Prem. Conf. Gén. des Poids et Mes.* Paris: Gauthier-Villars.

Some forty or more copies of the international kilogram were constructed. The principal copies, or 'témoins', and other working copies are preserved at the International Bureau of Weights and Measures, Sèvres, Paris. Other copies are distributed, as national reference copies, to the various countries signatory to the Metric Convention. One such copy, No. 18, designated the British Copy of the Kilogram, is kept in this country.

Balances for comparing standards

Consideration will next be given to the balances used for the comparison of precision standards. The accuracy attained with an ordinary type of knife-edge balance of good quality is surprisingly high, and a precision of the order 1 part in 10^7 has for many years been attained in the comparisons of pounds or kilograms. The principle of double weighing is normally employed, each standard being weighed from each arm of the balance in turn. Due allowance is made for the atmospheric buoyancies of the standards, which are computed from a knowledge of the volumes of the standards, as experimentally determined, and the air density determined at the time of each weighing. The densities of the standards are determined by weighing them in air and in water. When a new standard is constructed, its density may with advantage be determined shortly before the final polishing of the standard.

Balances of special design for this class of weighing were in use on the Continent 50 years ago. These were provided with arrangements for interchanging the standards undergoing comparison without opening the shutters of the balance, thus enabling a double weighing to be made with the minimum of disturbance to the temperature of the balance. Balances of this type, constructed by the well-known firm of Rüprecht, Vienna, gained a high reputation and have long been in use at the International Bureau of Weights and Measures, Paris.* An accuracy of the order 1 part in 10^8, or somewhat finer, was attained in the comparison of kilograms as the result of repeated weighings. In this country, however, no substantial progress was made until recent years, when a new balance, designed and constructed at the National Physical Laboratory, was installed. Some of the principal features of this balance will be described briefly here, including also a special technique of weighing which has enabled a striking improvement in accuracy to be made. Figure 1 (plate 6) gives a general view of the instrument with its cover removed. Provision is made for weighing masses up to 1 kg. in air or *in vacuo*, though there is no intention of carrying out *in vacuo* any standardizations which should properly be made under ordinary conditions of atmospheric pressure. The balance is installed in a closed vault and is so designed that the whole operation of weighing, including the interchange of the standards during a double weighing, can be controlled from outside the vault. To minimize wear on the standards two loose pans are provided, and once the standards are placed on these, they are not dis-

* 1881, *Trav. Bur. int. Poids Mes.* **1**.

turbed during the whole of a sequence of weighings. Beneath these pans each pan suspension has an aperture cut in it in the form of a cross, open towards the centre of the balance, and to interchange the pans on the suspensions a ring surrounding the centre of the base, and bearing two arms with suitably shaped ends which can pass through these apertures, is first raised, lifting the pans off their suspensions, then rotated through 180°, and again lowered. Allowance, of course, has to be made for the difference between the unloaded pans, which can be determined by direct weighing, as often as is found necessary. Alternatively, the standards can be weighed on each pan in turn, and the mean result taken.

Another feature of the balance is the design of the two series of stirrups, supported on crossed knife-edges, through which the load is transmitted to the beam. These are arranged so that in combination they provide precise location of the loads transmitted by them on each terminal knife of the beam.

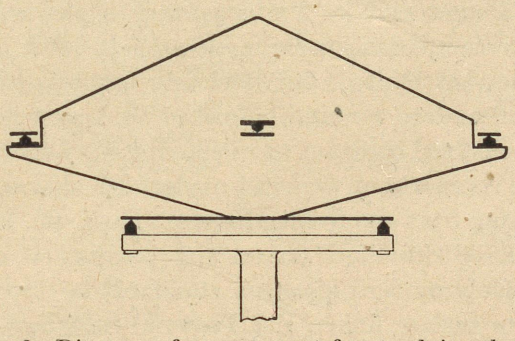

FIGURE 2. Diagram of arrangement for steadying the beam.

But even with these special features the improved accuracy which is available with the balance would not have been attained without the adoption of a special technique for carrying out the weighings. In ordinary circumstances a knife-edge balance would be fully arrested between successive determinations of its equilibrium point and also whenever the loads on the pans are being changed. During arrest the knives would be separated from the bearing planes. Many years ago Poynting (1878) showed that the residual errors associated with the use of the balance for fine weighings can be considerably diminished if the balance can be brought to rest, and the interchange of standards on the pans safely effected, while the knives are still in contact with their bearing planes. In the N.P.L. balance this principle is applied by directly steadying the beam after determining its equilibrium position. To enable this to be done, a slightly flexible metal strip is attached horizontally to the lowest part of the beam (figure 2). When the balance is swinging, a pair of agate points suitably mounted on an independent bridge below the beam can be raised so as just to meet the underface of the strip as the beam passes through the horizontal position, and so bring the balance temporarily to rest without separating the knives from their bearing planes. A separate control is provided for this operation, which can readily be carried out. In this condition of the

balance, the pan-hooks can be held in arrest, and the pan plates interchanged without disturbing the beam and the stirrups. The balance is then set free to swing, and the double weighing completed without separating the knives and bearings. An accuracy closely approaching 1 part in 10^9 has been attained in the comparison of kilograms on this balance.

Stability of the pound and the kilogram

With regard to the stability of the primary standards of mass there is no 'natural' control to which reference can be made as in the use of the wave-length of light to check the standards of length. Deductions as to the stability of the pound and the kilogram have necessarily to be based on such evidence as may be found in the results of repeated comparisons of different standards over the period of time considered. So far as the pound is concerned, the results of intercomparison of the Imperial Standard Pound and its Parliamentary copies extend back to 1846, though only two intercomparisons were made prior to 1892. For various reasons the evidence is somewhat limited, but it clearly suggests that in relation to its copies the Imperial Standard Pound diminished by 1 part in $3\frac{1}{2}$ million between 1846 and 1883 but remained constant to within about 1 part in 10 million between 1883 and 1933, when comparisons were last made.* The decrease in mass was attributed to wear resulting from too frequent usage. It should, however, be borne in mind that the Imperial Standard Pound and its original copies are somewhat inferior to the relatively modern kilogram standards in respect to the quality of the platinum and its surface finish. The Imperial Standard is the sole ultimate standard, whatever its mass may be; and only in the event of its replacement owing to loss or damage would the copies be used for reproduction of the standard.

Evidence as to the stability of the metric standard of mass will first be considered as from 1889, when the International Prototype Kilogram was installed. To avoid wear, this standard has been preserved unused for at least 50 years, and though arrangements have been made more recently for its recomparison with certain copies and also with the Kilogramme des Archives, the results are not yet available. Many of the copies have occasionally been re-verified by mutual intercomparisons, and the new values obtained for them, based on reference to certain standards at the Bureau (including the témoins), have been found to be in very close accord with those originally assigned to them (Guillaume 1927). Of sixteen copies so compared in 1889 and again in 1899, only four showed any change exceeding 0·02 mg. (viz. 2 parts in 10^8). Most of the copies which had been kept out of service between the two sets of intercomparisons showed only minute changes, comparable with the order of accuracy of weighing. Similar results were obtained for the interval 1899 to 1911, and so on. It is of interest to note the high stability of the British Copy

* 1936, *Report by the Board of Trade on the comparisons of the Parliamentary Copies of the Imperial Standards.*

(no. 18), which has been standardized at the Bureau on three occasions. The resulting values, which are given in table 3, do not differ among themselves by more than 2 parts in 10^8.

TABLE 3. BRITISH COPY OF THE KILOGRAM

Year	Mass (g.)
1889	1000·000 070
1924	1000·000 051
1933	1000·000 058

In addition to the evidence obtained from comparisons within the pound and kilogram systems respectively, there is also available,* as a check, a series of four well-established determinations of the relationship between the two systems, the results of which are given in table 4.

TABLE 4

Date	Value of the Imperial Standard Pound in grams	Referred to
1846	453·592 652	Kilogramme des Archives
1883	453·592 428	International Kilogram
1922	453·592 343	
1933	453·592 338	

These results, when plotted, lie on a smooth curve showing a continuous diminution of the pound, as compared with the kilogram. From 1846 to 1883, the diminution amounted to 1 part in 2 million, of which rather more than one-half was suggested by the evidence of the comparisons of the pound and its copies. From 1883 to 1933, the diminution amounted to 1 part in 5 million, which again was more than that suggested by the other source of comparison. Even disregarding the value obtained in 1846, which depends on the now discarded Kilogramme des Archives, the diminution of the pound between 1883 and 1933 is more than can be attributed to experimental error. For this period there is good evidence of the relative stability of the kilogram copies amongst themselves. Moreover, the quality of the material of which these were constructed is superior to that of the platinum pounds, which are of much earlier date. Furthermore, experiments made at the International Bureau, in which one of the kilogram standards of platinum-iridium was kept for a year in a stream of air at 100° C, demonstrated that the change in mass was almost negligible (Guillaume 1927). These considerations in combination give reasonable assurance that the kilogram can be regarded as a

* 1936, *Report by the Board of Trade on the comparisons of the Parliamentary Copies of the Imperial Standards.*

stable standard, and it must be concluded that the pound has changed. It is not proposed to speculate on possible causes of its changes.

In connexion with the determinations of the relationship between the pound and the kilogram, it is of interest to remark that in the United States, where both the pound and the kilogram systems are in use, the pound is defined as bearing a fixed ratio to the international kilogram. The value accepted for this purpose was that determined in 1883.* The British pound, having diminished by 1 part in 5 million since 1883 in relation to the kilogram, is therefore smaller than the U.S. pound by that amount.

Secondary and other standards

The fundamental standards serve as the ultimate basis of weighings for purposes of trade, industry and scientific work, for which secondary and other standards are needed. Before considering how these are derived from the fundamental standards, a brief reference will be made to the materials available for their construction. For most purposes these should be non-magnetic, highly resistant to corrosion, and not too difficult to machine and polish.

On account of its high stability, platinum, preferably alloyed with a suitable proportion of iridium or similar constituent, is pre-eminently the most suitable material for the construction of a precision standard of mass. Owing to its high cost, however, it is not often used for this purpose, except for standards of specially high status, and also for small denominations for which the cost of the metal is not such a serious consideration. Rock crystal has sometimes been used for the construction of precision standards but it is readily electrified and is by no means easily discharged completely. A nickel-copper alloy containing these metals in approximately equal proportions has also been used, but not extensively. Stellite, an alloy containing cobalt, chromium, and a small proportion of tungsten or molybdenum, has also been used, but owing to its hardness the cost of making standards of this material is relatively high. Brass, without any protective coating, cannot, of course, be regarded as a suitable material for a precision standard; its use is still far more extensive than is justified by its properties, and should be restricted to weighings of an appropriately lower class. Plated brass is sometimes satisfactory, but the ordinary process of plating does not always ensure protection from chemical action. Of the metals used for plating, nickel and gold are not found very satisfactory, while platinum has been less extensively employed since the introduction of chromium and rhodium. During the last 25 years, some experience has been obtained in the use of nickel-chromium alloy and stainless steel. The commercial variety of the former, containing 80 % nickel and 20 % chromium, is normally satisfactorily non-magnetic and is being used with some success for secondary standards, and also for analytical weights. Its stability, though reasonably satisfactory, is not, however, comparable with that of platinum.

* The value actually accepted was that quoted in full in the original report, viz. 453·592 4277.

The stainless steel which has been in use in recent years is one which purports to be reasonably non-magnetic, being of the austenitic variety containing 18 % chromium and 8 % nickel. This type, however, has not been found sufficiently non-magnetic to give complete confidence in its use and should be superseded by a more reliable variety, e.g. that containing 25 % chromium and 20 % nickel, which is far superior to the 18/8 type in regard to non-magnetic properties. In spite of metallurgical progress there are not many suitable materials for precision work generally, and the choice for the time being is largely restricted to nickel-chromium, stainless steel and plated brass.

In order to determine and maintain a secondary standard pound or kilogram, occasional comparisons have to be made between it and a copy of the fundamental standard; these follow the usual procedure of double weighing, with strict allowance for air buoyancy. The density of the secondary standard, which is usually in the vicinity of 8 g./ml. differs widely from that of the platinum standard, which is about 21 g./ml. The differential buoyancy correction therefore amounts to 1 part in 10,000 of the mass being determined and accordingly requires to be assessed with great care. Assuming that both density values have been ascertained with sufficient precision, the accuracy of assessment of the buoyancy correction depends on the precision with which the density of the air is determined at the time of weighing. This is computed on the basis of the ascertained current values of the pressure, temperature and humidity of the air within the balance. Precautions are taken to introduce fresh air into the balance case but the chemical composition of the air is not actually determined. This may preclude the attainment of an accuracy finer than 1 part in 20 million in deriving a secondary standard of mass from the primary. Of course the buoyancy difficulty might be circumvented by carrying out the weighings *in vacuo*, but other sources of doubt would presumably be introduced depending for example on the variability of the adsorbed gases on the surfaces of the standards. Whether or not some suitable technique can eventually be evolved for overcoming such difficulties, it appears that the accuracy at present attained is ample for all ordinary purposes.

Further considerations of buoyancy and conventions for adjustment of weights

From the secondary standards are derived the more ordinary everyday standards of mass which for convenience will be referred to by the less explicit term 'weights'. In practice most weights, apart from the smallest denominations, are made of brass or of a material of a similar density. In general the range of densities of the materials in use rarely exceeds 7 % of their mean value. The differences in buoyancy between like denominations will therefore normally lie within 1 part in 100,000 of the mass. These differences, of course, vary somewhat with the air density but as the latter rarely varies by more than 10 % under most ordinary conditions of weighing, the buoyancy difference remains constant to within 1 part in a million of the mass. This enables a large amount of routine weighing to be made in practice without elaborate attention to buoyancy corrections. Thus it is the general practice

to adjust weights on the basis of balancing in air a standard of mass of some conventional density representing brass, the material most commonly used for the construction of weights. This system of adjustment is used for purposes of trade, industry and science, where ordinary and not exceptional precision is required. For trade, the conventional density of brass associated with the standard in this country* is 8·143 g./ml.† Inspectors' standard weights and trade weights are adjusted to balance the standard in air of normal density; but as has been said before small changes in air density do not seriously affect the result.

Though buoyancy allowances are not normally made in trade transactions based on weight, a fine point arises in monetary transactions in converting from sterling (which is based on the pound) to the currency of a metric country (which is based on the kilogram). The conventional density 8·143 associated with the standard used for trade weighings in this country differs somewhat from that adopted abroad, and on this account the effective conversion from pounds to kilograms, or vice versa, will differ from the pure ratio of the respective units of mass. This difference, which is by no means negligible, appears to be a matter which ought to be referred to the International Committee of Weights and Measures, with a view to arriving at some agreed procedure.

Weights used in industry and science (as distinct from trade) are normally adjusted to balance in air a standard of mass of density 8·4 g./ml. and are calibrated on this basis in air whose density is sufficiently near the normal value not to affect the result appreciably. A typical example of this is a set of analytical weights, containing multiples and submultiples of a gram. These are usually so constituted that, once the value of the head weight is ascertained, the values of the remaining weights can readily be determined by intercomparisons among the weights of a set. Analytical weights are standardized on this basis at the N.P.L. to an accuracy of 1 part in a million for weights of 10 g. and larger, and to 0·01 mg. for smaller weights; this is quite adequate for the great majority of industrial and scientific purposes. As a result of this procedure the weights can, in effect, be treated as standards of mass of density 8·4 g./ml., even though their actual densities may differ slightly from this value. In any chemical weighings where allowances for buoyancy are of importance, these can be assessed so far as the weights are concerned by means of an inclusive correction for their buoyancy based on a density of 8·4 g./ml. This procedure is much simpler than that of calibrating weights according to their true masses, which would involve a knowledge of the actual density of each individual weight, and individual application of its buoyancy correction.

Receptacles for standards

In order to maintain the high stability of weights it is important that the receptacles in which they are stored should be appropriately designed and constructed,

* 1871, *Fifth Report of the Standards Commission*, Appendix xii, p. 170.

† There is no need here to discuss the reason for the adoption of this particular density value, which was introduced 100 years ago.

and should not contain any material which is likely to affect adversely the general surface condition of the standards. Manley (1933, 1935, 1945) has investigated the conditions of housing of weights in their cases and has studied the growth of films on the surfaces of weights of different materials under a variety of conditions of storage. His work, which is a substantial contribution to the knowledge of this subject, should be consulted in connexion with the designing of receptacles for weights.

The temperature scale

By J. A. Hall

The direct realization of the thermodynamic temperature scale involves the use of either a perfect heat engine or of a perfect gas, neither of which can be attained experimentally. The scale, therefore, must be reproduced by the use of one of the 'permanent' gases, the appropriate corrections to give the thermodynamic scale being deduced from the measured departures from the $PV = RT$ relationship under the particular experimental conditions to be used. The most generally employed gases are hydrogen, helium and nitrogen, and measurements are usually made in terms of pressure at constant volume. A gas thermometer, however, is an inconvenient instrument, and the experimental difficulties are considerable, increasing greatly at high temperatures.

The first step towards making the gas scale readily available was taken by Chappuis in 1888, when he compared four standard mercury-in-glass thermometers with his constant-volume hydrogen thermometer. The corrections needed to reduce the readings of these thermometers (which were used as absolute instruments to reproduce the 'mercury in verre dur' scale) to those of the constant-volume hydrogen scale were determined over the range 0–100° C to an accuracy of about $\pm 0{\cdot}005°$ C, and similar thermometers made from the same glass were distributed among various national standardizing laboratories and similar institutions. So was the 'échelle thermométrique normal' made generally available.

The next stage was the development of other methods of measuring temperature (e.g. the platinum resistance thermometer) which are capable of being read, in certain parts of the scale, to much higher accuracy than the gas thermometer itself. Such instruments, however, have not, in general, any theoretical connexion with the thermodynamic scale, and they can only be used to define it in so far as they have been accurately compared with a gas thermometer. They do not, therefore, improve the position as regards the accuracy with which we can define the thermodynamic scale. If, however, secondary instruments of this type are compared directly (or through some suitable intermediary) with a gas thermometer, they enable us to define the thermodynamic scale as accurately as the gas thermometer observations permit, while at the same time allowing us to reproduce a practical scale to a higher order of accuracy.

Such a practical scale is the International Temperature Scale, which was brought into being at the 7th Conference of Weights and Measures in 1927. As an

example of the distinction between accuracy and reproducibility—a distinction which is always found to take a prominent place in temperature measurement—we may take the case of the boiling-point of sulphur. A study of all gas-thermometer data available at that time showed that the boiling-point lay between 444·50 and 444·60° C, and was almost certainly nearer the latter figure. By the use of a resistance thermometer, however, it is possible to reproduce the point to an accuracy of ± 0·005° C. On the International Temperature Scale, therefore, the sulphur point was fixed at 444·60° C by definition, though it was admitted that the second decimal figure was not accurately known. By this means we have a scale which can be reproduced to within ± 0·005° at different times and in different laboratories, and which is certainly in agreement with the thermodynamic scale to within ± 0·1°. Since that date, Blaisdell & Kaye (1941) have analysed all the published work on the subject, including recent experiments at the Massachusetts Institute of Technology, and recommend a revision of the value to 444·7° C.

Some idea of the way in which the accuracy of realization and the reproducibility of the thermodynamic centigrade scale vary over a wide range of temperatures is given in the following table.

Absolute accuracy of realization and reproducibility of the thermodynamic centigrade scale

Temperature °C	Accuracy of Realization	Reproducibility	Method
− 182·97	± 0·02	± 0·02	resistance thermometer
0	—	± 0·0003	,,
100	—	± 0·003	,,
444·6	± 0·1	± 0·005	,,
1063	± 1	± 0·05	,,
		± 0·1	thermocouple
		± 0·2	optical pyrometer
2000	± 6	± 2	,,

The method by which the International Temperature Scale seeks to reproduce the thermodynamic centigrade scale is as follows. A range of fixed points which had been the subject of gas-thermometer measurement was selected. They were chosen so as to cover the temperature range from − 182·97 (boiling-point of liquid oxygen) to 1063° C (melting-point of gold), and thence up to the highest temperatures by the use of an agreed value of the radiation constant C_2. Between the fixed points the platinum-resistance thermometer and the platinum- 10 % rhodio-platinum thermocouple were chosen as interpolation instruments. The resistance thermometer was selected to cover the range − 182·97 to 660° C. It is calibrated by the usual quadratic law based on the ice, steam and sulphur points for temperatures above 0° C, while an extra calibration point at − 182·97° C provides the additional term required to define the gas scale accurately below zero.

The platinum thermocouple is used over the range 660 to 1063° C (melting-point of gold) and is calibrated by a quadratic equation through the gold, silver (960·5° C) and antimony (630·5° C) points. The antimony point is not a primary fixed point, and the value of the freezing-point of the particular specimen in use is determined by the resistance thermometer, thus ensuring continuity of the scale at this point. Unfortunately, however, the dividing point of the scale was fixed (for some reason which is not now clear) at 660° C. This has led to the curious result, pointed out by the Bureau of Standards at discussions on the revision of the scale which took place in 1939, that the freezing-point of pure aluminium cannot be measured on the International Temperature Scale. If a determination of the freezing-point is made with a resistance thermometer, the value found is just in excess of 660° C, and thus falls within the domain of the thermocouple. If, then, a thermocouple determination is made, the value is found to be just below 660° C and should therefore be measured by the resistance thermometer. The Bureau of Standards estimate that the discrepancy between the two parts of the scale is about 0·15° C, and in order to eliminate this difference, the 1939 meeting of the Comité Consultatif de Thermométrie* recommended that the scale should, in future, be divided at 630·5° C, the approximate value of the antimony point. The outbreak of war, however, made it impossible for the Conference on Weights and Measures to meet, and this recommendation has not been ratified.

Above the gold point extrapolation is by means of a radiation scale using monochromatic light, and taking 1063° C as the melting-point of gold and 1·432 as the value of C_2 in Wien's equation. These two constants are sufficient to define the scale.

There are one or two points which may be mentioned in amplification of the figures given in the table, which refer to the results obtained by using the apparatus and following the technique laid down in the specification of the International Temperature Scale.

It has been suggested (notably by the Physikalisch-Technische Reichsanstalt) that the triple point of water would provide a more reproducible fixed point than the normal freezing-point, but this proposal has not so far gained acceptance, as the view is held by some other workers that little is gained in accuracy to compensate for the loss in convenience. The value of the triple point is about 0·0098° C, of which about 0·007° is accounted for by the change in pressure and the remainder by the absence of dissolved air (the international specification calls for an air-saturated mixture of ice and water).

It will be seen from the table that it is the steam-point which, almost alone, limits the precision obtainable in the determination of the fundamental interval of a thermometer, though the extremely careful work carried out by Beattie and his collaborators (1935–6) at the Massachusetts Institute of Technology has somewhat altered this aspect of the problem. By using a closed system with an artificial atmosphere of helium in place of the usual open type of hypsometer they were able to obtain a fourfold improvement in reproducibility—somewhat better than

* 1939, *P.V. Com. int. Poids Mes.*

$\pm 0{\cdot}001°$ C. By the use of the same technique they obtained a reproducibility of about $\pm 0{\cdot}002°$ C in the sulphur boiling-point.

Variations in the amount of deuterium oxide present in the water will have an effect on both the freezing- and boiling-points. As far as I have been able to ascertain, the maximum range of concentration which has been measured in water from natural sources is from 1 in 5600 to 1 in 8900. The melting- and boiling-points of D_2O are $+3{\cdot}8$ and $101{\cdot}42°$ C, so one arrives at an elevation of the freezing-point above that of pure H_2O varying from $0{\cdot}00043$ to $0{\cdot}00068°$ C, with the corresponding figures of $0{\cdot}00016$ and $0{\cdot}00025°$ C for the boiling-point. Evidently, then, heavy water need not worry us at the present stage of thermometric precision.

When the International Temperature Scale was first adopted, there was no very reliable evidence as to how closely the resistance thermometer scale agreed with the thermodynamic scale in the region between 0 and 100° C where extremely high precision (of the order of $0{\cdot}001°$ C) is frequently required. A thorough intercomparison of resistance thermometers with a large number of mercury thermometers of the same construction as those used by Chappuis in his original intercomparison with the gas thermometer was therefore undertaken at the National Physical Laboratory (Hall 1930). This work established identity of the scales to within two or three thousandths of a degree over the range 0–50° C, while the discrepancies between 50 and 100° C certainly did not exceed $0{\cdot}01°$ C and were probably a good deal less. It is not possible to be more precise, as Chappuis's observations above 50°C were confined to two temperatures only. Two pairs of observations were taken in chloroform vapour at 60° C and two pairs in alcohol vapour at 78° C. At 60° C the overall spread was $0{\cdot}007°$ C, but there was a difference of $0{\cdot}012°$ between the means of the two pairs of observations at 78° C. Giving weight to all these observations leads to a difference between the international scale and the thermodynamic scale of $0{\cdot}007°$ at 80° C. One pair of the observations at 78° C is quite consistent with the resistance thermometer scale, and if Chappuis's equation is modified by ignoring the other pair of observations, then the difference is reduced to $0{\cdot}003°$ C.

The question of the eventual elimination of the thermocouple as a standard interpolation instrument has been considered, and a certain amount of experimental work with the resistance thermometer has been done at the gold point. Moser (1930), at the Physikalisch-Technische Reichsanstalt, has obtained values ranging from $1061{\cdot}92$ to $1062{\cdot}45°$ C, while some unpublished work carried out at the N.P.L. at about the same time led to provisional values in good agreement with the latter figure. The values found by Callendar (1899) and by Heycock & Neville (1895) when corrected to a sulphur boiling-point of $444{\cdot}60°$ C (instead of $444{\cdot}53°$ C), were $1061{\cdot}2$ and $1062{\cdot}2°$ C. Bearing in mind the fact that the platinum available at that time was far from pure by modern standards, the agreement with the recent work is remarkable.

The internationally accepted value of 1063° C for the gold point is based on the gas-thermometer observations of Holborn & Day (1900) and of Day & Sosman (1911), which led to values of 1064 and $1062{\cdot}4°$ C respectively. There is thus no justification for regarding the gold point as being known to a greater absolute

accuracy than $\pm 1°$ C, and therefore no evidence that the quadratic extrapolation of the platinum-thermometer equation from the sulphur boiling-point does not hold up to the gold point. If 444·70° C is adopted as the value of the sulphur boiling-point, as suggested by Blaisdell & Kaye, the platinum-thermometer values for the gold point are increased by 0·7° C, and the agreement with the gas thermometer is even better. In view of the importance of the gold point as the start of the radiation scale, however, it is necessary to assign to it a definite numerical value, and a small correction term would be necessary to bring the readings of all platinum thermometers to the same value at the gold point, should the platinum thermometer become the recognized means of interpolation up to that temperature.

In using the radiation scale, one of the chief difficulties is to establish and verify the adequacy of suitable black-body conditions. Two methods are available for the optical pyrometer determination of the gold point (and also of the palladium point (1555° C)—a valuable secondary fixed point on the scale). One is the wire method, in which a short length of gold wire is used to complete the junction of a thermocouple inside the black-body enclosure. A second couple is used to control the rate of heating of the furnace and to maintain the furnace steady at the melting-point after the melting-point of the wire has been determined by observing the arrest in the thermo-e.m.f. and ultimate rupture of the circuit. This method, however, is not capable of as high precision as the use of a small ingot in which a black-body enclosure is immersed. The chief problem is to secure uniform temperature conditions in the furnace, and this has been solved in a variety of ways, such as by the use of multiple windings with or without the additional precaution of enclosing the crucible or black-body enclosure in a metal block. A reproducibility of $\pm 0·2°$ C can be obtained at this point. This is equivalent to $\pm 0·6$ at 2000° C, but in practice the reproducibility at the higher temperature is only about $\pm 2°$ C. The additional uncertainty arises from possible errors in the value of the mean effective wavelength to be used in comparing the brightnesses of 2000 and 1063° C and in the angles of the two sectors which have to be used in turn in order to effect the big reduction in brightness (about 1200 to 1), which is necessary to compare the two temperatures.

A measurement of the absolute value of a temperature above 1063° C on the thermodynamic scale by optical means, however, depends on an absolute knowledge of the gold point and of the constant C_2 in Wien's (or Planck's) equation. An uncertainty of 1° at 1063° C is equivalent to 3° at 2000° C, and there is still the uncertainty in C_2 to be considered. In 1927 the value of 1·432 cm.deg. was internationally adopted. In 1939 the Comité Consultatif agreed that this figure was undoubtedly too low, but decided not to change to the value of 1·436, which was then considered the most probable, on the grounds that the change was hardly significant and that it was better to defer the matter until it seemed improbable that the value would soon need to be changed again. Since then Birge (1941) has derived from atomic constants a value of $1·4384_8$, to which he assigns an accuracy of $\pm 0·0003_4$. If, then, the uncertainty in C_2 be taken as $\pm 0·003$, one arrives at an additional uncertainty of $\pm 3°$ C in temperature at 2000° C, making a total of

$\pm 6°$ C. Here, again, the reproducibility attainable with the practical instrument is superior to the accuracy with which the scale is known.

The 1939 meeting of the Comité Consultatif de Thermométrie proposed that Planck's law should be substituted for Wien's law as the means of defining the radiation section of the International Temperature Scale, thus enabling it to reproduce the thermodynamic scale to higher temperatures. This proposal, which has not yet been ratified, would only affect a temperature of 2000° C by 0·3° or 3500° C by 0·7°. At 5000° C, however, the difference is 17° and at 6000° C, 50°.

Coming lastly to the most fundamental point, the absolute zero, the 1927 Conference did not attempt to relate the International Temperature Scale to the absolute scale, but only to the Centigrade thermodynamic scale. The position was reviewed by the Comité Consultatif in 1939 when the numerically lowest value considered was $-273{\cdot}144°$ C, obtained at Leiden, while the highest was a provisional value of $-273{\cdot}16$ to $-273{\cdot}17°$ C relating to the work of Beattie, of which the final result had not then been published.

Considerable discussion took place as to the choice between $-273{\cdot}15$ and $-273{\cdot}16°$ C, and finally the Committee passed a resolution that, in their opinion, 'according to the experiments completed at the present time', the most probable value was $-273{\cdot}15 \pm 0{\cdot}02°$ C. Since that date, Beattie (1941) has given a figure of $-273{\cdot}165 \pm 0{\cdot}015°$ C.

An interesting suggestion was placed before the 1939 meeting on behalf of the National Research Council of the United States, to the effect that the scale should be based on the absolute zero and the ice point instead of on the ice point and the steam point, the position of the absolute zero being fixed so as to give the steam point a value of 100·000° C at the present time. In this way a change in the value of the absolute zero would alter the numerical value of any point on the scale except the ice point: that is, the steam point would, in future, be just as liable to alteration in value as any other fixed point on the scale. While it was admitted that this plan would offer advantages to the worker at very low temperatures, it was agreed that, while the position of the absolute zero was still uncertain in the second decimal place, the inconvenience to the metrologist (who would be faced with the prospect of appreciable changes in the temperature known as 20° C) would of itself make it inadvisable to adopt the suggestion at the present time.

Finally, some mention may be made of the real need of industry for a temperature scale reproducible to the order of accuracy which has just been outlined. Mr Barrell has mentioned above the need for an accuracy of one or two thousandths of a degree at 20° C in order to secure adequate precision in the length of the yard and metre, and two other examples will show how the Laboratory is being pressed in other parts of the scale. At temperatures up to about 100° C, the oil technologists are regularly demanding an accuracy of 0·005° C for the determination of kinematic viscosity, while at high temperatures the steel industry is beginning to talk in terms of an accuracy of about 5° at 1600° C. The International Temperature Scale, therefore, has little enough in hand to satisfy modern industrial needs.

Electrical standards

By L. Hartshorn

Ideal units

To the theoretical physicist electrical standards are entirely unnecessary. A standard of some kind is of course essential if numerical values of the various concepts are to have any meaning in terms of practical experience, but if standards of length, mass and time have been established, the theoretical physicist can define the unit for any electrical property by simply writing down an equation. The theory of electromagnetism plays so important a part in electrical practice that the theoretical units derived in this way, by writing down the simplest possible sequence of equations that will cover the field under investigation, have long been recognized as an ideal system of units by both theoretical and practical men. Like many other ideals it was utterly impracticable when it was first conceived (by Weber in 1851 following Gauss in 1833) and for long afterwards, and it says much for the idealism of the electrical world that it followed the recommendations of the B.A. Committee of 1862, and adopted the system for all classes of work, theoretical and practical. It is curious when we look back to note that the unit first realized, the B.A. ohm of 1865, was in error by 1·3 %. The accuracy with which these theoretical units have been realized has, however, steadily improved down the years, and, although it has never kept pace with that of the most precise purely electrical work, the margin between the two is now so small that it is of no significance to anybody outside standardizing laboratories. An accuracy of 1 part per 100,000 has now been realized for all the more important electrical quantities. The present note outlines some of the more interesting metrological problems that have arisen in the course of this work.

Practical standards

The most precise purely electrical work mentioned above consists largely of measurements made by means of the Wheatstone bridge and its various modifications, and the potentiometer. These devices have now been brought to such a state of perfection that it is a fairly simple matter to compare resistances and standard cells with an accuracy of 1 part per million. It follows that with equipment of this kind, and various combinations of resistors and standard cells, measurements of resistance, voltage, current, power, quantity can all be made without much difficulty with an accuracy about ten times as great as that with which the theoretical units are known. Moreover, modern resistors and standard cells appear to be stable over a period of at least a few years with something like the same accuracy, although this is a point not easily substantiated. It follows that if the highest possible precision at any one time were the chief requirement, the best we could do would be to adopt a selected group of resistors and standard cells as primary standards, i.e. on the same footing as the metre kilogram, and secondly, to relate all other electrical measurements to them. This is, indeed, the

course followed in the standardizing laboratories. Each national laboratory sends representative coils and cells, with their estimated values in theoretical units (or whatever other unit is called for in the current agreed international specification), to the International Bureau of Weights and Measures, where they are compared, and as a result of the comparison 'mean international units' are adopted with a precision of 1 part per million. In this way arbitrary units are accepted by the national laboratories for the purpose of securing the greatest possible degree of international uniformity, but the procedure ensures that the differences between these arbitrary units and the theoretical (or specified) unit are as small as it is possible to make them; for when assigning their values the national laboratories take into account all the available evidence concerning the theoretical or other specified units.

At the present time the specified units are the 'international units' defined by reference to a column of mercury and the silver voltameter, these units having been adopted by the International Conference held in London in 1908, contrary to the opinions of the President, Lord Rayleigh, because the Conference as a whole could not be persuaded that the theoretical units were really practicable.

Recent work has, however, shown that the theoretical units are now more practicable than the specified units, and there is little doubt that the international ohm, ampere, etc., will soon be dropped in favour of the theoretical ohm, ampere, etc. The object of the pioneers, viz. strict consistency between theory and practice, will then have been achieved as far as is possible, though the arbitrary element in the units employed at the standardizing laboratories is always likely to remain.

Relations between electrical and mechanical quantities

Returning now to the work that has proved beyond reasonable doubt that the theoretical units are practicable, note that the problem to be solved is to establish links between the mechanical quantities that are measurable by reference to the standards of mass, length and time, and the various electrical quantities. In theory, *the* link is energy which is common to the two systems, but unfortunately this quantity, in spite of its dominating importance in physical science, can only be measured by indirect and correspondingly inaccurate methods; and this link, introduced by Thomson (Kelvin) in 1862, is of no direct value in modern metrological practice.

The links that would be of most value in practice are those directly connecting the three fundamental quantities length, mass and time with some electrical quantity. The simplest of such relations is that between time and frequency, a property of alternating currents, but this barely takes us into the electrical world. Length is directly linked to capacitance and inductance. Of these only the inductance link has been established with the accuracy now required, and the unit of inductance is therefore the starting-point of the theoretical system. Several electrical quantities, including resistance, can be measured in terms of inductance and frequency by the technique of the a.c. bridge, but they are all what the electrical

engineer calls 'dead' quantities, mere ratios of the 'live' quantities, and to complete the system we must have a link between a 'live' quantity and mass. There is no direct link with mass alone, but in the current balance there is a system in which current is related to force and the geometry of the circuits. It therefore gives a somewhat indirect link between current and mass, length and time, expressed by the equation

$$I^2 = mg/D \quad \text{or} \quad I^2 \frac{dM}{dz} = mg.$$

where I denotes current, m mass, g gravitational acceleration, and D the dynamometer constant of the fixed and moving coils, which is a derivative of mutual inductance and directly linked with length.

These few links are sufficient to determine the whole system of electrical and magnetic quantities: standard resistors are calibrated in terms of mutual inductance and frequency, standard cells in terms of current and resistance, and everything else is measured by reference to those standards and the standard of inductance.

Mechanical to electrical transfer standards

The problem of establishing these links between the electrical and mechanical units consists essentially in constructing apparatus on which it is possible to make measurements of the highest precision of some electrical quantity and also of the mechanical quantities to which it is related by theory. It is necessary to satisfy at the same time the conditions for precise mechanical measurements, for precise electrical measurements, and those postulated in the theoretical equations. These are very severe conditions, and there is some excuse for those who hold that a system of units which was dependent on the realization of at least two such links was impracticable. For mechanical precision attention must be confined to materials that are sensibly rigid and of low temperature coefficient of expansion. For electrical precision only the best conductors and the best insulators must be used, and for theoretical precision there must be the closest possible approach to linear circuits of zero resistance in a medium that is perfectly non-conducting and non-magnetic.

As is well known three such links have been established at the N.P.L., the Campbell standard of mutual inductance, the Ayrton-Jones current balance, and the Lorenz apparatus. A detailed consideration of the way in which the difficulties have been met in each of these is beyond the scope of a short paper, but it may be noted that mutual inductance is a common factor in the three links, and it follows that the accuracy of the whole system of measurements turns very largely on the accuracy with which inductors of suitable size and form can be constructed and measured. The main features of this side of the work will therefore be noted by way of illustrating its general character.

The type of construction employed in all this work at the N.P.L. is that of the single-layer solenoid, wound with thin bare copper wire under tension on a marble

cylinder. The tension in the wire ensures that the geometry of the coil is almost entirely determined by that of the marble, this material having been chosen for its rigidity, low temperature coefficient of expansion ($4–6 \times 10^{-6}$ per 1° C), and tolerably good insulating and machining properties. Lord Rayleigh recently showed that the dimensional stability of marble is far from perfect, and its insulating properties may become poor owing to its hygroscopic character, but nevertheless under suitable conditions it has given satisfactory results, surpassed only by the most recent American work with cylinders of pyrex glass, the working of which is, of course, far more laborious. Accurately defined radial dimensions are automatically obtained by winding on to a cylindrical surface, but the axial dimensions of the coils are equally important, and the precise axial location of the wire is far more difficult. It becomes essential to fix the position of every turn of the coil by winding the wire in helical grooves cut into the surface of the marble cylinder. The machining of these grooves with the necessary precision is one of the most important steps in realizing the units.

It is of the greatest importance that the finished coil shall have the highest possible degree of geometrical uniformity, not only because the theoretical formulae can only be applied to circuits of regular form, but also because only in such a case can the geometry of the circuit be completely specified by a finite number of measurements of length. In order to secure this uniformity, not only must the helical groove be uniform but the wire must be of uniform circular cross-section. One coil was found to show irregularities of diameter because the wire was of elliptical cross-section and the ellipse had rotated during the winding. In the most recent American work, the final drawing of the wire and winding of the coil were carried out in one operation, the wire passing through specially selected dies straight on to the cylinder.

Corrections for departure from theoretical conditions

Appreciable departures from uniformity are inevitable when dealing with a material like marble, and it is therefore necessary to make measurements of diameter and axial length for a very great number of pairs of points throughout the length of the helix, and to make allowance for the observed irregularities by making approximate calculations of the effect of each and applying them as 'corrections' to the theoretical formula for a uniform helix. The whole process of both measurement and calculation is very laborious, but quite straightforward: the various turns of the helix are regarded as equivalent to circles of a diameter and axial position equal to the mean measured value for the corresponding portion of the helix.

This non-uniformity of the helix is not the only feature in which some departure from the conditions postulated in the theory is inevitable, and in every instance the corresponding 'correction' must be estimated and applied. Thus the wire although thin (0·6 mm. diameter) is not a linear conductor. As a first approximation one naturally regards the current as concentrated in the axis of the wire, but in some cases

this approximation is not close enough. In order to find a better it is necessary to know the distribution of current throughout the cross-section, and this is not known. If the wire is regarded as equivalent to a bundle of parallel filaments, allowance must be made for the fact that the outer ones will be longer than the inner ones, and therefore of higher resistance if the resistivity of the material is uniform over the cross-section of the wire. Thus the outer filaments must be credited with less current than the inner ones so that the equivalent single filament is not in the axis of the wire. But here again an unjustifiable assumption has been made: the wire is under tension and the inner filaments are therefore compressed by pressure on to the marble, while the outer ones are stretched; the assumption of uniform resistivity is not justified. The best one can do here is to calculate the correction on the most plausible assumptions. Fortunately, the uncertainty is not large enough to be of any real consequence, though this effect of variable resistivity is believed to affect the temperature coefficient of the best American inductors. Such corrections are less important in mutual inductors than in self-inductors, because in the mutual inductance the uncertainty is confined to large quantities, the distances between the primary and secondary, while in the self-inductor it appears also in much smaller quantities, e.g. distance between adjacent turns.

A correction must also be applied to allow for the fact that materials like marble and pyrex glass are not strictly non-magnetic. Marble is diamagnetic, its permeability being about 10 parts per million less than unity, but since the cylinder is always hollow the 'medium' is by no means all marble, and the 'correction' for permeability only amounts to less than -3 parts per million in practice.

The effect of the finite resistance of the coils must also be considered. A definite voltage is required to drive the current against this resistance, and the coil possesses an electric field, as well as the magnetic field, in terms of which the theoretical units are defined. This field may give rise to attractive forces in the current balance or to induced voltage in the Lorenz apparatus, or to 'capacitance effects' when an inductor is used with a.c. These effects can usually be made negligible by a suitable choice of the electrical conditions, e.g. the potential distribution with respect to earth, or the frequency of the a.c., which must be kept sufficiently low; 10 cyc./sec. is usual.

Conclusion

This very brief survey is sufficient to show the complexity of the problems that have arisen in attempts to approximate as closely as possible to an ideal system of electrical units. So many disturbing factors are discovered in any one piece of apparatus that one is always asking how many have been missed. It is a melancholy historical fact that the experimenter's estimate of his 'probable error' is almost invariably far less than his actual error proves to be. There is, however, one good criterion of accuracy. If observers in different countries get consistent results for the same quantities by different methods of measurement, then they must have realized the same system of units, and it is but reasonable to suppose it is the one they were both looking for.

All the determinations of the ohm and the ampere that have been published from 1870 to the present time are summarized in figures 3 and 4. They have, as far as possible, been reduced to common bases by reference to the surveys given by

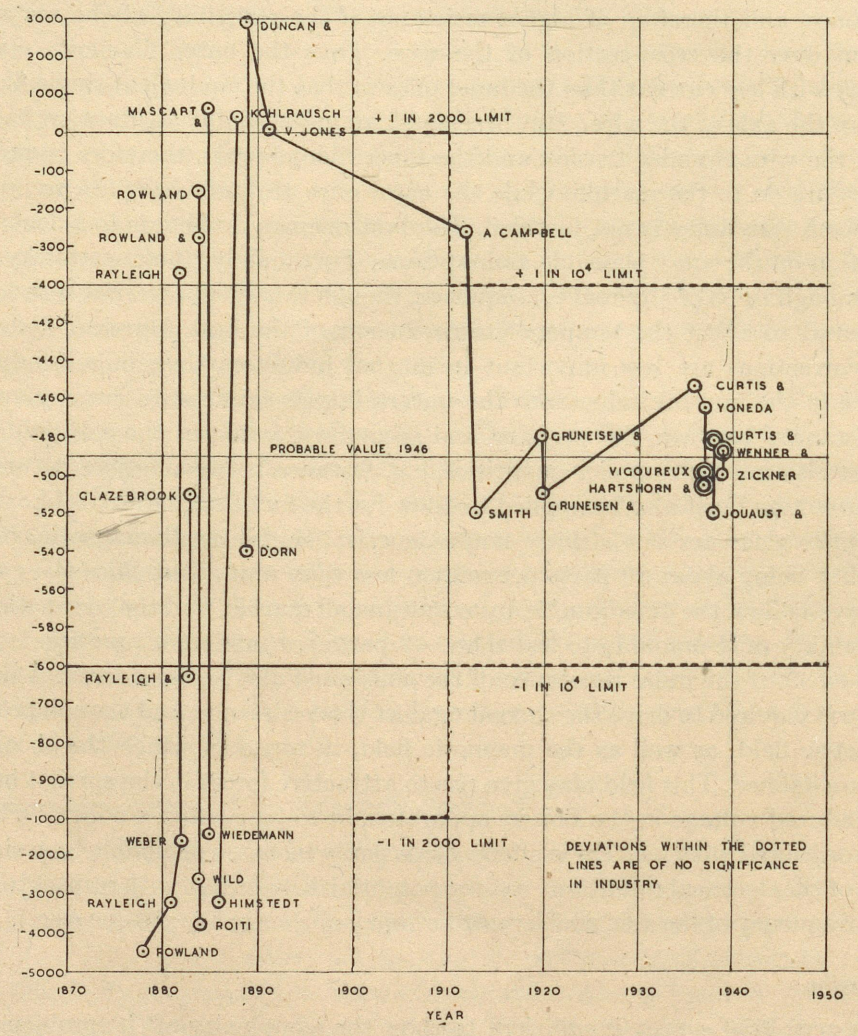

FIGURE 3. Determinations of the ohm. Only one author is named for each determination; the symbol '&' following a name means that there were collaborators. For further details see Smith (1922) and Curtis (1944). Two values are marked 'Gruneisen &'; they indicate an uncertainty in the value of the international ohm used by these observers.

Smith (1922) in Glazebrook's *Dictionary of Applied Physics*, vol. 2 and by Curtis (1944). These charts illustrate well for both the ohm and the ampere the steady approach to definite values that are consistent with all the observations made by all the methods within what may reasonably be regarded as their limits of error.

There is good reason to believe that the points in double rings obtained in the most recent measurements at the N.P.L. and N.B.S. represent the most accurate determinations, and it is seen that these deviate from the final value marked on the charts by little more than 1 part in 100,000. The maximum deviation of the three values for the ampere is only 4 parts per million, and of the four values for the

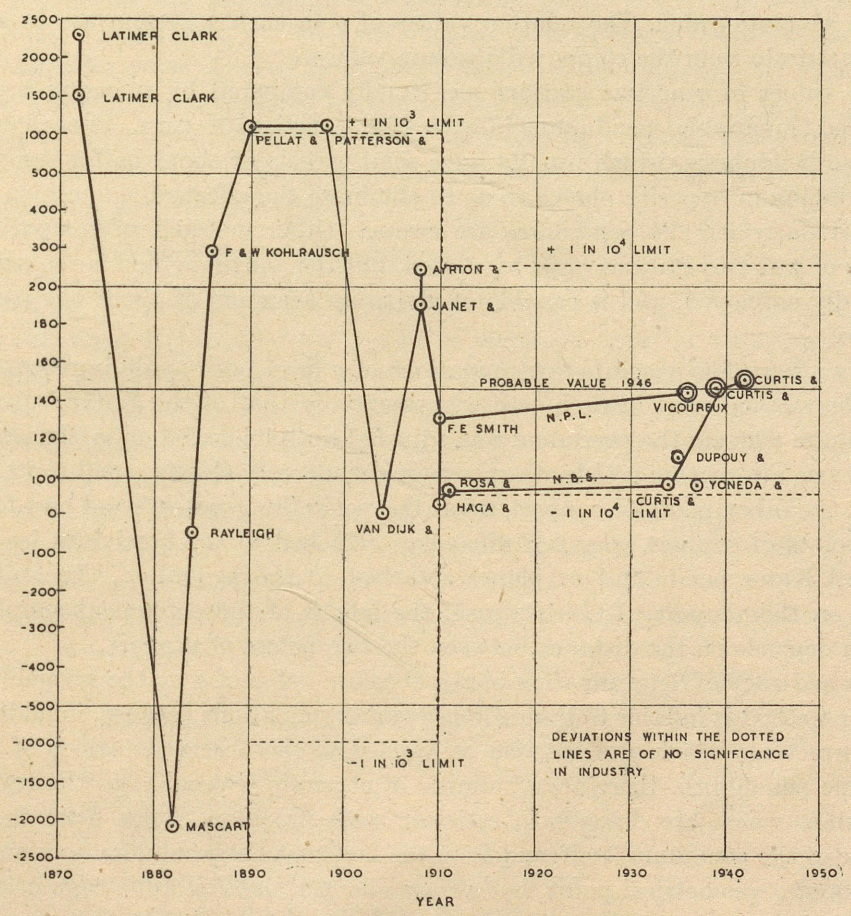

FIGURE 4. Determinations of the ampere. The symbol '&' following a name has the same meaning as in figure 3. For further details see Smith (1922) and Curtis (1944).

ohm only 12 parts per million. It is exceedingly improbable that any of these results are significant to 1 part per million, and there is no reason to suppose that the ampere is known with greater certainty than the ohm. It may, however, be concluded that the uncertainty in both values is approximately 1 part per 100,000, or about one-tenth of the smallest amount that is significant in industrial measurements.

The acceleration due to gravity

By J. S. Clark

Most determinations of the acceleration due to gravity are relative measurements, the resulting values of g being made to depend on some one reliable determination of the absolute value. The relative values of g in such a system are in general more accurate than the computed absolute values.

The values of g at two stations are usually compared by swinging a pair of so-called 'invariable' pendulums in each of the stations in turn. At each station, the two pendulums, which usually have semi-periods of about half a second, are set swinging in opposite phases so as to eliminate the effect of the motion of the support on which the pendulums are swung. Other methods of comparing the values of g at two stations have been used, but the above method is the one most generally employed, and is capable of giving an accuracy of about one part in a million.

Only a very few absolute determinations of g have been made in recent times, and the method used in each case was essentially that of the Kater 'reversible' pendulum, wherein the pendulum was adjusted until its period of oscillation about one of two alternative points of support was made very closely equal to its period about the other point of support when the pendulum was reversed end for end. The points of support may be knife-edges attached to the pendulum (as in the original Kater pendulum) or planes attached to the pendulum, the knife-edge being on the support. In either case, the length of the equivalent simple pendulum depends on the distance between the two points of support.

The accuracy of determination of the absolute value of g by the reversible pendulum method is inferior to that of relative determinations because, in addition to the corrections which also have to be applied to the observed periods of the invariable pendulums, there are a number of corrections peculiar to the reversible pendulum which are difficult to estimate with precision. These arise from the flexure of the pendulum itself, and from the fact that the pendulum does not oscillate about a geometrical point, but swings about a material knife-edge in contact with a plane surface. The knife-edge usually has a small, but finite, radius of curvature, and it undoubtedly suffers deformation under load. It is likely that the principal cause of uncertainty in the results obtained by means of reversible pendulums is due to the use of knife-edges.

Since 1909, the accepted international base for gravity measurements has been Potsdam. The accepted value, 981·274 cm./sec./sec., is the result of an absolute determination made by Kühnen & Furtwängler (1906) in the 'Pendelsaal' at the Königliche Preussische Geodätische Institut in Potsdam, and described by them in 1906. It corresponds with the value 981·275 cm./sec./sec. for the 'Ostkeller' of the Geodetic Institute.

Recent absolute determinations of g indicate that the Potsdam value is too large.

In 1936, Heyl & Cook published the result of an absolute determination made at the National Bureau of Standards, Washington, viz. $980{\cdot}080 \pm 0{\cdot}003$ cm./sec./sec. This result is 0·020 cm./sec./sec. lower than the value derived from the Potsdam value by means of a direct connexion between the two stations made in 1933 by Brown (1936) of the United States Coast and Geodetic Survey.

In 1939, the author published the result of an absolute determination made at the N.P.L., viz. $981{\cdot}181_5 \pm 0{\cdot}001_5$ cm./sec./sec. This result is 0·0138 cm./sec./sec. lower than the value derived from the Potsdam value by means of number of transfer measurements adjusted by Bullard & Jolly in 1937.

In 1940, Browne & Bullard published the results of direct intercomparisons made between the N.P.L., Teddington, and the N.B.S., Washington. These relative measurements gave the difference

$$g(\text{Teddington}) - g(\text{Washington}) = 1{\cdot}0969 \text{ cm./sec./sec.},$$

the difference between the two absolute determinations being 1·1015 cm./sec./sec.

In 1942, Dryden published the results of his analysis of the corrections which Kühnen & Furtwängler applied in the course of their original Potsdam determination. He suggested that the systematic errors present in the individual Potsdam determinations arose from other causes than those discussed by them, and that in the absence of further knowledge these errors should be considered as of a random nature, in which case a straight mean value, about 12 parts in a million lower than the value adopted by Kühnen & Furtwängler, would better represent the true value of g at Potsdam.

The following figures summarize the above absolute and relative determinations:

		Residuals
(A) Potsdam (amended by Dryden)	$= 981{\cdot}262$	$0{\cdot}002_5$
(B) N.B.S. (Heyl & Cook)	$= 980{\cdot}080$	0·003
(C) N.P.L. (Clark)	$= 981{\cdot}181_5$	$0{\cdot}000_5$
A–B (E. J. Brown)	$= +1{\cdot}174$	$0{\cdot}002_5$
B–C (Browne & Bullard)	$= -1{\cdot}096_9$	$0{\cdot}001_1$
C–A (Bullard & Jolly 1936)	$= -0{\cdot}078_7$	$0{\cdot}000_2$

The least-square solution of these six results gives

A (Potsdam) = $981{\cdot}259_5$ cm./sec./sec.
B (N.B.S.) = 980·083
C (N.P.L.) = 981·181

from which the residuals quoted above have been calculated. Using the original (Kühnen & Furtwängler) Potsdam value 981·274, the least-square solution gives

		Residuals
Potsdam	$981{\cdot}265_5$	$0{\cdot}008_5$
N.B.S.	980·086	0·006
N.P.L.	981·184	$0{\cdot}002_5$

No attempt has been made to weight the individual results contributing to these calculations. There would be obvious difficulty in doing so, and the smallness of the residuals indicates that no important change in the calculated values would be likely to result from any reasonable degree of weighting that might be suggested.

According to Dryden (1942), the Sub-Committee on Gravity of the National Research Council Committee on Fundamental Physical Constants has recommended a reduction of values in the Potsdam system by 17 parts in a million in those cases where the most precise absolute values are desired. The above analysis, however, supports the view that values in the Potsdam system should all be reduced by $0{\cdot}014_5$ cm./sec./sec. to give the closest approximation to the absolute values.

It seems unlikely that any future absolute measurements made with reversible pendulums will lead to appreciable improvement in accuracy, despite the very high precision with which measurements of length and time can now be made. There is, however, at least one other possible method of determining g absolutely, which does not involve the corrections associated with the use of a pendulum and knife-edges, and that is by observing the time of free fall of a body in vacuo.

Standard gravity

For certain purposes, e.g. the measurement of barometric height, which varies with the acceleration due to gravity, the need for relating the results to some gravity standard has long been recognized. Originally this standard was taken to be gravity in latitude 45°, at mean sea-level. No particular value of gravity was at first associated with this standard, and the reduction of results on this basis was made by means of simple theoretical formulae providing for changes of gravity with latitude and altitude. Later, when the need arose for associating a particular value with the gravity standard, the value 980·665 cm./sec./sec. was accepted by the Third International Conference for Weights and Measures in 1901.* This value was subsequently found to be somewhat too high, but it was deliberately retained by the Fifth International Conference in 1913 as the value of standard gravity for reference purposes, and was thereby given a conventional status distinct from the original conception of standard gravity. The same value was used in the definition of the standard atmospheric pressure to which boiling-points on the International Temperature Scale are referred.†

A different view of standard gravity, however, was taken in regard to meteorological work under the auspices of the International Meteorological Committee, and the geophysical basis, viz. gravity in latitude 45° at mean sea-level, was retained. Associated with this is the rounded value 980·62 cm./sec./sec.‡

* 1901, *C.R. 3rd Conf. Gén. Poids Mes.*

† 1927, *C.R. 7th Conf. Gén. Poids Mes.*; 1933, *C.R. 8th Conf. Gén. Poids Mes.*

‡ *Organisation Météorologique Internationale*, no. 45, Comm. Mét. int. Proc.-verb. Berlin, 1939. Lausanne, 1941, p. 75.

The concurrent use of two different conceptions of standard gravity, each supported by the authority of an international organization, is unsatisfactory and is a cause of confusion which should be eliminated. The whole subject of gravity in its bearing on geodesy, physics, meteorology, etc., needs to be reviewed with due regard to changes which now appear necessary in the absolute basis of gravity.

The barometric standard

By F. A. Gould

Fundamental considerations

In connexion with the establishment of some of the standards discussed in other papers of this series, an accurate knowledge of atmospheric pressure is necessary. Examples of this may be found in the determination of the steam point and other basic points on the international temperature scale; also in the determination of air density in connexion with certain precision weighings. The mercury barometer provides the most accurate means of determining atmospheric pressure. Barometer scales were originally graduated in units of length, and the process of determining pressure consisted, in principle, of two stages, viz.

(i) the determination of the true height of the mercury column from the scale reading, and

(ii) the translation of that height into a conventional pressure unit.

The first stage is largely a matter of instrumental convention and technique, which will be considered in a later section of this paper. In the second stage it is evident that if the density of mercury and the value of gravity in the vicinity of the barometer are known, the pressure can be expressed in absolute units, e.g. dynes/sq.cm., in accordance with the fundamental hydrostatic equation: $p = h\rho g$. Further, the scale can be graduated in units of length so chosen that the reading taken under specified conditions of temperature and gravity is identical with the pressure expressed in absolute units. In effect, such a scale would represent the result of multiplication of the three quantities, h, ρ and g, in the hydrostatic equation. This principle is adopted in the graduation of the 'millibar' scale (1 millibar = 1000 dynes/sq.cm.).

Apart from the millibar, which is of comparatively recent introduction, the conventional pressure unit adopted is a column of mercury of unit length (inch or millimetre) measured at 32° F (0° C) and subject to standard gravity.

The use of this reference temperature follows a long-established practice, but there are, unfortunately, two conceptions of standard gravity, each supported by the authority of an international organization.* The International Meteorological Committee retain the original conception of standard gravity, i.e. gravity at mean sea-level in latitude 45°, and now associate with it the value 980·62 cm./sec./sec.

* See 'The acceleration due to gravity' in this series of papers.

On the other hand, the International Conference for Weights and Measures has defined standard gravity as being equal to 980·665 cm./sec./sec., regarding it as a conventional reference standard distinct from the original geophysical conception. This value is used by physicists, chemists and engineers generally in work of high precision carried out in this country. In addition, the International Conference for Weights and Measures* has defined standard atmospheric pressure as the pressure exerted by a column of mercury, 760 mm. high, and of density 13·5951 g./c.c., subject to an acceleration of 980·665 cm./sec./sec. due to gravity. This definition is followed in precision pressure measurements made in the determination of physical standards and constants.

Fundamental standard barometers

(*a*) *Early history.* For many years the standardization of barometers was carried out at Kew Observatory where there were two mercury barometers, both having tubes of large diameter and designed to be read by cathetometer. These were installed between 1855 and 1860, and served as the fundamental standards of the Observatory. In 1912, when barometer testing was transferred to the N.P.L., the two standards remained at Kew, and a Fortin type barometer, having a tube of internal diameter 19 mm., was used as the principal reference standard at the Laboratory pending the design and construction of a new primary standard barometer, to be installed at Teddington. The Fortin barometer was compared with the Kew standards before being put into service and was subsequently standardized occasionally from first principles at Teddington. It was later compared with the new primary standard barometer, which was installed at the N.P.L. in 1931.

During the interval, 1912–31, the Fortin barometer remained in exceptionally good condition without need of overhaul, and no appreciable change in its error was found. A high degree of accuracy was attained in the maintenance of a barometric standard in rather difficult circumstances, and no appreciable discontinuity was introduced by the use of different standard barometers in 1912 and 1931.

(*b*) *Primary Standard Barometer at the N.P.L.* In this barometer a departure has been made from the usual conception of an instrument based on the use of a glass barometer tube containing the mercury column (see figure 5, plate 6). Instead of glass, a block of stainless steel is used, suitably bored to take the barometric column of mercury, which is of large diameter at the top and bottom, where the mercury surfaces are viewed through optically flat and parallel glass windows sealed to the body of the barometer. Provision is made for the vacuum space above the mercury column to be renewed, as required, by a suitable pumping system. The measurement of the length of the column is referred to a line-standard of length mounted vertically near the column, and is made by means of a vertical comparator which carries a pair of micrometer microscopes disposed one above the other. The comparator can be traversed so that the microscopes are brought opposite either to the mercury surfaces or to the line-standard as required.

* 1927 and 1933, *C.R. Conf. Gén. Poids Mes.*

The steel body of the barometer is also bored vertically to take a mercury thermometer having a bulb which is adjacent to and extends over the whole length of the barometric column. This thermometer, being immersed in mercury and surrounded by the same mass of steel as the barometric column, records very closely the mean temperature of the latter. The reader is referred to the original account (Sears & Clark 1933) of this instrument for further details, including the optical system for reading the position of each mercury surface.

(*c*) *Reduction of measurements.* The first stage in the determination of pressure with this barometer is the measurement of the true height of the mercury column at the prevailing temperature, which can be controlled thermostatically. The height is then corrected to give the equivalent height of the column at 0° C. The coefficient of thermal expansion of mercury which is used for this purpose is sufficiently well established to provide for this correction without any appreciable loss in accuracy.* Further, to express the pressure in terms of a column of mercury at 0° C and under standard gravity 980·665 cm./sec./sec., the height of the column at 0° C is multiplied by the ratio of gravity at the N.P.L. to standard gravity, i.e. by $\frac{981{\cdot}181_5}{980{\cdot}665}$.

Alternatively, if the pressure is desired in dynes/sq.cm., the height of the column, reduced to 0° C but subject to gravity at the N.P.L., is multiplied by the density of mercury at 0° C, which is taken to be 13·5951 g./c.c., and also by the value of gravity at the N.P.L., viz. $981{\cdot}181_5$ cm./sec./sec.

(*d*) *Accuracy.* It is estimated that under reasonably steady conditions the barometric height can be determined to an order of accuracy of $\pm 0{\cdot}002$ mm., viz. to 1 part in 400,000 approximately. The accuracy associated with the absolute determination of gravity made at the N.P.L. in 1937 is $\pm 0{\cdot}0015$ cm./sec./sec., (Clark 1939), corresponding to 1 part in 700,000. So far, however, the density of the mercury used in this barometer has not been ascertained, and this is the chief cause of uncertainty in the determination of pressure. The ordinary method of purifying mercury by distillation under reduced pressure results in a partial separation of its isotopes. For this reason the densities of different specimens of mercury vary slightly according to their history. The evidence available from relative and absolute density determinations suggests that the density of mercury should not be regarded as constant to closer than ± 1 part in about 150,000 of the mean value 13·5951 g./c.c. assumed. When due allowance for all sources of error has been made, it is considered that an accuracy of ± 1 part in 100,000 is attained in the determination of the atmospheric pressure with the Primary Standard Barometer.

Secondary standard and other mercury barometers

(*a*) *Usual types.* There are numerous varieties of design of mercury barometers, and these vary considerably in different countries. It is proposed here to refer

* See, for example, *Proc. Amer. Acad. Arts Sci.* **74**, 371, 1941.

briefly to two general types of barometers which have long been in use in this country, viz. the Fortin and Kew types. In the Fortin barometer, settings are made at the lower and upper mercury surfaces. For the former, a fiducial point fixed in the ceiling of the cistern serves as the zero to which the mercury surface is brought through the agency of Fortin's leather bag and an adjusting screw. The level of the top of the barometric column is determined by a setting with a cursor carrying a vernier which is read against the scale of the instrument. In the Kew barometer only a single setting is required, viz. at the top of the column, this being effected as in the Fortin barometer. To compensate for changes in level of the mercury in the cistern, the scale is contracted uniformly. The amount of contraction depends on the diameters of the tube and cistern.

Of the two types, the Fortin barometer is often preferred as an observatory or laboratory standard, but the Kew barometer is much more widely used for general purposes owing to its greater simplicity of design. For high accuracy, the tubes of barometers should be of large diameter. Small tubes are used where portability is of greater importance.

(*b*) *Scale units and conventions employed.* The scales of barometers of the Fortin and Kew types are normally graduated on brass. The inch scale of a mercury barometer is nominally correct at the temperature 62° F associated with the definition of the Imperial Standard Yard. Under this convention the scale measures correctly in inches the current length of the mercury column when the temperature of the barometer is 62° F.* The convention is applied to all inch barometers, irrespective of their type. Thus the readings of all inch barometers should agree at 62° F.

In conformity with the temperature 0° C at which the international metre is defined, the millimetre scale of a mercury barometer measures correctly in millimetres the length of the mercury column when the temperature of the barometer is 0° C. Accordingly, the readings of all millimetre barometers should agree at 0° C.

The millibar scale is employed almost exclusively for meteorological purposes, and the current conditions underlying its use were formulated by the Meteorological Office in 1914. The scale is so graduated that its reading gives the pressure correctly in millibars when the barometer is at a temperature of 285° A (12° C),† and is at mean sea-level in latitude 45°.

It is unfortunate that the conventions governing the graduation of the inch, metric and millibar scales lack uniformity. This causes some confusion in the correlation of corresponding readings on the scales and also in their reduction; and renders it difficult to prescribe for a fourth scale, viz. a scale of altitudes, which is

* Effect of capillary action. In practice, barometers are adjusted to agree ultimately with a fundamental standard instrument in which the effect of capillary action is negligible. This adjustment involves a slight displacement of the 'zero' of the scale, so that the reading corresponds, not to the length of the actual mercury column, but to the length which the column would have in the absence of capillarity.

† For meteorological purposes, temperatures expressed in °A are derived from temperatures measured in °C by adding 273°.

used on one type of long-range barometer. Consideration should therefore be given to the possibility of simplifying the current system of scale conventions.

(*c*) *The testing of mercury barometers.* The testing of mercury barometers is undertaken at the N.P.L., where they are compared directly with a secondary standard of the Laboratory. The standard used for this purpose, a long-range instrument of appropriate design, is compared as required with the Primary Standard Barometer at the prevailing atmospheric pressure. This comparison is supplemented by others made from first principles, using as basis a barometric column in a large-bore tube in which the mercury levels are read with a cathetometer. It is estimated that an accuracy of $\pm 0{\cdot}03$ mm. is attained in the determination of the errors of the secondary standard.

In the routine tests, mercury barometers are set up in a large airtight chamber in which five instruments of ordinary design are compared with the secondary standard at the same temperature and pressure. The pressure in the chamber is set and controlled barostatically at any value in the range required, and the settings on the barometers are effected by suitable controls from outside the chamber, enabling the barometers to be read in the usual manner by means of their cursors and verniers. An accuracy of the order $\pm 0{\cdot}1$ mm. is attained in the standardization of barometers whose design admits of this precision. In many instruments, particularly those having tubes of small diameter in which the amount of capillary action is both considerable and variable, the accuracy attainable cannot be guaranteed to closer than $\pm 0{\cdot}2$ mm., or even $\pm 0{\cdot}3$ mm.

(*d*) *Reduction of barometric readings.* The term 'reduction' relating to barometric readings is normally understood to cover the corrections which have to be applied to the readings in order to express the pressure in some conventional form, either in absolute pressure units or in terms of a column of mercury measured under specified conditions of temperature and gravity. If the latter form of expression is chosen, it is important that these conditions should be clearly stated. For example, the definition of the gallon lacks precision on account of the omission to state the conditions.*

In the more precise determinations the reduction is made from first principles with due allowance for errors in measuring the height of the column, for its temperature, and for the value of gravity at the station where the barometer is read. So far as the temperature reduction is concerned, the Fortin and Kew types of barometer have a somewhat different temperature coefficient. To avoid misunderstanding, the appropriate reduction formulae for the respective types are given in the certificates issued for barometers tested at the N.P.L. unless provision for effecting the reduction is otherwise made. If the value of gravity at the station is not known it can be assessed to a reasonably good approximation, in general, by reference to *International Critical Tables.*† With this information the equivalent height of the column under 'standard' gravity can readily be computed.

* See 'The measurement of volume' in this series of papers.

† *International Critical Tables*, **1**, 401. New York and London: McGraw-Hill.

For ordinary purposes published tables of temperature and gravity reductions are available.* These lack satisfactory provision for the temperature reduction of Kew barometer readings in inches and millimetres, and are confusing in regard to the two different conceptions of standard gravity employed. More comprehensive reduction tables for inch and millimetre barometers are needed, but before these can be prepared the whole subject of gravity values needs reconsideration with due regard to changes which now appear necessary in the absolute basis of measurement of gravity.†

Note. The scope of this paper has been restricted to determinations of pressure covering broadly the whole natural range of atmospheric pressures and based on the mercury barometer as standard. For the measurement of pressures of a higher order of magnitude, pressure gauges are ordinarily employed. These are standardized by determining the pressure applied by a piston loaded with known weights. Pressure gauges of all ranges up to 12 tons/sq.in. are tested on this basis at the N.P.L. to an accuracy lying within ± 1 part in 2000.

The measurement of volume

By Verney Stott

Units of volume

There are two kinds of units of volume, those directly derived from the corresponding unit of length, and those defined in terms of the volume occupied, under specified conditions, by a definite mass of water. In any system of units, once the fundamental unit of length has been defined, a hypothetical cube with edges of unit length clearly becomes a unit of volume. For practical purposes, however, hollow vessels are very convenient, and have long been used for measuring volumes of liquid, but to determine their capacity from linear measurements is not nearly so simple as to determine the weight of water required to fill them. Consequently units of volume came into existence defined in terms of the space occupied by a definite mass of water under specified conditions. The two types of unit are defined independently and the relation between them is a matter of experimental determination.

In the older systems of units there is no simple numerical relation between the two types. For example, the number of gallons in a cubic foot is not a whole number. In the metric system an attempt was made to link the two types of unit in a simple manner through the definition of the kilogram, and was achieved to a high degree of accuracy, but, as will be seen in the next section, even in the metric system the two types of unit are now defined separately and the relation between them is one based on experiment.

* *The Meteorological Observer's Handbook*, London: Meteorological Office; *Smithsonian Meteorological Tables*, Washington: Smithsonian Institute.

† See 'The acceleration due to gravity' in this series of papers.

Metric units

The founders of the metric system sought to ensure a simple numerical relationship between the two types of unit by defining the kilogram as the mass of a quantity of water occupying 1 dm.^{3} at its temperature of maximum density. Since, however, a cubic decimetre of water is manifestly unsuitable as a standard of mass, practical realization of the object in view necessitated making a standard of mass, of suitable material, strictly conforming to the above definition of the kilogram. The original Kilogramme des Archives was accepted as fulfilling this condition, and the litre, the volume of a kilogram of water at its temperature of maximum density, was regarded as equal to the cubic decimetre. Subsequently, however, the original definition of the kilogram was abandoned because doubt had arisen as to whether the Kilogramme des Archives did conform precisely to that definition, and the kilogram is now simply the mass of the International Prototype Kilogram.

The litre was separately defined* as being the volume occupied by a mass of 1 kg. of pure water at its temperature of maximum density and under a pressure of 1 atm. The reference to atmospheric pressure was introduced because water is slightly compressible. For pressures in the neighbourhood of 1 atm. and at ordinary room temperature a change in pressure of 1 mm. of mercury causes a change in volume of 0·000066 ml./l. Since the litre is defined on a mass basis, the buoyancy effect of the air will always result in the apparent weight in air of 1 l. of water being less than 1 kg. For example, against weights of density 8·4 g./ml. and in air of density 0·0012 g./ml., the weight of the quantity of water of temperature 4° C which occupies 1 l. at that temperature (and hence has a mass of 1 kg.) is 998·943 g. At higher temperatures the weight will be still less owing to the decrease in density of the water. For example, under the same conditions of weighing as above, the weight of a quantity of water of temperature 20° C and occupying 1 l. at that temperature is 997·176 g.

The present definitions of the kilogram and the litre contain no reference to the cubic decimetre, and when the litre was redefined arrangements were made for the accurate determination of the relation between the litre and the cubic decimetre. Three separate determinations were made.† The principle of each method was to determine by linear measurements the volumes of bodies of simple geometrical form and then to determine the mass of water displaced by the bodies by weighing them first in air and then in water. The methods differed only in the means employed to determine the linear dimensions. Guillaume used three hollow bronze cylinders, closed at the ends, of volumes approximately 780, 1300 and 2000 cm.^{3} and having diameters approximately 10, 12 and 14 cm. respectively and determined their dimensions by mechanical means. Chappuis used three glass cubes of 4, 5 and 6 cm. edge and employed a Michelson interferometer to measure the distances between the faces. The third determination was made by De Lepinay, Buisson and

* See *Trav. Bur. Int. Poids Mes.* **12** (1902).

† See *Trav. Bur. Int. Poids Mes.* **14** (1910).

Benoit using two quartz cubes of 4 and 5 cm. edge. They also utilized an interference method to determine the separation of the faces of the cubes but one differing from that employed by Chappuis. The final means of the individual determinations were:

using bronze cylinders	1 l. = 1000·029 cm.^{3},
using glass cubes	1 l. = 1000·026 cm.^{3},
using quartz cubes	1 l. = 1000·027 cm.^{3},

and the value finally accepted on the basis of all the results was

$$1 \text{ l.} = 1000{\cdot}027 \text{ cm.}^3$$

It is a tribute to the skill with which the Kilogramme des Archives was constructed in the eighteenth century that the litre approximates so closely to the cubic decimetre.

The difference in magnitude between the litre and the cubic decimetre and consequently between the millilitre and the cubic centimetre may often be ignored in comparison with the accuracy desired in a determination, but the distinction between the units should be clearly borne in mind and the difference taken into account when necessary. For example, densities expressed in g./ml. will differ numerically by approximately 3 parts in 100,000 from the same densities expressed in g./cm.^{3}, and so when densities of liquids are given to five decimal places the results expressed in g./ml. and those expressed in g./cm.^{3} will differ significantly in the fifth place.

To avoid much of the confusion which exists at present, it would be an advantage to express density—mass per unit volume—in g./ml. on all occasions, not only because of the difference just noted but also as affording a much better basis than specific gravity. This view is gaining acceptance; for example, density expressed in g./ml. is used throughout the *International Critical Tables*, and British Standard hydrometers are adjusted to indicate density in g./ml. at 20° C.

At one time confusion existed with volumetric glassware because some vessels were marked 'c.c.' although the unit used was the volume of a quantity of water having an apparent weight in air of 1 g. It has been stated previously that 1 l. of water of temperature 20° C has a weight in air of 997·176 g., so that a '1000 c.c.' vessel containing water of temperature 20° C having a weight in air of 1 kg. would be nearly 3 ml. greater in capacity than one containing either 1000 cm.^{3} or 1000 ml. at 20° C. Volumetric glassware, however, is now calibrated in terms of the millilitre, marked 'ml.' and also with the standard temperature 20° C; with such glassware no confusion can arise.

Imperial units

The gallon is the same type of unit as the litre. It is the volume of ten Imperial standard pounds of distilled water weighed in air 'against brass weights with the water and the air at the temperature of sixty-two degrees on Fahrenheit's thermometer and with the barometer at 30 in.' (§ 15, Weights and Measures Act, 1878).

The definition does not give precisely the conditions of weighing, and the Board of Trade assumes values of 0·00121698 g./ml. for the density of air and 8·143 g./ml. for the density of the brass weights to define the conditions under which 1 gal. of water of temperature 62° F has a weight of 10 lb. On this basis the gallon is equivalent to 4·54596 l. For conversion to units based on the Imperial units of length the relation 1 gal. = 277·42 cu.in. may be used.*

Heavy water

Prior to the discovery of isotopes, distilled water was regarded as a perfectly definite and homogeneous substance, and this assumption is implicit in the definitions of the litre and of the gallon. The average ratio of D_2 to H_2 in water is 1 to 6500, and if a sample of water contained D_2 in this ratio the complete removal of the D_2 would decrease the density by 17 parts in a million (Dorsey 1940). The variation in the D_2 content of ordinary distilled water is considerably less than that corresponding to the complete removal of D_2, and the lack of precision in the definition of the litre, in the light of the discovery of isotopes, is not likely to cause any practical difficulty in the measurement of volume.

Values of the density of water have, however, been published giving seven significant figures, e.g. to take only the values at one particular temperature from the tables, 0·9982336 g./ml. at 20° C (Chappuis as recalculated by the National Bureau of Standards (Tilton & Taylor 1937)) and 0·9982303 g./ml. at 20° C (Thiesen, Scheel & Dieselhorst 1900). The difference between these two values exceeds 3 parts in a million. The density of 'pure' water is therefore not known accurately to seven places of decimals, and the isotopic constitution would have to be taken into account in any attempt to establish the density to this degree of accuracy.

Volumetric measurements

Measurements of volume at the National Physical Laboratory have been mainly concerned with the verification of volumetric glassware. There is a great variety of such apparatus, some of which is limited in use to specific purposes, e.g. butyrometers, haemacytometer dilution pipettes, etc. The following details of the accuracy of certification offered for certain simple types of apparatus in general use serve to indicate the precision of measurement attainable in practice.

Type of Apparatus	Total Capacity (ml.)	Accuracy of Certification (v) (ml.)	v as Fraction of Total Capacity
measuring flask	1000	0·1	1 in 10,000
measuring flask	100	0·02	1 in 5000
pipette	100	0·02	1 in 5000
pipette	10	0·01	1 in 1000
pipette	1	0·005	1 in 200

* The present U.S.A. gallon derives from an old 'wine gallon' and is defined as being 231 cu.in.—inches being defined in the U.S.A. by the relation 1 m. = 39·370000 in.

The accuracy is lower for the smaller capacities than for the larger ones. The development of micro-analysis has created a demand for more accurate measurement of small volumes of liquid. A syringe-pipette recently designed at the Laboratory, in which liquid is expelled from a glass barrel by means of a well-fitting piston working between stops, enables an accuracy of 1 part in 1000 to be obtained on volumes of 1 ml. An accuracy approaching 1 part in 5000 is obtainable with a micrometer operated burette of similar capacity recently made at the Laboratory.

The photometric units and standards

From the Light Division, National Physical Laboratory

Historical

The candle was legalized by the Metropolitan Gas Act of 1860 which referred to the testing of gas in the metropolitan area. Apparently no unit was ever legalized for any other part of the country or for any other purpose. It had many disadvantages, and the Gas Referees who, under the Board of Trade, were responsible for gas testing under the Act, in their published 'Notification' for 1898 discarded the sperm candle in favour of the pentane lamp. What legal power they had to do this is not clear, but it might be held to derive from their position under the Act of 1860. The value of the unit was unchanged, at any rate to the order of accuracy with which it had been maintained.

Now that there is no test for the illuminating power of gas in the metropolitan area, the last vestige of legal status for the standard sperm candle or, in fact, for the pentane lamp, seems to have disappeared.

The unsatisfactory nature of the flame standards used by the different countries, viz. the pentane lamp in Great Britain and the U.S.A., the Carcel lamp in France and the Hefner lamp in Germany, led to proposals to use electric lamps as custodians of the unit of candle-power (Fleming 1902). A large number of comparisons of carbon-filament lamps were carried out in the various national laboratories (Paterson 1909), and as a result it was found that the unit employed in the U.S.A. was 1·6 % greater than the British unit, while the French 'bougie décimale' was 1 % greater. Both these countries agreed to adjust their units to conform with the British unit, and in 1909 the three laboratories concerned issued an identical statement in their respective countries to the effect that from 1 April 1909 they would all use the same unit. The text of this statement is given in a paper by Paterson (1910).

The constancy of the unit was assured by repeated exchanges of specially constructed electric lamps between the national laboratories so that the position was fairly satisfactory, at any rate from the practical point of view, although there was no primary standard. In 1921 the name 'International Candle' was given to this agreed unit. Germany, which had not been invited to co-operate, did not come into the scheme and continued to use the Hefnerkerze, which was approximately nine-tenths of a candle.

The present position

The definition of the international candle is incomplete, in that it does not specify how the unit is to be realized in light of any colour other than that of the electric lamps referred to in the definition. These lamps run at a colour temperature slightly below 2000° K, whereas a commercial gas-filled tungsten lamp may run at a colour temperature of 2800° K or more. The completion of the definition had been accomplished implicitly by the Commission Internationale de l'Eclairage in 1924 when it adopted a table of values of the visibility function (the relative sensitivity of the eye to radiant energy of different wave-lengths in the visible spectrum). For some time, however, no attempt was made to use this as a basis for heterochromatic photometry, with the result that the practical units at higher colour temperatures, derived from the carbon-filament lamps at the various national laboratories, showed disagreements of various amounts, the most serious being a progressive change in the ratio of the international candle to the Hefnerkerze from 1·11 to 1·17 on stepping up to a colour temperature of 2600° K.

After a preliminary discussion in 1927, the four national laboratories began co-operative work on the problem of devising a practical means by which the unit at higher colour temperatures could be derived in accordance with the agreed visibility function. As a result of this work it was found that the unit in use in Great Britain, U.S.A. and France for measuring tungsten filament vacuum lamps (i.e. at the colour temperature 2360° K) was too small by about $1\frac{1}{2}$ % and that at higher colour temperatures it was smaller still.

While this work was going on, important developments were taking place, at first at the Bureau of Standards in America and later at the other national laboratories, towards the establishment of a primary standard of light, i.e. a standard quite independent of electric lamps and one reproducible from a written specification.*

This standard consists essentially of a small tube of thoria immersed in a crucible of pure platinum. The tube forms a 'cavity', or 'black-body' radiator, the brightness of which depends solely on its temperature. The temperature of the whole crucible is first raised until the platinum is melted and it is then slowly cooled. The brightness of the mouth of the tube is measured and the value obtained at the 'arrest point', which marks the stage at which the platinum is solidifying, is used to define the unit of luminous intensity. It is, perhaps, fortunate that this standard has a colour temperature, 2046° K, which is close to that of the carbon-filament lamps used to maintain the international candle. The average value found at the various laboratories for the brightness of this standard is $58{\cdot}9 \pm 0{\cdot}1$ international candles per sq.cm.

Until 1929 photometry was not among the subjects dealt with by the International Committee of Weights and Measures, but in that year it was added to the terms of reference of the Consultative Committee on Electricity, and in 1935 a Consultative

* *P.V. Com. Int. Poids Mes.* 1931, **14**, 249; 1933, **16**, 254, 256, 261; 1937, **18**, 247.

Committee on Photometry was formed. This Committee recommended the adoption of a new unit of intensity, such that the above black-body standard should be exactly 60 units instead of 58·9. Though this sensibly alters the candle at this temperature the change is not serious for the temperature 2360° K, since the alteration almost exactly compensates the error at that temperature previously referred to.

The international adoption of the new unit was prevented by the war, though it came into force independently in Germany. It is expected that as soon as international co-operation is restored it will become universal.

The other photometric units, viz. the lumen (luminous flux), the foot-candle or metre-candle (illumination; flux received per unit area) and the foot-lambert or apostilb (brightness; flux emitted per unit area of perfect diffuser) are derived by formal definition from the unit of luminous intensity. The only one of these for which material working standards are required is the lumen. The most convenient method of preparing such standards is first to make point-to-point measurements of luminous intensity for a source which is, as nearly as possible, symmetrical about one axis and which can be rotated rapidly about that axis. A tungsten filament vacuum lamp of suitable design is used. The total luminous flux from the lamp can be found by integration from the mean polar curve of luminous intensity thus obtained. Other working standards of luminous flux can then be prepared by means of a spherical photometric integrator.

Standards of radiation

Radiation covering the ultra-violet, visible and infra-red regions of the spectrum can be standardized on a common basis, namely, that of energy. It is convenient to use the electrical units of energy for this purpose, so that the standards of radiation are ultimately based on the units of voltage and resistance.

The evaluation of radiant flux density in absolute units can be obtained by the use of a variety of radiometers. In all of the precision instruments the underlying principle involved is that the radiant energy is degraded into heat by absorption by lamp black or a black-body cavity, and the resulting heat measured either by comparison with heat produced electrically or by the absorption of the heat by Peltier cooling. The efficiency and accuracy of the instruments depend on the closeness with which the conditions of radiative and electrical heating approximate to each other as regards heat loss and distribution.

The accuracy to which the radiant flux density can be determined is very much lower than that attained in the establishment of electrical standards; consequently, the small errors associated with the latter are of no consequence. Scales of radiation maintained at the National Bureau of Standards, the Smithsonian Institute and Uppsala have been compared with the scale maintained at the N.P.L. (Guild 1937) and the general measure of disagreement among these scales probably does not exceed 0·5 %. The internal consistency in the maintenance of the N.P.L. scale is of the order of 0·2 %.

The absolute radiometer, like the majority of absolute instruments, is not convenient as a working instrument and is consequently replaced by thermopiles or calibrated lamps for substandards.

For radiation measurement generally the achievement of an accuracy of even 1 % demands much careful work so that a better accuracy than this is rarely required except by standardizing laboratories.

Spectral energy distribution

In addition to measurements of total radiation it is important to be able to determine the way in which the energy is distributed in the spectrum. This is particularly important in the visible region. When this distribution is known the three response functions, which are internationally agreed as a definition of the normal observer, enable brightness and colour to be derived. Unfortunately, in the visible spectrum the accuracy of direct spectral energy determinations is very much lower than that attained in related measurements such as spectral transmission or reflexion, and is also lower than the discriminating power of the eye. To ensure internal consistency up to visual standards spectral distributions are obtained indirectly by means of tungsten lamps used as working standards of energy distribution. They are calibrated on a colour temperature scale based on visual comparisons with a black-body furnace.

Acoustical standards of measurement

By R. S. Dadson

Introduction

The last few decades have seen rapid advances in the field of applied acoustics which are of profound significance to the community, but which need no enumeration here. In these advances, the increasing perfection of acoustical measuring instruments, and developments in the absolute measurement of sound, have played an important part and are still finding new applications. The present paper attempts to summarize the principles of those absolute methods of measurement which form the basis of the modern science of acoustics, with some discussion of the practical techniques adopted to meet different requirements and the degree of precision now attainable. No attempt is made to treat of the details of individual methods, in regard to which full references are given. Except where otherwise stated, the discussion is restricted to the measurement of sounds of simple-harmonic type of audible frequency, in air under normal atmospheric conditions.

The measurable quantities which together determine the oscillatory conditions at a point in a sound field are:

(*a*) the sound pressure, i.e. the alternating component of the total pressure at the point;

(*b*) the three components of the displacement, or of the particle velocity, relative to the co-ordinate axes.

In practice, however, it is seldom necessary for all of the four quantities referred to in (*a*) and (*b*) to be specified. Largely owing to the fact that the response of the ear is most readily interpreted in terms of sound pressure, the latter is the quantity of greatest significance in practical problems. Measurements of sound pressure are commonly carried out by means of microphones, and the calibration of such microphones in absolute terms is one of the most important applications of the basic measurements. Reference will be made in the section on 'Calibration of microphones' to the methods used at the National Physical Laboratory for this purpose.

Determinations of the acoustical pressure in sound fields are seldom direct; generally they are derived indirectly by calculation from measurements of particle velocity or displacement. In order to obtain satisfactory results by this procedure it is necessary to work with sound fields in which the theoretical relations between pressure and particle velocity are of reasonably simple form and capable of accurate realization in the laboratory. The conditions commonly employed are plane stationary waves in tubes, and progressive spherical waves in an absorbent-lined cabinet. These two procedures are appropriate for the calibration of standard microphones in terms of their 'pressure sensitivity' and 'field sensitivity' respectively, as will be further discussed in the section dealing with this work. By the use of devices such as the pistonphone it is possible to generate known acoustical pressures in a small enclosure over the lower part of the audio-frequency range, and thence to obtain absolute pressure calibrations of suitable microphones. This method is independent of the above-mentioned indirect methods, and since the ranges of frequency over which the two procedures are applicable overlap, a useful check of accuracy is made possible.

It is not within the scope of this paper to give details of the different varieties of microphones in use for practical sound measurements. They may be of the condenser, moving-coil, piezo-electric, or pressure-gradient types, all of which have their special applications. Of these the condenser microphone, introduced by Wente (1917), has been found to be particularly suitable for use in the laboratory for standardization purposes. This it owes to its simple and comparatively rigid construction, the possession of a flat and extremely stiff diaphragm which, for many practical purposes, may be regarded as a rigid boundary, its reasonably high sensitivity, and above all its great stability of calibration over long periods of time. There has lately been an increasing tendency to use piezoelectric microphones also as standards. Thus in practice a condenser microphone carefully calibrated in absolute terms may be regarded virtually as having the status of an absolute standard for the measurement of sound pressures under the appropriate experimental conditions. The unit of sound pressure is the dyne/cm.^{2}.

Absolute measurement of particle velocity: the Rayleigh disk

For the purpose of the absolute measurement of particle velocity at a point in a sound field the Rayleigh disk is widely used. The development of accurate acoustical measurements has been very closely bound up with the study of this most useful

and simple device. Its action is based on the well-known fact that a flat object suspended in a stream of fluid is acted upon by a couple which tends to turn it at right angles to the direction of flow. It was proposed by Lord Rayleigh (1880, 1882) that this effect should be turned to account for the absolute measurement of sound, and Koenig (1891) obtained the following expression for the torque T on an infinitely thin circular disk, which has formed the basis of subsequent work:

$$T = \tfrac{1}{6}\rho d^3 v^2 \sin 2\theta. \qquad (1)$$

In this expression d, the diameter of the disk, is assumed to be small compared with the wave-length of the sound, and the density of the material of the disk is assumed to be very large compared with ρ, the density of the medium. v is the root-mean-square value of the particle velocity in the sound wave, and θ the angle between the normal to the disk and the direction of flow. The medium is assumed to be frictionless and the flow laminar.

The disk, carefully shielded from draughts, is suspended in the sound field on a fine fibre usually of glass or quartz, measurements being made either of the torque required to maintain the disk at a fixed inclination to the lines of flow, or of the actual deflexion of the disk in response to the sound. The value of θ is normally chosen to be 45°, at which value the sensitivity of the device is a maximum. Practical details of the methods of calibrating and using Rayleigh disks will be found in a particularly useful paper by Barnes & West (1927).

In the application of the Rayleigh disk a number of small departures from Koenig's formula are encountered which have been studied in detail by many workers. A very comprehensive investigation has been made by Scott (1945). Zernov (1908) and Scott have shown experimentally that on account of the finite thickness of the disk the torque tends to exceed the value predicted by Koenig's formula to an extent which increases with the ratio of thickness to diameter. According to Scott the excess varies from about 1 to 10 % in torque (equivalent to 0·5–5 % in particle velocity) over a range of the ratio of thickness to diameter of from 0·006 to 0·12. To minimize this effect, therefore, the disks should be as thin as possible. A small tendency in the opposite direction is also found which originates from the fact that, owing to lack of infinite inertia, the disk is not completely immobile under the influence of the fluctuating torque. Appropriate corrections have been derived by Wood (1935) and King (1935), but, for most practicable types of disks used in air, would only amount to the order of 1 % in torque (0·5 % in particle velocity). King has also given a comprehensive theoretical treatment of the effect of the diffraction of the sound by the disk. The departure from Koenig's formula so arising, which is only appreciable at the higher frequencies, reaches about 1 % excess in torque (0·5 % in particle velocity) when the wave-length falls to some 15 times the diameter of the disk, increasing approximately as the square of the frequency. In the case of disks used in a plane-wave system in a tube, there is a further small effect due to the proximity of the walls, which, according to Scott's measurements, may amount to an excess of some 2 % in torque (1 % in particle

velocity) when the diameter of the disk reaches about one-third of that of the tube. Barnes & West have shown that appreciable errors may arise over narrow bands of frequency close to the internal resonances of the disk; these errors, however, are very localized in frequency and may be eliminated if care is taken to avoid using any particular disk at frequencies close to these resonances.

Barnes & West have concluded that if normal precautions are taken to ensure that the conditions presupposed in Koenig's formula may reasonably be expected to be valid, the measurement of particle velocity may be effected with the Rayleigh disk to an accuracy within 2 %.

Merrington & Oatley (1939) and Scott have suggested as a result of their investigations that there is a residual uncertainty in the constant in Koenig's formula which may lead to over-estimation of particle velocity of up to about 3% over certain ranges of frequency. The origin of this effect is so far obscure and appears to deserve further study. Nevertheless, this conclusion is not greatly at variance with the figure of 2 % estimated by Barnes & West. These estimates of the order of accuracy of Rayleigh disk measurements are in line with the experience over a period of years at the N.P.L. in the use of the instrument as a reference standard for the calibration of microphones. In the use of a disk for the comparison of sounds of identical frequency it is possible that the accuracy may be somewhat improved, in that uncertainties in the constant in Koenig's formula will largely be eliminated.

During the history of its development and use the Rayleigh disk has proved itself within the limits mentioned to be a reliable instrument, the performance of which justifies its continued use as a reference standard.

Absolute measurement of displacement: the smoke particle method

Carrière (1929), Andrade (1931), and subsequently Andrade & Parker (1937), have investigated the use of illuminated smoke particles for the measurement, by direct observation, of the displacement amplitude of sound waves in a tube over a wide range of frequency. Theoretical considerations indicate that particles of sufficiently small cross-section and inertia introduced into the sound field may be regarded as vibrating with very nearly the full amplitude of the wave motion. In practice the observations are made in a plane-wave system in a tube. The particles are illuminated by a source such as an arc lamp and their excursions observed by microscope or by photographic means. Of various substances tried, magnesium oxide smoke has proved especially suitable.

Scott employed this method as a reference standard in his investigation of the residual errors of the Rayleigh disk, and it has also been used by Cook (1940) for assessing the accuracy of the thermophone and reciprocity methods for the absolute pressure calibrations of microphones, which will be discussed in a later section.

As regards precision, it appears that an accuracy of 1 % or better, in the measurement of displacement amplitude, may be realized over the range of frequency for which the motion of the smoke particles may reasonably be regarded as indis-

tinguishable from that of the medium. For particles of magnesium oxide smoke of radius about $0{\cdot}3\mu$, which is typical of the sizes found in practice, this condition would be expected to hold up to a frequency of about 4000 cyc./sec., with an error of perhaps 1 or 2 % at 5000 cyc./sec. (Scott). Since, for given sound pressure or particle velocity, the displacement amplitude is inversely proportional to the frequency of the sound, it becomes necessary to use somewhat intense sounds at the upper frequencies in order to obtain sufficiently long traces for measurements of the highest accuracy. It is also worthy of note that the smoke method as at present used yields the value of the total excursion (peak to peak) of the particles. Purity of wave form is therefore of particular importance if it is desired to relate the results to quantities such as the root-mean-square pressure or particle velocity determined by other methods.

The technique of observation with smoke particles, although of comparatively recent introduction, has already proved of great value in sound measurement, and gives as close an approach to a truly absolute measurement as any method yet available.

Absolute determination of sound pressure and allied measurements

In so far as the techniques described in the sections on absolute measurement of particle velocity and displacement relate to measurement of pressure, they have relied on the absolute determination of the particle velocity or displacement in sound waves of simple form (such as stationary plane waves or progressive spherical waves) and the calculation therefrom of the sound pressure making use of the known relations between the various quantities. Consideration is now given to an independent class of absolute measurements based on the generation of known acoustic pressures in a small rigid-walled enclosure, by means of which it is possible to obtain directly the pressure calibrations of microphones of certain types. Two pressure generators of this nature, known respectively as the thermophone and pistonphone, have been widely used for the calibration of condenser microphones; it is convenient to consider these two instruments together.

The satisfactory operation of this method depends on obtaining a high degree of uniformity of sound pressure throughout the enclosure. The range of application is thus restricted to frequencies at which the wave-length is large compared with the dimensions of the enclosure.

The thermophone, introduced by Arnold & Crandall (1917) and further developed by Wente (1922), Ballantine (1932) and others, consists of a small metal-walled enclosure containing strips of gold or platinum foil through which is passed a.c. superposed on a much larger direct current. The resultant heating and cooling of the strip generates an alternating pressure in the enclosure which can be calculated provided the many constants of the instrument are accurately known and correct assumptions regarding the *modus operandi* of the system are made. In practice, however, these calculations are very complicated, and some of the constants and correction factors involved are not altogether free from uncertainty.

The pistonphone operates on much simpler principles. The alternating pressure in the enclosure is generated by the simple-harmonic vibration of a piston, the amplitude of which is either prescribed by mechanical means or directly measured. The calculation of the pressure is comparatively straightforward, and the physical constants involved are few in number and easy to determine.

Several authors (Wente, Ballantine, Cook, Ernsthausen and others) have assessed the performance of the thermophone and pistonphone by using them to calibrate condenser microphones which have also been calibrated by independent means. The pistonphone has generally proved a reliable instrument, and there appears to be general agreement that it may be relied upon to give an accuracy within 3 or 4 %. On the other hand, published accounts of the use of the thermophone are inconsistent as to its precision. Whilst certain workers (e.g. Wente, Ballantine) have succeeded in using the thermophone as an absolute instrument with a precision comparable with that of the pistonphone, others (e.g. Cook) have reported considerable discrepancies which they attribute to uncertainties in the behaviour of the thermophones they employed.

Two other methods, which will only be mentioned briefly, may conveniently be grouped with the pistonphone and thermophone; both these methods allow of the calibration of microphones of suitable types by means of purely electrical measurements. The first, introduced by Gerlach (1923) and further developed by Ballantine, is often called the electrostatic actuator method, and was designed for the calibration of condenser microphones. An additional electrode in the shape of a grille is placed close to the diaphragm and an alternating e.m.f. superimposed on a large, steady polarizing e.m.f. is applied between the two. This results in an alternating force on the diaphragm which may be calculated from the form and dimensions of the electrode. This method is reputed to be comparable in accuracy with the pistonphone. The second method, which has received increasing attention during recent years, is based on the principle of reciprocity as applied to linear reversible electroacoustic transducers.* Accounts of the method have been published by Maclean (1940), Foldy & Primakoff (1945), Cook and others; the latter author has made an extensive investigation of the application of reciprocity to the calibration of microphones of the condenser and crystal types, and has found the results to agree generally with those afforded by the pistonphone and electrostatic actuator to an accuracy of the order 4 or 5 %. The principle of reciprocity appears to offer considerable promise as a supplement to the existing methods.

Calibration of microphones

The absolute measurements discussed in the foregoing sections are suitable only for fundamental laboratory determinations, and most practical sound measurements are carried out by means of microphones, associated with electrical amplifying and indicating equipment. The calibration of such microphones is therefore a

* In its simplest form the method is analogous to the well-known Hopkinson test of the performance of electrical machines.

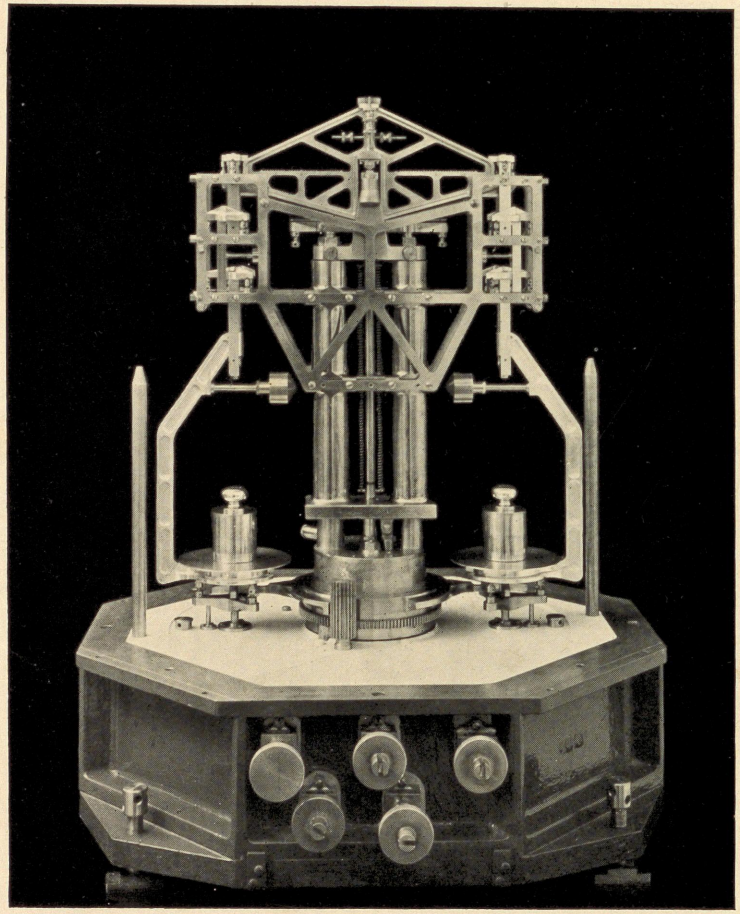

FIGURE 1. Precision balance at The National Physical Laboratory. Cover removed.

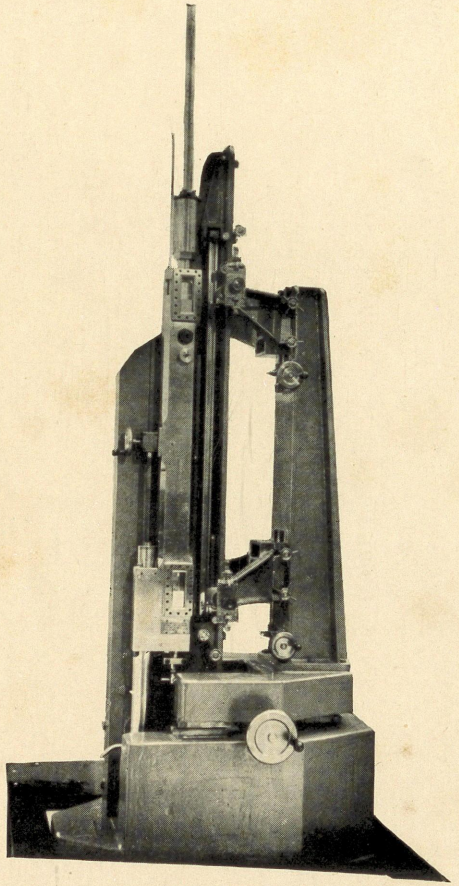

FIGURE 5. National Physical Laboratory primary standard barometer.

(Facing p. 212)

particularly important application of the basic measurements. Even for purposes of microphone calibration it is not always necessary to refer directly to absolute methods, and it has been the practice at the N.P.L. to maintain certain high-quality microphones, carefully calibrated in absolute terms, as reference standards against which other microphones may be compared. This procedure gives ample accuracy for ordinary purposes as well as resulting in simplification and saving of time. The microphones chosen as standards are of the condenser type (Wente 1917; Oliver 1930), which have been found by repeated tests to maintain stability of calibration over very long periods.

Owing to the disturbance of the sound field caused by the presence of a microphone, including the resonance of the cavity normally existing in front of the diaphragm, it is necessary to distinguish between two different ways of expressing the sensitivity (Aldridge 1928; West 1929). There is, first, its 'field sensitivity', which is the ratio of the response of the microphone when placed in a progressive sound wave to the sound pressure which existed at the same position before the introduction of the microphone. This quantity determines the performance of the microphone when employed to investigate free sound fields, and is the calibration appropriate to most ordinary sound measurements. Secondly, there is the 'pressure sensitivity' which is the ratio of the response of the microphone to the actual pressure actuating its diaphragm. This form of calibration determines the performance of the microphone when used to determine the pressure set up in a small enclosure, as, for instance, in the case of an artificial ear for the measurement of the acoustical output of telephone receivers.

The determination of the field sensitivity of the standard microphone is carried out, between the frequencies 300 and 10,000 cyc./sec., in a progressive wave in a cabinet heavily lagged with sound-absorbing material, in one side of which is situated a loud-speaker serving as the source of sound. Measurements of the sound particle velocity are made by means of the Rayleigh disk at a series of points on the axis of the loud-speaker and are converted into the corresponding sound pressures from the known relations in the progressive wave. The microphone is substituted for the disk and its response measured at the same positions. At frequencies below 300 cyc./sec. reflexions from the walls of the cabinet are no longer negligible, with the result that the method ceases to be valid. However, at these low frequencies the dimensions of the standard microphone are small compared with the wavelength of the sound, and since the field and pressure sensitivities then become practically indistinguishable, the determination of the pressure sensitivity suffices to determine the field sensitivity also. The Rayleigh disks employed at the N.P.L. are normally of glass, 1 cm. in diameter and of the order of 0·015 cm. thick, and are suspended on quartz fibres about 5μ in diameter. Smaller disks, 0·5 cm. in diameter, are also employed at the upper frequencies. For the accurate determination of frequency, reference is made to the N.P.L. Primary Frequency Standard (Essen 1938.)

The pressure sensitivity is determined from Rayleigh disk measurements in a stationary wave system set up in a cylindrical tube, the diameter of which is

usually chosen to be approximately equal to that of the microphone diaphragm, which closes one end of the tube. The stationary waves are set up by a pure-tone source at the other end of the tube, the Rayleigh disk being situated at an odd number of quarter wave-lengths from the microphone diaphragm, i.e. very closely at a velocity antinode. From the particle velocity determined by the deflexions of the disk the sound pressure actuating the diaphragm of the microphone may be deduced from the known relations in the stationary wave, and compared with the microphone response. Care must be taken in practice to avoid transverse resonances in the tube; in the case of the particular design of microphone concerned, the diaphragm of which is about 5 cm. in diameter, such resonances may be encountered in the frequency range above about 3500 cyc./sec. The use of stationary waves in hydrogen, in which the wave-length at a given frequency is nearly four times its value in air, may provide a means of extending the range of such measurements to higher frequencies.

The stationary wave method is not employed at the N.P.L. at frequencies below 62·5 cyc./sec. on account of the inconveniently long tube required, and at the lower end of the frequency range, from 10 to 400 cyc./sec., the pressure calibrations of the standard microphones have been determined by means of a moving-coil pistonphone.

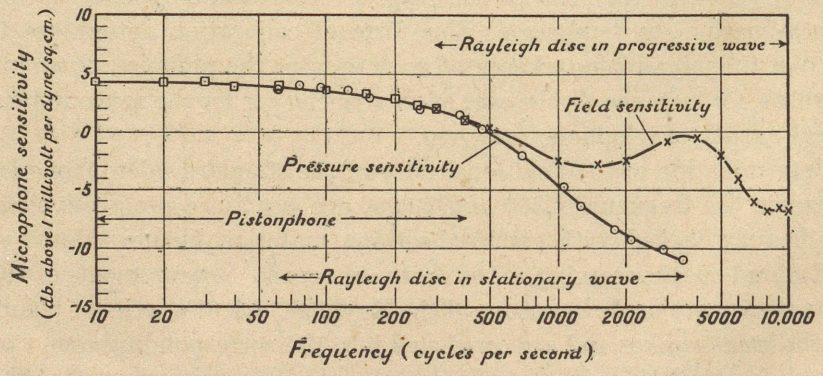

FIGURE 6. Calibration curves of standard condenser microphone.

Calibration curves determined by Mr N. Fleming for one of the standard condenser microphones in use at the Laboratory are shown in figure 6. Over the range 62·5–400 cyc./sec. the pressure sensitivity has been determined both with the Rayleigh disk and pistonphone, the agreement between the results of the two methods being of the order of 3 % which may be considered satisfactory. Good agreement is also shown between the pressure and field sensitivities, determined by the Rayleigh disk in stationary and progressive waves respectively, in the region 300–400 cyc./sec., where the two curves tend to become indistinguishable.

The applications of absolute measurements: measurement of noise

The application to industrial and other practical problems of the absolute measurements discussed in the preceding sections virtually reduces to the use of

microphones which have been calibrated in absolute terms, usually by comparison with microphones maintained as laboratory standards. These applications vary so widely in nature that the question of the precision of the measurements involved can only be treated in the broadest possible way. Frequently the sounds concerned are very complex, and the circumstances in which they arise can only be approximately specified. An accuracy closer than about 10 %, that is to say of the order 1 db.,* is rarely demanded in such measurements.

In recent years much attention has been paid to the problems of measurements associated with the suppression of noise, and in 1936 the British Standards Institution laid down a standard procedure for the measurement of noise by subjective means, and defined the terms to be adopted. In brief, the loudness of noise is judged by comparison, in free air, with a standard pure tone of frequency 1000 cyc./sec. under certain specified experimental conditions. If the 'normal' observer (i.e. an average of a group of persons of normal hearing) decides that a noise is equally loud to a 1000 cyc./sec. tone of intensity n db. above a reference level corresponding to a root-mean-square sound pressure of 0·0002 dyne/sq.cm. (which is very close to the normal threshold of hearing for the standard frequency), the noise is said to have an 'equivalent loudness' of n British Standard phons. An International Commission held in Paris in 1937 reached provisional agreement on the international standardization of the phon scale. It would be outside the scope of this paper to discuss the question of the standard procedure for such noise measurements in any detail, in which connexion the British *Standard Glossary of Acoustical Terms and Definitions* (1936) and a paper by Churcher & King (1937) should be consulted. The need for suitable objective instruments for the measurement of noise has also long been realized, and useful progress has been made in the design of objective meters employing a microphone, amplifier and suitable networks simulating the characteristics of the ear, and designed to give readings in phons for various types of noises of common occurrence (Davis 1938; King, Guelke, Maguire & Scott 1941). The precision with which such measurements may, in general, be made and interpreted is difficult to assess owing to the widely differing types of noise encountered, and the variety of circumstances, psychological and otherwise, in which they occur. In the more restricted case of reasonably steady noises, an accuracy of the order 2 to 3 phons should usually be possible if suitable precautions are taken.

The author is indebted to Mr N. Fleming for information concerning some of the past work on acoustical standards at the National Physical Laboratory.

* The decibel notation is commonly employed in acoustics on account of the very wide range of intensity which can be accommodated by the ear. Two powers W_1 and W_0 are said to be separated by an interval of n db. where $n = 10 \log_{10} (W_1/W_0)$. If the conditions are such that the ratio of the pressures P_1 and P_0 (or of the corresponding particle velocities) is the square root of the power ratio, then $n = 20 \log_{10} P_1/P_0$ also. In most practical circumstances a variation of less than 1 db. is scarcely noticeable to the ear.

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THE NEWTON TERCENTENARY LUNCHEON

TRINITY COLLEGE, CAMBRIDGE

Wednesday, 7 July 1946

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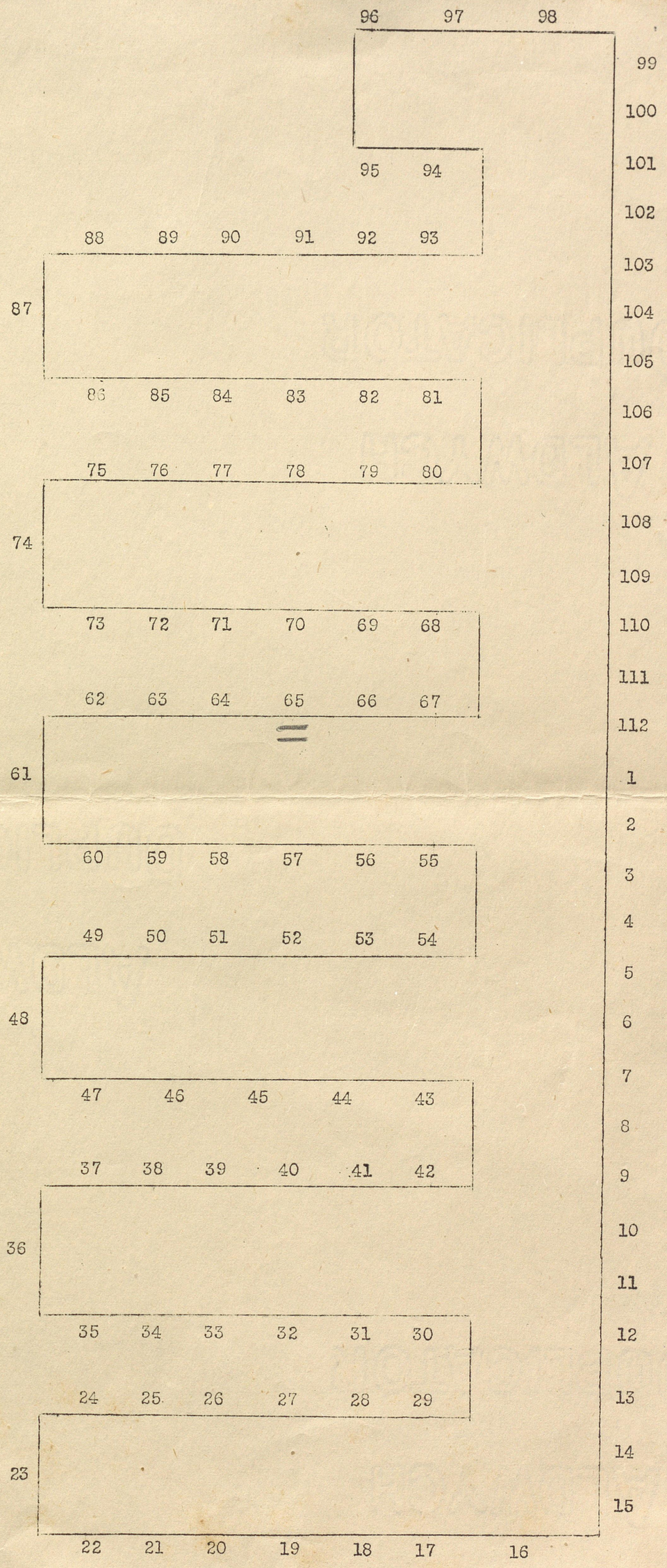
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Mr R. Daubney	East Africa
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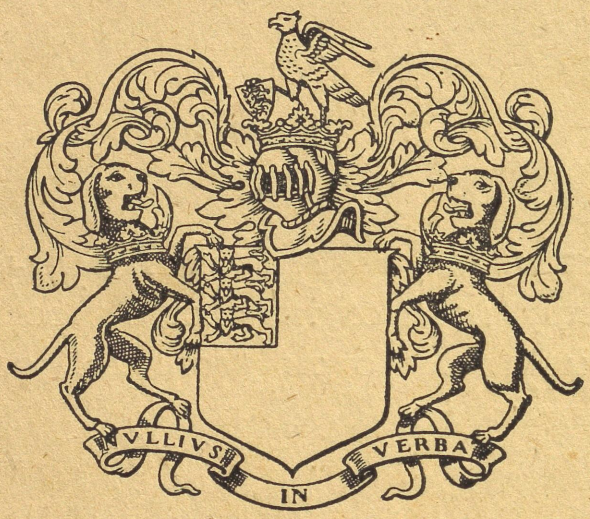
Professor C.E. Hercus	New Zealand
Professor J.N. Mukherjee	India
Dr P.J. du Toit	South Africa
Dr G.A.C. Herklots	Hong Kong

THE ROYAL SOCIETY



Sir ROBERT ROBINSON
President

Celebration of the tercentenary of the birth of Sir Isaac Newton, President of the Royal Society from 1703-1727

Qui genus humanum ingenio superavit

CONVERSAZIONE
18 *July* 1946

REFRESHMENTS WILL BE SERVED IN THE ANTE-ROOM AND MEETING ROOM ON THE GROUND FLOOR AND IN THE MAIN LIBRARY OF THE GEOLOGICAL SOCIETY ON THE FIRST FLOOR

By the courtesy of the President and Council of the Geological Society, their rooms have been opened for this occasion

EXHIBITION OF PORTRAITS, ENGRAVINGS, BUSTS, MEDALLIONS, MANUSCRIPTS, MANUSCRIPT LETTERS AND RELICS OF SIR ISAAC NEWTON

SIR ISAAC NEWTON

Sir Isaac Newton was born at Woolsthorpe in Lincolnshire in 1642 and

CORPORATION OF LONDON

CELEBRATION OF THE TERCENTENARY OF THE BIRTH OF SIR ISAAC NEWTON

RECEPTION AT GUILDHALL

FRIDAY, 19th JULY, 1946.

IMPORTANT MEMORANDUM

If unable to be present, you are earnestly requested to return the enclosed Admission Cards to "THE TOWN CLERK, 55-61, MOORGATE, LONDON, E.C.2," to permit of a re-issue.

G1037 500 7 46

May these material records and objects serve to remind us of the very personal endeavour and achievement of that great spirit, Newton,

EXHIBITION OF PORTRAITS, ENGRAVINGS, BUSTS, MEDALLIONS, MANUSCRIPTS, MANUSCRIPT LETTERS AND RELICS OF SIR ISAAC NEWTON

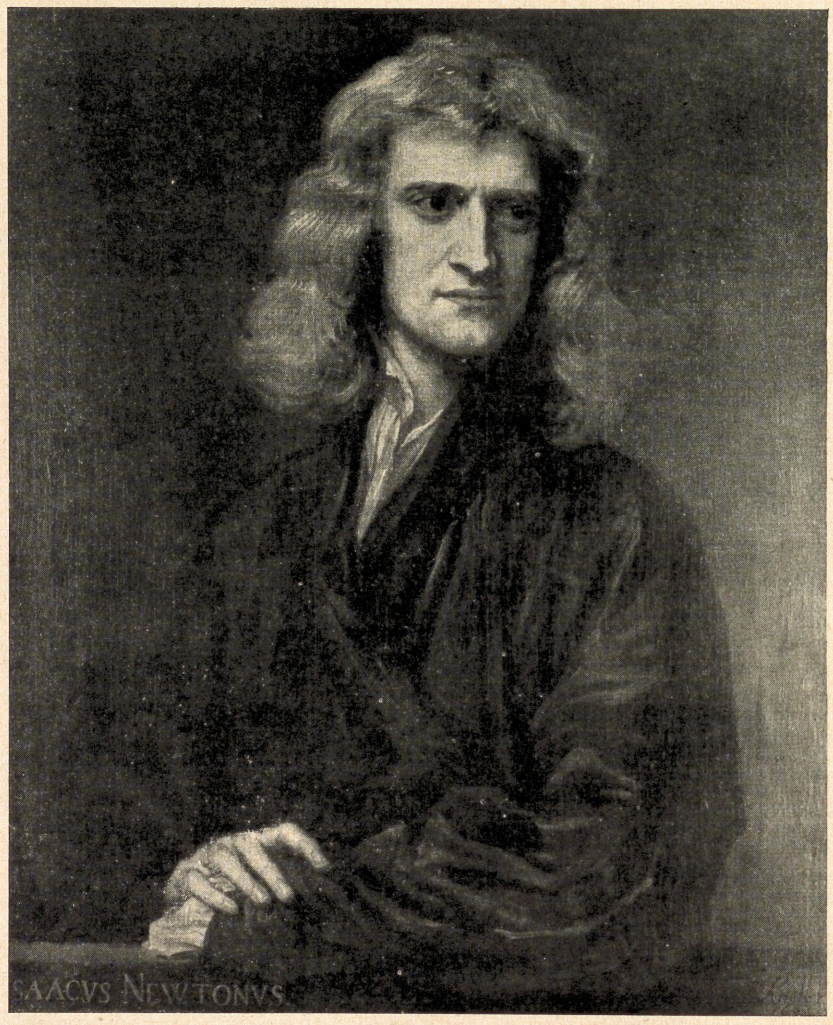
SIR ISAAC NEWTON

Sir Isaac Newton was born at Woolsthorpe in Lincolnshire in 1642 and accordingly the tercentenary of his birth was commemorated by the Royal Society in 1942, but circumstances of war forbade the presence of foreign guests and in various other ways restricted our assembly and curtailed our ceremonies. The present celebrations are designed to honour Newton's memory more worthily than was then possible.

The Royal Society was very closely associated with Newton's scientific life. He first came before the world when in 1671 he presented to the Society the reflecting telescope which he had made with his own hands, in consequence of which he was elected a Fellow on 11 January, 1671/2. His first publication was the letter containing his *New Theory of Light and Colours* which appeared in the *Philosophical Transactions* in 1672. The *Principia*, universally acclaimed as the greatest scientific work ever written, was, as a result of Halley's efforts, published under the auspices of the Society in 1687. In 1703 he became President of the Royal Society and continued in that high office until his death in 1727. As President he took a very active part in the affairs of the Society and it is probable that in the latter years of his life it was his chief interest.

The Society has a rich store of relics associated with Newton, which forms the basis of the present collection of Newton exhibits. Prominent among them are the reflecting telescope made by him and the original manuscript from which the *Principia* was printed. There are also shown a number of pieces of Newtonian interest which the Society has been fortunate enough to secure on loan.

May these material records and objects serve to remind us of the very personal endeavour and achievement of that great spirit, Newton,



NEWTON AT ABOUT THE TIME
OF WRITING OF THE *PRINCIPIA*

From a portrait by Godfrey Kneller in the possession of the Earl of Portsmouth

COUNCIL ROOM

1. The Mace of the Royal Society presented by King Charles II in 1663.

2. The Charter Book of the Royal Society showing the signature of Isaac Newton in 1671.

3. Two Portraits of Sir Isaac Newton, one by Charles Jervas and the other by J. Vanderbank.*

MAIN LIBRARY

1. The manuscript of the *Principia* from which the first edition was printed. It was written by an amanuensis, probably Humphrey Newton, but contains corrections in Newton's hand. Some of the original letters which passed between Newton and Halley are shown ; also copies of the three editions of the work, including the ordinary, the large paper and the extra large paper copies of the third edition. Only a few extra large copies were printed, for special presentations ; the copy shown is the one which Newton presented to Sir Hans Sloane. Of the two copies of the first edition shown, one was presented by Newton to Flamsteed, the first Astronomer Royal.

2. The original Reflecting Telescope made by Newton with his own hands in 1671 ; a rough sketch of the telescope

*Another portrait by Vanderbank is in the Ante-Room on the Ground Floor and a Bust of Newton by Roubiliac is in the Vestibule.



THE REFLECTING TELESCOPE, MADE BY NEWTON
WITH HIS OWN HANDS, IN 1671

made by him and sent to the Society. Also are exhibited copies of the first, second, third and fourth editions of Newton's *Opticks* with various translations.

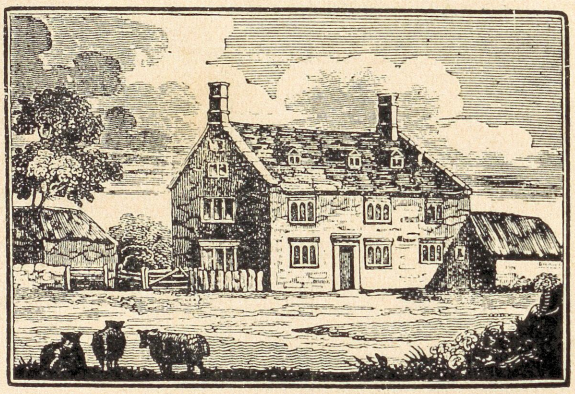
3. The manuscript of the *Commercium Epistolicum* (first published in 1712) with copies of the first and second editions. The work is that of a committee appointed by the Royal Society to consider the claims of Newton and Leibniz regarding the invention of the Method of Fluxions.

4. A Staffordshire figure of Newton and a Sèvres bust of Newton; plaster statuette from Roubiliac's statue at Trinity College, Cambridge; ivory bust by Cheverton from the sculpture by Roubiliac; plaster facsimile of ivory bust in the British Museum; ivory medallion by Le Marchand; Wedgwood medallions and medals of Newton.

5. An original drawing of the birthplace of Newton at Woolsthorpe in Lincolnshire as it is at the present time. Specially drawn by Mr Hanslip Fletcher for *The Sunday Times* and lent by them. Dr Stukeley's drawing of the house in the manuscript of his *Memoirs* of Newton. Other drawings and paintings of Newton's birthplace are also shown.

6. A Solar Dial cut in stone made by Newton when a boy: it was taken from the wall of his birthplace, the Manor House at Woolsthorpe, in 1884.

Newton's Birth-Place at Woolstrope.



These premises, the paternal residence of Newton, the house in which that great man was born, and in which he was reared and educated by his widowed mother, stands in a small romantic valley, about a mile west of the North Road, and five miles south of Grantham. At the school of this latter town he was educated, and used to walk daily to it, like other country boys, with his satchel at his back, or, after he was boarding in the town, on Monday mornings. The stone-work of the house is still scratched with several rude dials of his early formation, on some of which also remain his own clumsy gnomons. His bed-room too is shown, as well as the corner separated by a partition constructed by himself, to serve as a study. It is the right-hand window on the first story; and he was born in the room beneath, on the ground-floor. The apple tree, whence he drew his hypothesis, *about gravitation, is still in existence and bearing, but bent to the ground and broken, as represented in the right-hand corner; and the pear-tree under which he used to sit, and which the residents assert was the subject of the above observation, is still standing and flourishing, both within fifty yards of the door in the dwelling.*

FROM AN OLD LEAFLET FIGURING AND DESCRIBING NEWTON'S BIRTHPLACE

MAIN LIBRARY—*continued*

7. Portrait of Sir Isaac Newton by Sir Godfrey Kneller.

8. Engravings of portraits of Newton.

9. Letter from Newton to Dr John North, shortly to become Master of Trinity College, Cambridge, on Music. It was presented to the Society in 1945 by Mr Roger North, a descendant.

10. Collection of the works by and relating to Newton in the Library of the Royal Society.

11. Newton's watch : two rules made of the wood of the apple tree at Woolsthorpe and other relics.

12. A selection of manuscripts and original letters of Newton from collections made by Lord Keynes and Mr Geoffrey Keynes.

13. Manuscripts and original letters of Newton from the Archives of the Royal Society.

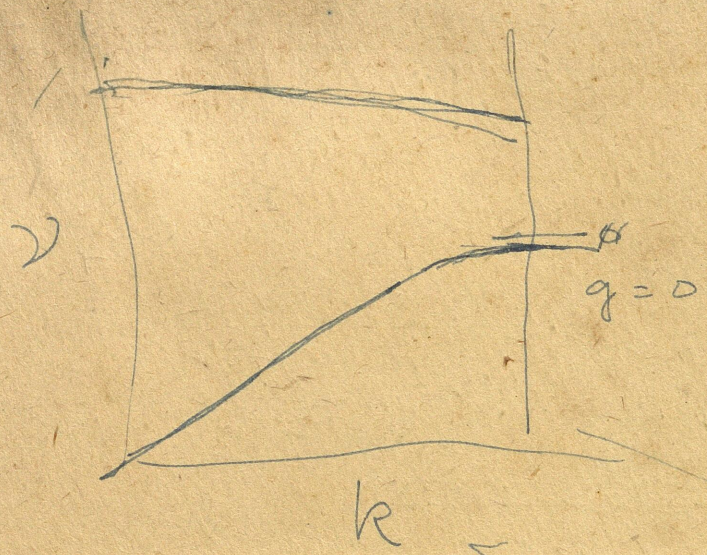
14. Mask of Newton's face, which belonged to Roubiliac, from the cast taken after death. Photographs of the monument and tomb-stone of Newton, in Westminster Abbey.



DEATH MASK OF NEWTON'S FACE

ACKNOWLEDGMENTS

The Society is indebted to Professor E. N. da C. Andrade for the arrangement of the programme and for the loan of a figure and a bust of Newton and of other items; to the Astronomer Royal (Sir Harold Spencer Jones) for the loan of an ivory bust of Newton; to Mr Geoffrey Keynes for the loan of manuscripts and original letters from the collection made by Lord Keynes, and from his own collection; to Major R. G. Warren for the loan of the portrait of Newton by Kneller, and to Dr E. Weil for the photographs of Newton's tomb-stone in Westminster Abbey; to Mr G. H. Wyatt for the loan of books from Newton's library; also to the Physical Society for the loan of blocks.



$$v = \frac{\nu}{k}$$

$$\underline{g} = \frac{d\nu}{dk}$$

$$\frac{\sin^2\theta}{\theta^2} + \frac{\sin\left(\theta + \frac{\pi}{2}\right)}{\left(\theta + \frac{\pi}{2}\right)^2}$$

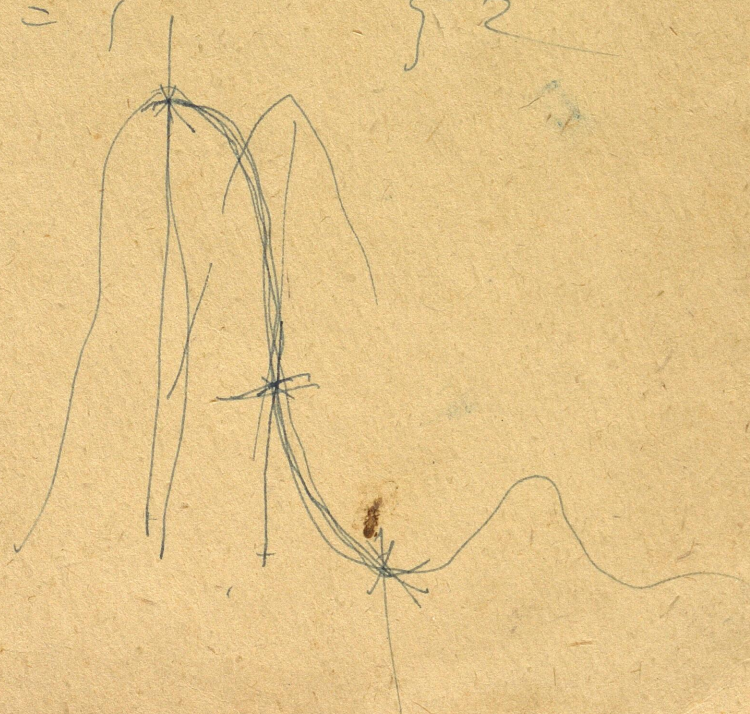
$$\frac{S_\varphi}{n\sigma_\varphi} = \frac{n^* kT}{V^2 \rho}\,\sigma_\varphi$$

$$= n^* kT\beta\,\sigma_\varphi \qquad \sum \frac{\sin^2 \xi}{\xi^2} \qquad \frac{\pi}{2}$$

$$= 1$$

$$k_x = \frac{n_x \pm 1}{2L_x}$$

$$k_y = n_y$$



□

NEWTON TERCENTENARY CELEBRATIONS

List of delegates

Algeria	Professor Bourion	Professor of Mathematics at the University of Algiers
Argentina	Dr J.B. Collo	
	Professor B.A. Houssay	For.Mem.R.S. Institute of Biology Buenos Aires
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	Dr A. Maccoll	London University
Belgium	Professor J. Cox	Rector of Lille University, Astronomer
	Professor C. Manneback	Louvain University, Physics
	Professor J. Timmermans	Professor of Chemical Physics at the University of Brussells
Canada	Professor J.S. Foster	F.R.S., Professor of Physics at McGill University
	Dr P. Gagnon	Laval University, Quebec.
	Professor O. Maass	F.R.S., Physical Chemist at McGill University
	Dr E.S. Moore	President of the Royal Society of Canada, Geologist at the University of Toronto.
China	Professor Y.R. Chao	Director of Linguistics, Chungking
	Professor P.Y. Chou	Theoretical Physicist
	Professor T.Y. Wu	Spectroscopist, Peiping
Colonial Empire	Mr A.G. Beattie	Director of Agriculture, Nigeria
	Mr R. Daubney	Kenya Veterinary Services
	Lord Hailey	Chairman of Colonial Research Committee
	Professor W.A.E. Karunaratne	Professor of Pathology at Ceylon University
	Dr H. Smith-Bracewell	Geological Survey, British Guiana
	Dr H.H. Storey	East African Agricultural Research Institute
Czechoslovakia	Professor B. Bydzovsky	Professor of Mathematics at Charles University, Prague
	Professor E. Cech	Professor of Mathematics at Masaryk University
	Professor V. Trkal	Professor of Theoretical Physics at Charles University, Prague
Denmark	Professor N. Bohr	For.Mem.R.S., Professor of Physics at Copenhagen University
	Professor A. Krogh	For.Mem.R.S., Professor of Physiology at Copenhagen University
	Professor J. Nielsen	Secretary of the Royal Danish Academy
	Professor N.E. Nørlund	For.Mem.R.S., Professor of Mathematics at Copenhagen University
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Eire	Dr F.E. Hackett	Member of the Royal Irish Academy
	Dr A.J. McConnell	Professor of Natural Philosophy at Trinity College Dublin
	Dr J.J. Nolan	Professor of Experimental Physics at University College Dublin

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	M. le Duc de Broglie	For.Mem.R.S., Member of the Academie des Sciences, Paris
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	Professor A. Denjoy	Member of the Academie des Sciences, Paris
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	Professor J. Hadamard	For.Mem.R.S., Member of the Academie des Sciences, Paris
	Professor G. Julia	Member of the Academie des Sciences, Paris
	Professor P. Langevin	For.Mem.R.S., Member of the Academie des Sciences, Paris
	M. E. de Margerie	For.Mem.R.S., Member of the Academie des Sciences, Paris
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	Professor F. Ries	Member of the Magyar Tudomanyos Akademia
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	Sir Kariamanikkam Krishnan	F.R.S.,Professor of Physics at Allahabad University
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	Professor F.A.Vening-Meinesz	For.Mem.R.S., Member of the Netherlands Academy
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	Professor H. Solberg	General Secretary of the Norweigen Academy
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	Professor I. Waller	Theoretical Physicistat Uppsala
Switzerland	Professor A. Mercier	Member of the Swiss Academy
	Professor M. Lugeon	For.Mem.R.S., Member of the Swiss Academy
	Dr G. Piotrowski	Member Institut National Genevois
	Professor L. Ruzicka	For.Mem.R.S., Member of the Swiss Academy
	Professor G. Tiercy	President of the Swiss Academy
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	Sir Alfred Egerton	Secretary of the Royal Society, Professor of Chemical Technology at Imperial College, London
	Professor F.E. Fritsch	F.R.S., Professor of Botany at the University of London
	Professor S. Goldstein	F.R.S., Professor of Applied Mathematics at Manchester University
	Professor A.V. Hill	Foreign Secretary of the Royal Society
	Professor W.V.D. Hodge	F.R.S., Professor of Astronomy and Geometry at Cambridge University

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	Dr V.V. Michkovitch	Member of the Yugoslavian Academy
Brazil	Senhor Dr J.J. Moniz de Aragao	H.E. The Brazilian Ambassador

20 SEP 1951

NOTES ON THE PREPARATION OF PAPERS TO BE COMMUNICATED TO THE ROYAL SOCIETY

ADOPTED BY THE COUNCIL OF
THE ROYAL SOCIETY
12 JULY 1951

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NOTES ON THE PREPARATION OF PAPERS TO BE COMMUNICATED TO THE ROYAL SOCIETY

ADOPTED BY THE COUNCIL OF
THE ROYAL SOCIETY
12 JULY 1951

INSTRUCTIONS TO AUTHORS

This pamphlet is issued by the Royal Society to assist authors of papers in the preparation and presentation of their material for publication.

Particular attention should be paid to the instructions which follow in the *Notes* and the paper should be drafted accordingly. A well-prepared typescript will, if accepted, be published far more rapidly than one which is badly prepared, as less time will be spent on editorial preparation and in the composing room.

For this reason it is important that authors should also be familiar with the conventions and rules embodied in this pamphlet, particularly under the following headings:

Copy	Tables	Abbreviations
Author's abstract	References	Miscellaneous recommendations
Sectional headings	Symbols	

If a paper is received by the Society prepared and presented in such a way that it fails to conform with a minimum standard of clarity, the Secretaries may find it necessary to return it for re-typing before accepting it for consideration by the referees.

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NOTES ON THE PREPARATION OF PAPERS TO BE COMMUNICATED TO THE ROYAL SOCIETY

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Copy

Papers should be clearly typewritten, with double spacing, on one side of the paper only, with a margin of about 1 in. on the left-hand side and at the head of each sheet; the sheets should be serially numbered and securely clipped together. Typescript must be carefully corrected by authors before being sent in. The paper should be non-absorbent to facilitate editorial marking. It is an advantage if authors can submit their papers *in duplicate*, one copy being the original. Each copy should if possible be accompanied by a set of sketches or photo-copies of the illustrations which are sufficiently clear to be understood by the referees. Original photographs and fair copies of drawings are also required.

Title

The title should be concise and typed on a separate covering sheet, which should also bear the names of the authors and that of the laboratory or other place where the work has been done. Where the title is long a short title suitable for the page headings should also be indicated.

Only in special cases should general titles be used (followed by I, II, etc., to indicate the number of the part); a specific title is usually better.

The names of joint authors should be arranged in alphabetical sequence unless there are special reasons for another order.

Contents

A list of contents is not printed for papers published in *Proceedings*, but only for longer papers published in *Philosophical Transactions*.

Author's abstract or synopsis

The Council of the Society has adopted the recommendations of the Scientific Information Services Committee as to the style of writing and content of author's abstracts or synopses.

Each paper must be accompanied by an abstract or synopsis *in triplicate*, which by Standing Order 37 should not exceed one page of *Proceedings* or 5 % of the length of the paper (whichever is the greater). The top copy should follow the title sheet of the paper and is printed in smaller type at the head of the published paper. The other two copies should be separate from the paper and are for office use; they should be headed by the title and the names of the authors.

Style of writing

The synopsis should be written concisely and in continuous English. It may be assumed that the reader has some knowledge of the subject, but the synopsis should be intelligible in itself without reference to the paper; for example, it should not cite sections or illustrations by their numerical references in the text. It is preferable to use the third person. Where possible scientific rather than proprietary terms should be used and unnecessary contractions avoided.

Content

The title of the paper is usually read as part of the synopsis, so that the opening sentence should be framed without repetition of the title. Usually the beginning of a synopsis should state the object of the investigation, and it is sometimes useful to indicate the treatment of the subject by such words as: brief, exhaustive, theoretical, etc. The synopsis should indicate newly observed facts, conclusions of an experiment or argument and, if possible, the essential parts of any new theory, treatment, apparatus, technique, etc. It should contain, or draw attention to, the names of any new compound, mineral, species, etc., and any new numerical data, such as physical constants. It may be important to refer to new items and observations, even though some are incidental to the main purpose of the paper; useful information may otherwise escape notice. The synopsis should indicate experimental methods, and, for new methods, the basic principle, range of operation and degree of accuracy. If it is necessary to refer to earlier work in the synopsis, the reference should be given in the same manner as in the text. Otherwise references should be left out.

Sectional headings

Papers should be divided up into sections, and these described by short headings. These headings are printed in capital and small capital letters without a full stop. They should be marked on the typescript by double underlining.

Subheadings when used will be printed in italics and centred. Mark these on the typescript by single underlining.

Sections may be numbered and, when necessary, reference should be made to them in the text by use of the section sign § with the number, e.g. see § 4.

Subsections should be lettered (*a*), etc., and sub-subsections numbered (i), etc.

Footnotes

Footnotes should be avoided unless really necessary.

Tables

Tabular matter costs more to print than letterpress, and should therefore be reduced to the minimum. Tables are printed without rules, that is, 'unboxed', unless rules are essential for their proper understanding.

Tables, however small, should be numbered seriatim in Arabic numerals, and referred to in the text by their numbers (e.g. 'see table 3'), since it may not be possible to print a table in its immediate context.

The places where tables are to be inserted should be indicated by a note (insert table 3 here) which should be ringed round.

Table headings should be brief, and will be printed in capitals and small capitals. Column headings should be in lower-case lettering except for the capital initial letters of proper names. The units of measurement should be placed at the head of the column in brackets wherever possible, as shown in the sample table.

Table 1. Removal of hydrogen atoms on molybdenum oxide

time (min)	pressure of hydrogen (mm)	photocell current (μA)
0	2·3	6·1
80	1·95	4·0
114	1·80	3·9
240	1·1	3·6

Illustrations

General

The author's name should be written on the back of all illustrations, and the number of the figure should also be shown there. This applies both to the rough copies or sketches for the use of the referees and to the originals which are for the use of the blockmaker.

The position of each illustration should be clearly marked in the typescript thus:

Figure 2 here (for legend see p. □)

References in the text to figures should be written in full and not contracted to 'Fig. 2' or 'Text-fig. 3' or 'Pl. 6, fig. 10'. Lower-case initials should be used, e.g.

'...the curves of figure 3 show'

'...are shown in the photographs (figures 6 and 7, plate □)'.

Illustrations are of two types: (1) line drawings (shaded by dotting or hatching if necessary), (2) wash drawings or photographs, which are usually reproduced as plates. If an author is not accustomed to drawing figures or making sketches for

reproduction it may be advisable for him to get a draughtsman to do the work or to ask the Society to arrange to have it done for him at his expense.

Descriptions of curves should not, except in special circumstances, be written on the figure, but the curves should be numbered or lettered and the description inserted in the legend. All lettering and numbering should be inserted lightly in pencil, and preferably in **blue pencil**. All lettering of words should be in lower-case except for proper names, where a capital should be used. Lettering of symbols should strictly follow the case and fount of type called for in the text. The block-maker's artist will draw these on the originals in a standard style of lettering and to a size to suit the reduction that will be made in the final size of the blocks.

An absolute minimum of lettering should be used on the drawing, and descriptions and explanations placed as far as possible in the legend. Any errors can be easily corrected where they occur in the type but are difficult and expensive to correct on the block.

Legends

These should be typed on a separate sheet at the end of the paper and should state concisely the points which the author wishes the reader to notice. Where a graph is the subject of the illustration the description of the coordinates should be given above the legend, e.g.

ord. distillation velocity constants abs. temperature (° C)

FIGURE 2. Test of theoretical mechanisms against Wohl's observations. ○ observed points; —— theory given in this paper; ..... vapour-pressure difference theory.

Legends should *not* be attached to original drawings, but may also be placed on the rough copies for the convenience of the referee.

Line drawings

Graphs. These should be drawn in waterproof black ink (Indian ink) on a smooth hard surface (Bristol board is recommended). If graph-paper is used it must be feint blue-lined. The use of a red-lined graph-paper, for example, involves additional cost in screening before engraving; grey-lined graph-paper is even more unsatisfactory and usually involves the expense of redrawing. The use of graph-paper can be avoided by 'pricking' through a curve on to Bristol board, using blue carbon paper and a hard pencil. If a curve is given only for illustration (not for measurement) no cross-lines are needed, but the axes should be graduated at suitable intervals. Where a curve is given for the purpose of measurement it is useful to retain cross-lines, but these should not be drawn too close together.

Size. The maximum size available for a figure, *including the legend,* is $5\frac{1}{4}$ by 8 in. in the *Proceedings* and in the *Philosophical Transactions* $6\frac{1}{2}$ by 9 in. Drawings should not usually be of more than foolscap size ($8\frac{1}{2}$ by $13\frac{1}{2}$ in.), and should be so prepared that they can be reduced, e.g. to half-size. No general rule can be given about the size to which a drawing can be reduced, but it should be remembered that some reduction usually improves the figure.

Drawing of lines. It is essential that each line should be drawn of uniform thickness throughout. The axes of coordinates should be of even thickness with curves, or only a shade thinner. The cross-lines, when used, should not be drawn too thin, a common fault, otherwise when etched they are liable to break, or time has to be spent in making them thicker. A thin grey line is always unsatisfactory and has to be strengthened.

Biological and other drawings

The preceding remarks apply also to simple sketches and elaborate drawings. Instead of written descriptions on a sketch, key lettering should generally be used and the reference inserted on the legend to the figure. Both key letters and indicating arrows should be inserted in pencil.

Frequently dotting is used as a method of shading in biological sketches, a series of heavy dots being graded off to very fine ones. This requires care and skill, otherwise some of the dotting may disappear when the drawing is reduced. Flat 'tints' of various patterns of dots, lines and shadings can be put on by the engravers. The area to be tinted should be indicated on the drawing by blue pencil only, and an instruction given for such area to be so tinted.

Unsuitable drawings

When drawings submitted by the author are found to be unsuitable for reproduction because they fail to attain the standard required by the Royal Society, they can be redrawn by the blockmaker's artist at the expense of the author.

Plates

When sending photographs for reproduction authors should supply unmounted glossy prints numbered and marked on the back with the author's name, the number of the figure and with top and bottom indicated, together with a key diagram showing how they should be arranged on the plate. When lettering has to be inserted, a rough set should be provided with lettering written as a guide for the engraver.

Duplicate figures

When the author can conveniently do so, it is desirable that duplicate figures (e.g. blue prints or photographic copies) should be supplied with each copy of the typescript, so that the original figures need not be handled prior to engraving.

References

References to the literature cited must be given in alphabetical order at the end of the paper. They should be arranged as follows:

(1) Name(s) with initials of the author(s).

(2) Year of publication of the paper or book.

(3) Short title of the periodical, as given in the *World List of Scientific Periodicals*, underlined to show that it is to be printed in italics; with the exception that in periodicals with English names the ordinary English usage of capital letters shall be followed, e.g. *J. Chem. Soc.*, *Proc. Linn. Soc.* The publications of the Society are

abbreviated as *Proc. Roy. Soc.* and *Phil. Trans.* A selection of the abbreviations for the most commonly quoted journals appears on pp. 12–20.

(4) Volume, in heavy Arabic numbers (with series number, if necessary). The volume numbers in the typescript should be underlined thus: 24.

(5) Beginning and, if desired, end page numbers of the paper.

(6) When the title of a book is cited, the name of the publisher, the place of publication, and number and date of the edition should be given.

The reference to a paper will then read as follows:

Brown, R. S. 1935 *Proc. Roy. Soc.* A, **45**, 61–73.
Crichton, M. D. 1936 *Ann. Mag. Nat. Hist.* (10), **18**, 201.
Jones, B. 1898 *The buried cities.* London: A. B. and Co.

References in the text are made by giving the author's name and date of publication, e.g. (Brown 1935). Such reference is usually placed in brackets unless the name of the author is part of the sentence, in which case the year only is required in brackets. Where more than one paper published in any one year by the same author are cited, each paper should be distinguished by a small letter, *a*, *b*, etc., placed after the date, e.g. (Brown 1935*a*). Where there are more than two authors to a paper, all the names should be given when the paper is first cited. Subsequent references may be given thus: (Brown *et al.* 1935).

References by serial numbers (e.g. A. N. Other [8]) are not permitted. In papers communicated to the Society for publication in the *Philosophical Transactions* B, titles of papers, abbreviated if necessary, may be included in the list of references. In papers for publication in *Philosophical Transactions* A or in *Proceedings* A or B, titles of references may be printed if the author expresses a special wish to have them inserted. A cross-reference may be given, if desired, from the reference in the list to the pages on which that reference occurs. For example:

Brown, R. S. 1935 *Proc. Roy. Soc.* A, **45**, 61–73 (see pp. 261, 264).

Proofs

Since papers and illustrations communicated to the Society should be prepared ready for the press, proofs are sent to authors for the correction of printers' errors. Should an author make alterations or additions which are considered excessive, he may be required to pay for them. Authors should pay particular attention to checking references and to filling in page references when this is necessary. As page proofs of papers published in the *Proceedings* are not sent to authors, the following reference system is used. A passage on (say) p. 2 of the slip proof is referred to on (say) p. 8 of the slip proof; the passage on p. 2 should have a line drawn down the side of it and a large capital A inserted in the margin, then on p. 8 where the proof reads 'see p. 00' a note should be written in the margin 'see A p. 2 of slip'. Succeeding references should be indicated by succeeding letters B, C, etc.

Mathematical texts

Particular care is necessary in the preparation of mathematical papers, since the printer is not familiar with the subject-matter.

Formulae and symbols

Although the verbal portion of the text is typewritten it is preferable to insert all formulae and even isolated symbols in the text in *clear handwriting*. These are normally set by the compositor in italic type unless the author calls for special founts such as **bold type** or gothic.

Greek letters should be underlined in a contrasting colour, preferably red, and a marginal note inserted opposite the line where each letter is first used (e.g. Gr. 'chi').

Where numerous different founts are required in one paper it will assist the compositor if a separate key is provided (not for printing) in which the different underlinings and the founts required are tabulated.

Please make sure that your written letters and symbols are absolutely clear and unambiguous, especially where capital and lower-case letters have a similar outline.

Miscellaneous recommendations

(i) Dates should be written thus: 7 July 1938, the month being written in full.

(ii) In titles of papers and, where practicable, in the text elements and chemical compounds should be written in full and not represented by their symbols, e.g. chlorine, not Cl; sulphuric acid, not H_2SO_4.

(iii) Generic and specific names should be underlined for printing in italics. Higher groups to be in Roman letters, with capital if in Latin form, but without if in English (e.g. Mammalia, mammals; Pteridophyta, pteridophytes). In zoology the trivial epithet should not have a capital (e.g. *Okapia johnstoni*). In botany the usage laid down in the *International Rules of Botanical Nomenclature*, 3rd ed. (1935), should be followed; the *Index Kewensis* and its supplements may be taken as a general guide. In zoology the usage laid down in *Règles Internationales de la Nomenclature Zoologique* should be followed. A revised edition of the *Règles* will be published by the International Trust for Zoological Nomenclature of 41 Queen's Gate, London, S.W. 7, but until this is available, authors should refer to the amendments and additions published in the *Bulletin of Zoological Nomenclature*, **4**.

Where the author of a species is given, his name should immediately follow the specific name without a comma, or in brackets if the species is referred to a different genus from that of the original description.

(iv) Do not use hyphens to denote ranges of temperature, time, etc. Always use the appropriate word in full. Examples:

> At temperatures between 5·7 and −25° C.
> For periods of 3 to 5 days from 3 January to 6 September 1949.
> 8 to 10 ml. of solution were withdrawn every 3 or 4 min.

(v) All decimals of less than unity should have the decimal point preceded by a zero (e.g. 0·1234 not ·1234). This rule also applies in tabular matter:

correct	incorrect
0·175	0·175
0·264	·264
0·756	·756
0·999	·999

(vi) Do not use a comma to divide large numbers into groups of three digits. If really necessary the division can be made by a space, e.g. 123 456 789 not 123,456,789.

(vii) The names of units of measurement used *in the text* should normally be given in full if they are referred to in general terms without a specific numerical value, e.g. 'The treatment involved the heating of several grams of the mixture for a period of half an hour'.

Where accurate numerical values are stated, the appropriate abbreviation for the unit should be used, e.g. '14·5 g of the mixture were placed in a thermostatically controlled oven at 200° C for 35 min.'

ABBREVIATIONS FOR NAMES OF PERIODICALS

The following list of the titles of journals and periodicals and the abbreviations to be used in the lists of references in all papers published by the Royal Society is composed of those items to which frequent reference is made.

Items not on the list should follow the style of *The World List of Scientific Periodicals* (Oxford University Press), modified where necessary to conform with the style of the list below (e.g. where the titles are in English the usual use of capital initial letters is preferred).

FULL TITLE	*ABBREVIATED TITLE*
Abhandlungen hrsg. von der Senckenbergischen Naturforschenden Gesellschaft. Frankfurt a. M.	*Abh. senckenb. naturf. Ges.*
Acta Crystallographica. Cambridge	*Acta Cryst.*
Acta mathematica. Stockholm	*Acta math., Stockh.*
Acta pathologica et microbiologica Scandinavica. Kjøbenhavn	*Acta path. microbiol. scand.*
Acta Universitatis Lundensis	*Acta Univ. lund.*
Advancement of Science. London	*Advanc. Sci.*
Aerotecnica. Roma	*Aerotecnica*
American Journal of Anatomy. Baltimore	*Amer. J. Anat.*
American Journal of Botany. Lancaster	*Amer. J. Bot.*
American Journal of Cancer. New York	*Amer. J. Cancer*
American Journal of Diseases of Children. Chicago	*Amer. J. Dis. Child.*
American Journal of Hygiene. Baltimore	*Amer. J. Hyg.*
American Journal of Mathematics. Baltimore	*Amer. J. Math.*
American Journal of Medical Sciences. Philadelphia	*Amer. J. Med. Sci.*
American Journal of Pathology. Boston	*Amer. J. Path.*
American Journal of Physiology. Boston	*Amer. J. Physiol.*
American Journal of Science. New Haven	*Amer. J. Sci.*
American Mathematical Society. Translation	*Amer. Math. Soc. Translation*
American Mineralogist. Lancaster, Pa.	*Amer. Min.*
American Naturalist. Boston	*Amer. Nat.*
Anatomical Record. Philadelphia	*Anat. Rec.*
Anatomischer Anzeiger. Jena	*Anat. Anz.*
Annalen der Physik. Leipzig	*Ann. Phys., Lpz.*
Annales de chimie (et de physique). Paris	*Ann. Chim. (Phys.)*
Annales de l'Institut Pasteur. Paris	*Ann. Inst. Pasteur*
Annales de physique. Paris	*Ann. Phys., Paris*
Annales de la Société polonaise de mathématique. Krakow	*Ann. Soc. polon. Math.*
Annales scientifiques de l'École normale superieure. Paris	*Ann. sci. Éc. norm. sup. Paris*
Annales de la Société Royale zoologique de Belgique. Bruxelles	*Ann. Soc. zool. Belg.*
Annali di matematica pura ed applicata. Milano.	*Ann. Mat. pura appl.*
Annals of Applied Biology. Cambridge	*Ann. Appl. Biol.*
Annals of Botany. London	*Ann. Bot., Lond.*

FULL TITLE	ABBREVIATED TITLE
Annals of Eugenics. Cambridge (now London)	*Ann. Eugen., Camb.* (or *Lond.*)
Annals and Magazine of Natural History. London	*Ann. Mag. Nat. Hist.*
Annals of Mathematical Statistics. New York	*Ann. Math. Statist.*
Annals of Mathematics. Princeton	*Ann. Math. Princeton*
Annals of the New York Academy of Sciences	*Ann. N.Y. Acad. Sci.*
Annals of Tropical Medicine and Parasitology. Liverpool	*Ann. Trop. Med. Parasit.*
Arbeiten aus der Biologischen Abteilung (Anstalt-Reichsanstalt) f. Land- u. Forstwirtschaft am Kais. Gesundheitsamte. Berlin	*Arb. biol. Abt.* (*Anst.—Reichsanst.*), *Berl.*
Arbeiten aus den Zoologischen Instituten der Univ. Wien u. der Zoolog. Station in Triest. Wien	*Arb. zool. Inst. Univ. Wien*
Archiv für Anatomie u. Physiologie. Leipzig	*Arch. Anat. Physiol., Lpz.*
Archiv für das Eisenhüttenwesen. (Stahl und Eisen. Ergänzung.) Düsseldorf	*Arch. Eisenhüttenw.*
Archiv für mikroskopische Anatomie (und Entwicklungsmechanik). Bonn	*Arch. mikr. Anat.*
Archiv für Protistenkunde. Jena	*Arch. Protistenk.*
Archiv für Psychiatrie u. Nervenkrankheiten. Berlin	*Arch. Psychiat. Nervenkr.*
Archives d'anatomie microscopique. Paris	*Arch. Anat. micr.*
Archives dermato-syphiligraphiques de la clinique de l'Hôpital Saint-Louis. Paris	*Arch. derm.-syph., Paris*
Archives internationales de physiologie. Liége et Paris	*Arch. int. Physiol.*
Archives italiennes de biologie. Pise	*Arch. ital. Biol.*
Archives of the Pathological Institute. (London Hospital)	*Arch. Path. Inst. Lond. Hosp.*
Archives of Pathology and Laboratory Medicine. Chicago	*Arch. Path. Lab. Med.*
Archives de zoologie expérimentale et générale. Paris	*Arch. Zool. exp. gén.*
Archivio zoologico (italiano). Napoli	*Arch. zool.* (*ital.*), *Napoli*
Arkiv för kemi, mineralogi och geologi. Uppsala	*Ark. Kemi Min. Geol.*
Arkiv för matematik, astronomi och fysik. Uppsala	*Ark. Mat. Astr. Fys.*
Arkiv för zoologi. Uppsala	*Ark. Zool.*
Astrophysical Journal (Univ. of Chicago). Chicago and N.Y.	*Astrophys. J.*
Beiträge zur Geophysik. Leipzig	*Beitr. Geophys.*
Beiträge zur Physik der freien Atmosphäre. Leipzig	*Beitr. Phys. frei. Atmos.*
Bericht der Deutschen Chemischen Gesellschaft. Berlin	*Ber. dtsch. chem. Ges.*
Bericht der Schweizerischen Botanischen Gesellschaft. Bern	*Ber. schweiz. bot. Ges.*
Biochemical Journal. Liverpool	*Biochem. J.*
Biochemische Zeitschrift. Berlin	*Biochem. Z.*
Biological Bulletin of the Marine Biological Laboratory. Woods Hole, Mass.	*Biol. Bull. Woods Hole*
Biological Reviews and Biological Proceedings of the Cambridge Philosophical Society	*Biol. Rev.*
Biologisches Zentralblatt. Leipzig	*Biol. Zbl.*
Biometrika. Cambridge	*Biometrika*
Botanical Gazette. Chicago	*Bot. Gaz.*
British Journal of Experimental Pathology. London	*Brit. J. Exp. Path.*
British Journal of Pharmacology	*Brit. J. Pharmacol.*
Bulletin de l'Académie R. de Belgique, Classe des sciences. Bruxelles	*Bull. Acad. Belg. Cl. Sci.*
Bulletin de l'Académie des sciences de l'U.R.S.S.	*Bull. Acad. Sci. U.R.S.S.*
Bulletin of the American Mathematical Society. Lancaster, Pa. and New York	*Bull. Amer. Math. Soc.*

FULL TITLE	ABBREVIATED TITLE
Bulletin de l'Association française pour l'étude du cancer. Paris	*Bull. Ass. franç. Cancer*
Bulletin of the Astronomical Institutes of the Netherlands	*Bull. astr. Insts Netherlds*
Bulletin biologique de la France et de la Belgique. Paris	*Bull. biol.*
Bulletin of the Calcutta Mathematical Society	*Bull. Calcutta Math. Soc.*
Bulletin of the Chemical Society of Japan. Tokyo	*Bull. Chem. Soc. Japan*
Bulletin of the Earthquake Research Institute, Tokyo Imperial University	*Bull. Earthq. Res. Inst. Tokyo*
Bulletin of the Geological Society of America. Rochester, N.Y.	*Bull. Geol. Soc. Amer.*
Bulletin d'histologie appliquée à la physiologie et à la pathologie et de technique microscopique. Paris	*Bull. Histol. Tech. micr.*
Bulletin de l'Institut astronomique. Leningrad	*Bull. Inst. astr., Leningr.*
Bulletin of the National Research Council. Washington	*Bull. Nat. Res. Coun., Wash.*
Bulletin et mémoires de la Société d'anthropologie de Paris	*Bull. Soc. Anthrop. Paris*
Bulletin de la Société de chimie biologique. Paris	*Bull. Soc. Chim. biol., Paris*
Bulletin. Société chimique de Belgique. Gand	*Bull. Soc. chim. Belg.*
Bulletin. Société chimique de France. Paris	*Bull. Soc. chim. Fr.*
Bulletin de la Société géologique de France. Paris	*Bull. Soc. géol. Fr.*
Bulletin de la Société Royale des sciences de Liége	*Bull. Soc. Sci. Liége*
Bulletin de la Société zoologique de France. Paris	*Bull. Soc. zool. Fr.*
Bureau of Standards Journal of Research. Washington	*Bur. Stand. J. Res., Wash.*
Canadian Journal of Mathematics. Toronto	*Canad. J. Math.*
Canadian Journal of Research. Ottawa	*Canad. J. Res.*
Cellule. Lierre	*Cellule*
Chemical Age. New York	*Chem. Age, N.Y.*
Chemical Reviews. New York	*Chem. Rev.*
Chemisches Zentralblatt. Berlin	*Chem. Zbl.*
Chemistry and Industry Review. London	*Chem. Ind. Rev.*
Commentarii mathematici Helvetici. Zürich	*Comment. math. helvet.*
Compositio Mathematica. Gröningen	*Compositio Math.*
Compte rendu de l'Académie des sciences de l'U.R.S.S.	*C.R. Acad. Sci. U.R.S.S.*
Compte rendu hebdomadaire des séances de l'Académie des sciences. Paris	*C.R. Acad. Sci., Paris*
Compte rendu hebdomadaire des séances et mémoires de la Société de biologie. Paris	*C.R. Soc. Biol., Paris*
Contributions to Embryology. (Publications of the Carnegie Institution.) Washington	*Contr. Embryol. Carneg. Instn*
Danmarks geologiske Undersøgelse. Kjøbenhavn	*Danm. geol. Unders.*
Dermatologische Zeitschrift	*Derm. Z.*
Deutsche medizinische Wochenschrift. Leipzig	*Dtsch. med. Wschr.*
Deutsche Zeitschrift für die gesamte gerichtliche Medizin. Berlin	*Dtsch. Z. ges. gerichtl. Med.*
Drapers' Company Research Memoirs. Biometric Series. London	*Drap. Co. Mem. Biom. Ser.*
Duke Mathematical Journal. Durham, D.C.	*Duke Math. J.*
Economic Geology. Lancaster, Pa.	*Econ. Geol.*
Elektrische Nachrichten-Technik. Berlin	*Elekt. Nachr.-Tech.*
Ergebnisse der Anatomie u. Entwicklungsgeschichte. Wiesbaden	*Ergebn. Anat. EntwGesch.*
Ergebnisse der exakten Naturwissenschaften. Berlin	*Ergebn. exakt. Naturw.*
Ergebnisse der Physiologie. Wiesbaden	*Ergebn. Physiol.*
Forschungsheft Verein Deutscher Ingenieure. Berlin	*Forschungsh. Ver. dtsch. Ing.*

FULL TITLE	*ABBREVIATED TITLE*
Fuel (in Science and Practice). London	*Fuel*
Fundamenta mathematicae. Warszawa	*Fundam. Math.*
Gazzetta chimica italiana. Roma	*Gazz. chim. ital.*
Genetica. 's Gravenhage	*Genetica*
Genetics. Princeton, N.J., Baltimore	*Genetics*
Geochimica et Cosmochimica Acta. London	*Geochim. Acta*
Geofysiske Publikationer. Kristiania (now Oslo)	*Geofys. Publ.*
Geografiska Annaler. (Svenska Sällskapet för Antropologi och Geografi.) Stockholm	*Geogr. Ann., Stockh.*
Geological Magazine. London	*Geol. Mag., Lond.*
Geophysical Memoirs. London	*Geophys. Mem.*
Gesammelte Abhandlungen zur Kenntniss der Kohle. Arbeiten des Kaiser-Wilhelm Instituts für Kohlenforschung in Mulheim-Ruhr. Berlin	*Gesamm. Abh. Kohle*
Göteborgs Kungl. vetenskaps- och vitterhetssamhälles handlingar	*Göteborg VetenskSamh. Handl.*
Handbuch der biologischen Arbeitsmethoden. Leipzig	*Handb. biol. ArbMeth.*
Helvetica chimica acta. Basel, Genf.	*Helv. chim. Acta*
Helvetica physica acta. Basileae	*Helv. phys. Acta*
Hereditas genetiskt arkiv. Lund	*Hereditas, Lund*
Heredity	*Heredity*
Hoppe-Seyler's Zeitschrift für physiologische Chemie. Strassburg	*Hoppe-Seyl. Z.*
Hospitalstidende. Kjøbenhavn	*Hospitalstidende*
Indian Journal of Physics. Calcutta	*Indian J. Phys.*
Industrial and Engineering Chemistry. Easton, Pa.	*Industr. Engng Chem.*
Ingenieur-Archiv. Berlin	*Ingen.-Arch.*
Internationale Revue der gesamten Hydrobiologie u. Hydrographie. Leipzig	*Int. Rev. Hydrobiol.*
Jahresbericht der Chemisch-technischen Reichsanstalt. Leipzig	*Jber. chem.-tech. Reichsanst., Lpz.*
Jahresbericht der Deutschen Matematikervereinigung. Leipzig	*Jber. dtsch. MatVer.*
Japanese Journal of Mathematics. Tokyo	*Jap. J. Math.*
Japanese Journal of Physics. Tokyo	*Jap. J. Phys.*
Japanese Journal of Zoology. Tokyo	*Jap. J. Zool.*
Jenaische Zeitschrift für Naturwissenschaft. Jena	*Jena. Z. Naturw.*
Johns Hopkins Hospital Bulletin. Baltimore	*Johns Hopk. Hosp. Bull.*
Journal of the Acoustical Society of America. Menasha, Wis.	*J. Acoust. Soc. Amer.*
Journal of Agricultural Research. Washington	*J. Agric. Res.*
Journal of Agricultural Science. Cambridge	*J. Agric. Sci.*
Journal of the American Chemical Society. Easton, Pa.	*J. Amer. Chem. Soc.*
Journal of the American Medical Association. Chicago	*J. Amer. Med. Ass.*
Journal of the American Society of Naval Engineers. Washington	*J. Amer. Soc. Nav. Engrs*
Journal de l'anatomie et de la physiologie normales et pathologiques de l'homme et des animaux. Paris	*J. Anat., Paris*
Journal of Anatomy (and Physiology). London	*J. Anat., Lond.*
Journal of Animal Ecology. Cambridge	*J. Anim. Ecol.*
Journal of Bacteriology. Baltimore	*J. Bact.*
Journal of Biological Chemistry. Baltimore	*J. Biol. Chem.*
Journal of Botany. London	*J. Bot., Lond.*
Journal of Cancer Research. Baltimore	*J. Cancer Res.*
Journal of Cellular and Comparative Physiology. Philadelphia	*J. Cell. Comp. Physiol.*
Journal of Chemical Physics. Lancaster, Pa.	*J. Chem. Phys.*

FULL TITLE	ABBREVIATED TITLE
Journal of the Chemical Society. London	*J. Chem. Soc.*
Journal de chimie physique (et Revue générale des colloïdes), électrochimie, thermochimie, radiochimie, mécanique chimique, stœchiométrie. Genève	*J. Chim. phys.*
Journal of Comparative Neurology (and Psychology). Philadelphia	*J. Comp. Neurol.*
Journal of Comparative Pathology and Therapeutics. Edinburgh, London	*J. Comp. Path.*
Journal of Dairy Science. Baltimore	*J. Dairy Sci.*
Journal de l'École polytechnique. Paris	*J. Éc. polyt. Paris*
Journal of Ecology. London	*J. Ecol.*
Journal of Experimental Biology. Cambridge	*J. Exp. Biol.*
Journal of Experimental Medicine. New York	*J. Exp. Med.*
Journal of Experimental Zoology. Philadelphia	*J. Exp. Zool.*
Journal of the Franklin Institute. Philadelphia	*J. Franklin Inst.*
Journal of General Chemistry. Moscow	*J. Gen. Chem., Moscow*
Journal of General Physiology. Baltimore	*J. Gen. Physiol.*
Journal of General Psychology. Worcester, Mass.	*J. Gen. Psychol.*
Journal of Genetics. Cambridge	*J. Genet.*
Journal of Geology. Chicago	*J. Geol.*
Journal of Helminthology. London	*J. Helminth.*
Journal of Heredity. Washington	*J. Hered.*
Journal of Immunology. Baltimore	*J. Immunol.*
Journal of Industrial and Engineering Chemistry. Easton, Pa.	*J. Industr. Engng Chem.*
Journal of Industrial Hygiene. New York	*J. Industr. Hyg.*
Journal of Infectious Diseases. Chicago	*J. Infect. Dis.*
Journal of the Institute of Metals. London	*J. Inst. Met.*
Journal of the Institution of Electrical Engineers. London	*J. Instn Elect. Engrs*
Journal of the Iron and Steel Institute. London	*J. Iron Steel Inst.*
Journal of the London Mathematical Society	*J. Lond. Math. Soc.*
Journal of the Marine Biological Association of the United Kingdom. Plymouth	*J. Mar. Biol. Ass. U.K.*
Journal de mathématiques pures et appliquées. Paris	*J. Math. pures appl.*
Journal of Morphology (and Physiology). Boston	*J. Morph.*
Journal of the Optical Society of America. Philadelphia	*J. Opt. Soc. Amer.*
Journal of Paleontology. Chicago	*J. Paleont.*
Journal of Parasitology. Urbana, Ill.	*J. Parasit.*
Journal of Pathology and Bacteriology. London	*J. Path. Bact.*
Journal of Pharmacology and Experimental Therapeutics. Baltimore	*J. Pharmacol.*
Journal of Physical Chemistry. Ithaca, N.Y.	*J. Phys. Chem.*
Journal de physiologie et de pathologie générale. Paris	*J. Physiol. Path. gén.*
Journal of Physiology. London and Cambridge	*J. Physiol.*
Journal de physique et le Radium. (Soc. franç. de physique.) Paris	*J. Phys. Radium*
Journal of Pomology (and Horticultural Science). Maidstone	*J. Pomol.*
Journal für praktische Chemie. Leipzig	*J. prakt. Chem.*
Journal für di reine und angewandte Mathematik. Berlin	*J. reine angew. Math.*
Journal of the Royal Aeronautical Society. London	*J. R. Aero. Soc.*
Journal of the Royal Anthropological Institute of Great Britain and Ireland. London	*J. R. Anthrop. Inst.*
Journal of the Royal Statistical Society. London	*J. R. Statist. Soc.*

FULL TITLE	ABBREVIATED TITLE
Journal of Scientific Instruments. London	*J. Sci. Instrum.*
Journal of Symbolic Logic. Menasha, Wis. & New York	*J. Symbolic Logic*
Journal of the Society of Chemical Industry. London	*J. Soc. Chem. Ind., Lond.*
Kitasato Archives of Experimental Medicine. Tokyo	*Kitasato Arch.*
Klinische Wochenschrift. Berlin	*Klin. Wschr.*
Kolloidzeitschrift. Dresden	*Kolloidzschr.*
Kongelige Danske Videnskabernes Selskabs Skrifter. Kjøbenhavn	*K. danske vidensk. Selsk. Skr.*
Kongliga Fysiografiska Sällskapets i Lund Förhandlingar. Lund	*K. fysiogr. Sällsk. Lund. Förh.*
Kongliga Svenska Vetenskapsakademiens Handlingar. Uppsala and Stockholm	*K. svenska VetenskAkad. Handl.*
Lancet. London	*Lancet*
Latvijas Biologijas Biedribas Raksti. Riga	*Latv. Biol. Biedr. Raksti*
Liebigs Annalen der Chemie. Leipzig	*Liebigs Ann.*
London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science. London	*Phil. Mag.*
Luftfahrtforschung. München	*Luftfahrtforsch.*
Matematicheskii Sbornik. Moscow	*Mat. Sborn.*
Mathematica Japonicae. Osaka	*Math. Japonicae*
Mathematical Gazette. London	*Math. Gaz.*
Mathematische Annalen. Leipzig	*Math. Ann.*
Mathematische Zeitschrift. Berlin	*Math. Z.*
Mathematisk-fysiske Meddelelser. Kgl. Danske Videnskabernes Selskab. Kjøbenhavn	*Math.-fys. Medd.*
Mémoires de la Société zoologique de France (to 1932)	*Mém. Soc. zool. Fr.*
Memoirs of the Geological Survey of the United Kingdom. London	*Mem. Geol. Surv. U.K.*
Memoirs and Proceedings of the Manchester Literary and Philosophical Society	*Mem. Manchr Lit. Phil. Soc.*
Memoirs of the Royal Meterological Society. London	*Mem. R. Met. Soc.*
Metallurgia. Manchester	*Metallurgia, Manchr*
Meteorologische Zeitschrift. Braunschweig	*Met. Z.*
Mineralogical Magazine. London	*Miner. Mag.*
Mining and Metallurgy. New York	*Min. & Metall.*
Minutes of Proceedings of the Institution of Civil Engineers. London	*Min. Proc. Instn Civ. Engrs*
Monthly Notices of the Royal Astronomical Society. London	*Mon. Not. R. Astr. Soc.*
Monthly Notices of the Royal Astronomical Society. Geophysical Suppl. London	*Mon. Not. R. Astr. Soc. Geophys. Suppl.*
Münchener medizinische Wochenschrift	*Münch. Med. Wschr.*
Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen. Math.-phys. Kl. Berlin	*Nachr. Ges. Wiss. Göttingen*
Nature, London	*Nature, Lond.*
Naturwissenschaften. Berlin	*Naturwissenschaften*
New Phytologist. Cambridge	*New Phytol.*
Norsk geologisk Tidsskrift. Kristiania (now Oslo)	*Norsk. geol. Tidsskr.*
Nova Acta Regiae Societatis scientiarum Upsaliensis. Upsaliae	*Nova Acta Soc. Sci. upsal.*
Nuovo cimento. Pisa	*Nuovo Cim.*
Observatory. London	*Observatory*
Onde électrique. Paris	*Onde élect.*
Organic Syntheses. New York	*Organic Synth.*
Österreichische Chemikerzeitung u. Zeitschr. f. Nahrungsmitteluntersuchung, Hygiene u. Warenkunde. Wien	*Öst. ChemZtg*

FULL TITLE	*ABBREVIATED TITLE*
Papers in Physical Oceanography. Cambridge, Mass.	*Pap. Phys. Oceanogr.*
Parasitology. Cambridge	*Parasitology*
Pflügers Archiv für die gesamte Physiologie d. Menschen u. d. Tiere. Bonn	*Pflüg. Arch. ges. Physiol.*
Pharmaceutisch weekblad voor Nederland. Amsterdam	*Pharm. Weekbl.*
Philosophical Transactions of the Royal Society. London	*Phil. Trans.* (A or B)
Physica (from 1934)	*Physica*
Physica. 's Gravenhage (up to 1934)	*Physica, 's Grav.*
Physica. Nederlandsch tijdschrift voor natuurkunde. Eindhoven (up to 1934)	*Physica, Eindhoven*
Physical Review. Cornell University. Ithaca, N.Y., Lancaster, Pa.	*Phys. Rev.*
Physics. Minneapolis	*Physics*
Physikalische Zeitschrift. Leipzig	*Phys. Z.*
Physikalische Zeitschrift der Sowjetunion. Charkow	*Phys. Z. Sowjet.*
Physiological Reviews. Baltimore, Md.	*Physiol. Rev.*
Phytopathology. American Phytopathology Society, Ithaca	*Phytopathology*
Plant Physiology. Lancaster, Pa.	*Plant Physiol.*
Portugaliae Mathematica. Lisbon	*Portugaliae Math.*
Proceedings of the American Mathematical Society. Menasha, Wis. and New York	*Proc. Amer. Math. Soc.*
Proceedings of the American Society for Testing Materials. Philadelphia	*Proc. Amer. Soc. Test. Mater.*
Proceedings of the Cambridge Philosophical Society	*Proc. Camb. Phil. Soc.*
Proceedings of the Edinburgh Mathematical Society	*Proc. Edinb. Math. Soc.*
Proceedings of the General Meetings for Scientific Business of the Zoological Society of London	*Proc. Zool. Soc. Lond.*
Proceedings of the Geologists Association, London	*Proc. Geol. Ass., Lond.*
Proceedings of the Imperial Academy (of Japan). Tokyo	*Proc. Imp. Acad. Japan*
Proceedings of the Indiana Academy of Science. Brookville	*Proc. Ind. Acad. Sci.*
Proceedings of the Institution of Mechanical Engineers. London	*Proc. Instn Mech. Engrs, Lond.*
Proceedings of the London Mathematical Society	*Proc. Lond. Math. Soc.*
Proceedings of the National Academy of Sciences. Washington	*Proc. Nat. Acad. Sci., Wash.*
Proceedings of the Physical Society of London	*Proc. Phys. Soc. Lond.*
Proceedings of the Royal Academy of Sciences. Amsterdam	*Proc. Acad. Sci. Amst.*
Proceedings of the Royal Entomological Society of London	*Proc. R. Ent. Soc. Lond.*
Proceedings of the Royal Irish Academy. Dublin	*Proc. R. Irish Acad.*
Proceedings of the Royal Society of Edinburgh	*Proc. Roy. Soc. Edinb.*
Proceedings of the Royal Society. London	*Proc. Roy. Soc.* (A or B)
Proceedings of the Society for Experimental Biology and Medicine. New York	*Proc. Soc. Exp. Biol., N.Y.*
Quarterly Journal of the Geological Society of London	*Quart. J. Geol. Soc. Lond.*
Quarterly Journal of Mathematics. Oxford series	*Quart. J. Math.*
Quarterly Journal of Microscopical Science. London	*Quart. J. Micr. Sci.*
Quarterly Journal of the Royal Meteorological Society. London	*Quart. J. R. Met. Soc.*
Rapport et procès-verbaux des réunions. (Conseil permanent international pour l'exploration de la mer.) Copenhague	*Rapp. Cons. Explor. Mer*

FULL TITLE	*ABBREVIATED TITLE*
Recueil des travaux chimiques des Pays-Bas et de la Belgique. Leyde	*Rec. Trav. chim. Pays-Bas*
Rendiconti del Circolo matematico di Palermo	*R.C. Circ. mat. Palermo*
Report of the British Association for the Advancement of Science. London	*Rep. Brit. Ass.*
Reports on Progress in Physics. London (Physical Society)	*Rep. Progr. Phys.*
Research Bulletin. Missouri Agricultural Experiment Station. Columbia	*Res. Bull. Mo. Agric. Exp. Sta.*
Reviews of Modern Physics. Minneapolis	*Rev. Mod. Phys.*
Revue belge des sciences médicales. Bruxelles	*Rev. belg. Sci. méd.*
Revue du médecin. Paris	*Rev. Médecin*
Revue de métallurgie. (*a*) Mémoires. (*b*) Extraits. Paris	*Rev. Métall.*
Revue scientifique. (Revue rose.) Paris	*Rev. sci., Paris*
Science. New York	*Science*
Science Progress in the Twentieth Century. London	*Sci. Progr. Twent. Cent.*
Science Reports of the Tôhoku Imp. University. Sendai	*Sci. Rep. Tôhoku Univ.* (*a*), (*b*), (*c*) or (*d*)
Scientific Papers of the Institute of Physical and Chemical Research. Tokyo	*Sci. Pap. Inst. Phys. Chem. Res., Tokyo*
Scientific Papers of the U.S. Bureau of Standards. Washington	*Sci. Pap. U.S. Bur. Stand.*
Senckenbergiana. (Senckenbergische Naturforschende Gesellschaft.) Frankfurt a. M.	*Senckenbergiana*
Sitzungsberichte der Kais. Akademie der Wissenschaften in Wien. Math.-Naturwiss. Kl.	*S.B. Akad. Wiss. Wien* (Abt. I, IIa, IIb or III)
Sitzungsberichte der Kgl. Bayerischen Akademie der Wissenschaften zu München. Math.-phys. Kl.	*S.B. bayer. Akad. Wiss.*
Sitzungsberichte der Kgl. Preussischen Akademie der Wissenschaften zu Berlin	*S.B. preuss. Akad. Wiss.*
Smithsonian Miscellaneous Collections	*Smithson. Misc. Coll.*
Spectrochimica Acta. London	*Spectrochim. Acta*
Stahl und Eisen. Düsseldorf	*Stahl. u. Eisen, Düsseldorf*
Sveriges geologiska Undersökning. Afhandlingar och Uppsatser. Stockholm	*Sverig. geol. Unders. Afh.*
Technical Bulletin. U.S. Department of Agriculture. Washington, D.C.	*Tech. Bull. U.S. Dep. Agric.*
Terrestrial Magnetism and Atmospheric Electricity. Baltimore	*Terr. Magn. Atmos. Elect.*
Trabajos del Laboratorio de investigaciones biológicas de la Universidad de Madrid	*Trab. Lab. Invest. biol. Univ. Madr.*
Transactions. American Geophysical Union. Washington	*Trans. Amer. Geophys. Un.*
Transactions of the American Institute of Mining (and Metallurgical) Engineers. New York	*Trans. Amer. Inst. Min. (Metall.) Engrs*
Transactions of the American Mathematical Society. Lancaster, New York	*Trans. Amer. Math. Soc.*
Transactions of the American Society of Mechanical Engineers. New York	*Trans. Amer. Soc. Mech. Engrs*
Transactions of the British Mycological Society. Worcester	*Trans. Brit. Mycol. Soc.*
Transactions of the Cambridge Philosophical Society	*Trans. Camb. Phil. Soc.*
Transactions of the Electrochemical Society. New York	*Trans. Electrochem. Soc.*
Transactions of the Faraday Society. London	*Trans. Faraday Soc.*
Transactions of the Geological Society of Glasgow	*Trans. Geol. Soc. Glasg.*

FULL TITLE	*ABBREVIATED TITLE*
Transactions of the North-East Coast Institution of Engineers and Shipbuilders. London	*Trans. N.-E. Cst Instn Engrs Shipb.*
Transactions of the Royal Society of Canada. Ottawa	*Trans. Roy. Soc. Can.*
Transactions of the Royal Society of Edinburgh	*Trans. Roy. Soc. Edinb.*
Verhandlungen der Anatomischen Gesellschaft. Jena	*Verh. anat. Ges. Jena*
Verhandlungen der Naturforschenden Gesellschaft in Basel	*Verh. naturf. Ges. Basel*
Veterinary Journal. London	*Vet. J.*
Wiener klinische Wochenschrift	*Wien. klin. Wschr.*
Wireless Engineer and Experimental Wireless. London	*Wireless Engr*
Wissenschaftliche Meeresuntersuchungen der Kommission zur wissenschaftlichen Untersuchung der deutschen Meere	*Wiss. Meeresuntersuch.*
Wissenschaftliche Veröffentlichungen aus d. Siemens-Konzern. Berlin	*Wiss. Veröff. Siemens-Konz.*
Zeitschrift für analytische Chemie. Wiesbaden	*Z. anal. Chem.*
Zeitschrift für angewandte Anatomie und Konstitutionslehre. Berlin	*Z. angew. Anat.*
Zeitschrift für angewandte Mathematik und Mechanik. Berlin	*Z. angew. Math. Mech.*
Zeitschrift für anorganische (und allgemeine) Chemie. Hamburg und Leipzig	*Z. anorg. Chem.*
Zeitschrift für Biologie. München & Berlin	*Z. Biol.*
Zeitschrift für Elektrochemie (u. angewandte physikalische Chemie). Halle	*Z. Elektrochem.*
Zeitschrift für Geophysik. Braunschweig	*Z. Geophys.*
Zeitschrift für die gesamte Neurologie und Psychiatrie. Berlin	*Z. ges. Neurol. Psychiat.*
Zeitschrift für des gesamte Schiess- u. Sprengstoffwesen. München	*Z. ges. Schiess- u. Sprengstoffw.*
Zeitschrift für Immunitätsforschung und experimentelle Therapie. Jena	*Z. ImmunForsch.*
Zeitschrift für induktive Abstammungs- u. Vererbungslehre. Berlin	*Z. indukt. Abstamm.- u. VererbLehre*
Zeitschrift für Kristallographie (und Mineralogie). Leipzig	*Z. Kristallogr.*
Zeitschrift für Metallkunde. Berlin	*Z. Metallk.*
Zeitschrift für mikroskopisch-anatomische Forschung. Leipzig	*Z. mikr.-anat. Forsch.*
Zeitschrift für Morphologie und Anthropologie. Stuttgart	*Z. Morph. Anthr.*
Zeitschrift für Physik. Braunschweig	*Z. Phys.*
Zeitschrift für physikalische Chemie, Stöchiometrie und Verwandstschaftslehre. Leipzig	*Z. phys. Chem.*
Zeitschrift für technische Physik. Leipzig	*Z. tech. Phys.*
Zeitschrift des Vereins Deutscher Ingenieure. Berlin	*Z. ver. dtsch. Ing.*
Zeitschrift für vergleichende Physiologie. Berlin	*Z. vergl. Physiol.*
Zeitschrift für wissenschaftliche Zoologie. Leipzig	*Z. wiss. Zool.*
Zeitschrift für Zellforschung und Mikroskopische Anatomie. Berlin	*Z. Zellforsch.*
Zentralblatt für Bakteriologie, Parasitenkunde u. Infektionskrankheiten. Jena	*Zbl. Bakt.*
Zoologische Jahrbücher. Jena	*Zool. Jb.* (Abt. 1, 2 or 3)
Zoologischer Anzeiger. Leipzig	*Zool. Anz.*
Zoologischer Jahresbericht. Hrsg. v. d. Zoolog. Station zu Neapel. Berlin	*Zool. Jber.*

PRINTERS' AND AUTHORS' PROOF CORRECTIONS

As many authors may not be aware that there exists a standard method of correcting proofs, published as British Standard 1219 : 1945, it is thought that they would appreciate having in this pamphlet a restatement of the main sections of the British Standard which will enable them to correct their proofs in the best and most readily understood way.

The following extracts from B.S. 1219 : 1945, *Printers' and authors' proof corrections*, are given by permission of the British Standards Institution, 24–28 Victoria Street, London, S.W. 1, from whom official copies of the Standard can be obtained, price 2*s.* 6*d.*

Symbols for correcting proofs

Wherever possible all corrections should be made in the margin; only such marks being made in the text as are required to indicate the place to which the correction refers.

When three or more corrections occur in one line, the corrections should be divided between the left and right margins, the order being always from left to right.

When an alteration is desired in a letter, word or words, the existing letter, etc., should be struck through and the letter or matter to be substituted should be written in the margin, followed by /.

(Words printed in italics in the marginal mark column below are instructions and not part of the marks.)

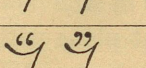
no.	marginal mark	meaning	corresponding mark in text
1	/	sign to show that marginal mark is concluded	
2	d/	delete (take out)	/
3	d/	delete and close-up	d above and below letters to be taken out
4	#	delete and leave space	/
5	stet	leave as printed	..... under letters or words to remain
6	caps	change to capital letters	═══ under letters or words to be altered
7	s.c.	change to small capitals	═══ under letters or words to be altered

no.	marginal mark	meaning	corresponding mark in text
8	caps & s.c.	use capital letters for initial letters and small capitals for rest of words	≡ under initial letters and = under the rest of the words
9	l.c.	change to lower-case	encircle letters to be altered
10	bold or clar	change to bold type	~~~ under letters or words to be altered
11	ital	change to italics	— under letters or words to be altered
12	insert rule	underline word or words	— under words affected
13	rom	change to roman type	encircle words to be altered
14	w.f.	(wrong fount) replace by letter of correct fount	encircle letter to be altered
15	ꝺ	invert type	encircle letter to be altered
16	X	replace by similar but undamaged character	encircle letter to be altered
17	⸝	substituted letters or signs under which this is placed to be 'superior'	encircle letters or signs to be altered
18	⸝	inserted letters or signs under which this is placed to be 'superior'	⸝
19	⸌	substituted letters or signs over which this is placed to be 'inferior'	encircle letters or signs to be altered
20	⸌	inserted letters or signs over which this is placed to be 'inferior'	⸌
21	⁀ *enclosing ligature or diphthong required*	use ligature (e.g., ffi) or diphthong (e.g., œ)	⁀ enclosing letters to be altered
22	*write out separate letters followed by* /	substitute separate letters for ligature or diphthong	/ through ligature or diphthong to be altered
23	⁀	close-up—delete space between letters	⁀ linking words or letters
24	#	insert space	⸌
25	# >	space between lines or paragraphs*	

* Amount of space may be indicated.

no.	marginal mark	meaning	corresponding mark in text
26	eq #	make spacing equal	between words
27	less #	reduce space	between words
28	trs.	transpose	between letters or words, numbered when necessary
29	centre	place in centre of line	indicate position with ⌜ ⌝
30	□/	indent one em	
31	□□/	indent two ems	
32	⌜	move to the left	
33	⌝	move to the right	
34	⌜	move lines to right	at left side of group to be moved
35	⌝	move lines to left	at right side of group to be moved
36	[ ]	move portion of matter so that it comes within the position indicated	[ ] at limits of required position
37	take over	take letter or word from end of one line to beginning of next	
38	take back	take letter or word from beginning of one line to end of preceding line	
39	↑	raise lines	over lines to be moved
40	↓	lower lines	under lines to be moved
41	‖	correct the vertical alinement	
42	=	straighten lines	through lines to be straightened
43	⊥	push down space	encircle space affected

no.	marginal mark	meaning	corresponding mark in text
44	n.p.	begin a new paragraph	before first word of new paragraph
45	run on	no fresh paragraph here	between paragraphs
46	spell out	the abbreviation or figure to be spelt out in full	encircle words or figures to be altered
47	out see copy	insert omitted portion of copy NOTE. The relevant section of the copy should be returned with the proof, the omitted portion being clearly indicated	ʎ
48	ʎ	(caret mark) insert matter indicated in margin	ʎ
49	,ʎ	insert comma	ʎ
50	,/	substitute comma	/
51	;ʎ	insert semi-colon	ʎ
52	;/	substitute semi-colon	/
53	⊙	insert full-stop	ʎ
54	⊙	substitute full-stop	/
55	⊙	insert colon	ʎ
56	⊙	substitute colon	/
57	?ʎ	insert interrogation mark	ʎ
58	?/	substitute interrogation mark	/
59	!ʎ	insert exclamation mark	ʎ
60	!/	substitute exclamation mark	/
61	(/)	insert parentheses	ʎ ʎ
62	[/]	insert (square) brackets	ʎ ʎ

no.	marginal mark	meaning	corresponding mark in text
63		insert hyphen	
64		insert en (half-em) rule	
65		insert one-em rule	
66		insert two-em rule	
67		insert apostrophe	
68		insert single quotation marks	
69		insert double quotation marks	
70		insert ellipsis	
71		insert leader	
72		insert shilling stroke	
73		refer to appropriate authority anything the accuracy or suitability of which is doubted	encircle words, etc., affected

NOTE. When fresh matter not in copy is to be inserted, the caret mark is to be used in the text and 'Take in A' (B, C, etc., as the case may be) written in the margin, the additional matter, whether written on the proof, or on attached slips, being lettered to correspond. In the case of large insertions, a horizontal arrow in the margin pointing between the lines replaces the caret mark.

PAGE PREPARED TO SHOW NUMEROUS CORRECTIONS

8. HAMILTON'S PRINCIPAL FUNCTION

It is the purpose of this section to examine the non-holonomic principal function in more detail. A definition of **S** as the limit of principal functions of tangential holonomic systems will be given, and finally we will consider from a different viewpoint how and why the non-integrability arises.

Equation (7·28) shows clearly the difference between a non-holonomic principal function $\mathbf{S}(q)$, and a holonomic one $S(q)$. The latter takes a definite value at each point of q space, but the change in value of $S(q)$ between two points in q space depends on the path taken. This result is a very natural one to expect since for a non-holonomic system there are always at least two co-ordinates for which successive variations lead to different final configurations depending on the order in which the variations are made. For example consider a sphere rolling on a flat plane with (x, y) the co-ordinates of its centre. A variation $\delta x . \delta y$ does not have the same result as a variation $\delta y . \delta x$.

The non-holonomic principal function $\mathbf{S}(q)$ will now be defined for a region $\tau > \tau_0$. Let the system have a configuration given by $q^{(0)}$ at $\tau = \tau_0$, and let the constrained momenta then be $p^{(0)}$. Let $S(a, q)$ be a solution of the Hamilton-Jacobi equation for the corresponding free system

$$\Omega\left(q, \frac{\partial S(a,q)}{\partial q}\right) = 0. \tag{8·1}$$

Choose initial conditions of this free system so that it passes through $q^{(0)}$ at $\tau = \tau_0$ with momenta $p = p^{(0)}$. Let the corresponding principal function be $S_0(a^{(0)}, q)$. If the actual value of $\mathbf{S}(q^{(0)})$ has been prescribed it can be arranged that $S_0(a^{(0)}, q^{(0)})$ also takes the same value.

Then
$$p_r^* = p_r^{(0)} = \frac{\partial S_0(a^{(0)}, q)}{\partial q_r} \quad \text{at } q = q^{(0)}. \tag{8·2}$$

Define $S^{(0)}(q) = S_0(a^{(0)}, q)$ for $\tau_0 < \tau < \tau_1$, where $\tau_1 - \tau_0 = \epsilon$, and ϵ is small. In this range

$$\dot{q}_r^* \doteqdot \lambda \frac{\partial \Omega}{\partial p_r}\left(q, \frac{\partial S^{(0)}(q)}{\partial q}\right). \tag{8·3}$$

This approximate equality becomes exact at $q = q^{(0)}$, and gives $\dot{q}_r^{(0)}$. From the theory of §5, the constrained momentum p_r^* may be expressed as a function of the locally free co-ordinates and momenta $p_r^* q, p$. Hence $\dot{p}_r^*$ may be obtained from

$$p_r^*\left(q, \frac{\partial S^{(0)}(q)}{\partial q}\right).$$

This rate of change is exact at $q = q^{(0)}$ denote it there by $\dot{p}_r^{*(0)}$. Now define

$$q_r^{(1)} = q_r^{(0)} + \epsilon \dot{q}_r^{(0)},$$
$$p_r^{(1)} = p_r^{(0)} + \epsilon \dot{p}_r^{*(0)}. \tag{8·4}$$

It is now possible to define a principal function of the free system $S_1(a^{(1)}/q)$ which has

$$p_r^{(1)} = \frac{\partial S_1(a^{(1)}, q)}{\partial q_r} \quad \text{at } q = q^{(1)}. \tag{8·5}$$

8. HAMILTON'S PRINCIPAL FUNCTION

It is the purpose of this section to examine the non-holonomic principal function in more detail. A definition of **S** as the limit of principal functions of tangential holonomic systems will be given, and finally we will consider from a different viewpoint how and why the non-integrability arises.

Equation (7·28) shows clearly the difference between a non-holonomic principal function $\mathbf{S}(q)$, and a holonomic one $S(q)$. The latter takes a definite value at each point of q space, but the change in value of $\mathbf{S}(q)$ between two points in q space depends on the path taken. This result is a very natural one to expect, since for a non-holonomic system there are always at least two co-ordinates for which successive variations lead to different final configurations depending on the order in which the variations are made. For example consider a sphere rolling on a flat plane with (x, y) the co-ordinates of its centre. A variation $\delta x . \delta y$ does not have the same result as a variation $\delta y . \delta x$.

The non-holonomic principal function $\mathbf{S}(q)$ will now be defined for a region $\tau > \tau_0$. Let the system have a configuration given by $q^{(0)}$ at $\tau = \tau_0$, and let the constrained momenta then be $p^{(0)}$. Let $S(a, q)$ be a solution of the Hamilton-Jacobi equation for the corresponding free system

$$\Omega\left(q, \frac{\partial S(a,q)}{\partial q}\right) = 0. \tag{8·1}$$

Choose initial conditions of this free system so that it passes through $q^{(0)}$ at $\tau = \tau_0$, with momenta $p = p^{(0)}$. Let the corresponding principal function be $S_0(a^{(0)}, q)$. If the actual value of $\mathbf{S}(q^{(0)})$ has been prescribed it can be arranged that $S_0(a^{(0)}, q^{(0)})$ also takes the same value. Then

$$p_r^* = p_r^{(0)} = \frac{\partial S_0(a^{(0)}, q)}{\partial q_r} \quad \text{at } q = q^{(0)}. \tag{8·2}$$

Define $S^{(0)}(q) = S_0(a^{(0)}, q)$ for $\tau_0 < \tau < \tau_1$, where $\tau_1 - \tau_0 = \epsilon$, and ϵ is small. In this range

$$\dot{q}_r^* \doteqdot \lambda \frac{\partial \Omega}{\partial p_r}\left(q, \frac{\partial S^{(0)}(q)}{\partial q}\right). \tag{8·3}$$

This approximate equality becomes exact at $q = q^{(0)}$, and gives $\dot{q}_r^{(0)}$. From the theory of § 5, the constrained momentum p_r^* may be expressed as a function of the locally free co-ordinates and momenta $p_r^*(q, p)$. Hence $\dot{p}_r^*$ may be obtained from

$$p_r^*\left(q, \frac{\partial S^{(0)}(q)}{\partial q}\right).$$

This rate of change is exact at $q = q^{(0)}$; denote it there by $\dot{p}_r^{*(0)}$. Now define

$$\begin{aligned} q_r^{(1)} &= q_r^{(0)} + \epsilon \dot{q}_r^{(0)}, \\ p_r^{(1)} &= p_r^{(0)} + \epsilon \dot{p}_r^{*(0)}. \end{aligned} \tag{8·4}$$

It is now possible to define a principal function of the free system $S_1(a^{(1)}, q)$ which has

$$p_r^{(1)} = \frac{\partial S_1(a^{(1)}, q)}{\partial q_r} \quad \text{at } q = q^{(1)}. \tag{8·5}$$

SYMBOLS, SIGNS AND ABBREVIATIONS

RECOMMENDED FOR BRITISH SCIENTIFIC PUBLICATIONS

A REPORT

BY

THE SYMBOLS COMMITTEE OF THE ROYAL SOCIETY

REPRESENTING

THE ROYAL SOCIETY
THE CHEMICAL SOCIETY
THE FARADAY SOCIETY
THE PHYSICAL SOCIETY

1951

Superseding the Report of the Joint Committee of the Chemical Society, the Faraday Society and the Physical Society on 'Symbols for Thermodynamical and Physico-Chemical Quantities and Conventions relating to their Use', issued in 1937

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INTRODUCTION

In 1937 a joint committee of the Chemical Society, the Faraday Society and the Physical Society issued a *Report on Symbols for Thermodynamical and Physico-Chemical Quantities and Conventions relating to their Use* (CFP, 1937). A few minor amendments were made at the instance of the Royal Society, and the *Report* was then adopted as the basis of practice in the publications of the four Societies and of a number of other British publishing bodies, including the Bureau of Abstracts. The recommendations in the *Report* were given further publicity in the following year when they were embodied (with additional recommendations on abbreviations) by the British Standards Institution in British Standard *Chemical Symbols and Abbreviations* (B.S. 813–1938).

In the preparation of CFP, 1937, attention was given to usages adopted by authors of well-known text-books, as well as to recommendations in earlier reports of other bodies dealing with symbols, including the International Conference on Physics, 1934, the Informal International Conference on Letter Symbols for Heat and Thermodynamics, 1936, and, as regards electrical quantities, the International Electrotechnical Commission. In submitting the *Report*, the joint committee drew special attention to the fact that, although recommendations on the use of physico-chemical symbols had been put forward in the past by a number of bodies, these bodies had nearly always been representative of either physicists or chemists, and not, as in that instance, of both. It was recognized that this constituted an important advance, for by bringing physicists and chemists together many differences had been readily adjusted and a wide measure of agreement attained over the whole of their combined fields of interest.

In order that the advantages of this co-operation should not be lost, the Royal Society set up in 1938 a standing committee on Symbols (R.S. Symbols Committee), on which the Chemical Society, the Faraday Society and the Physical Society are represented, to consider from time to time any directions in which CFP, 1937, should be revised. In accordance with this undertaking the Royal Society Symbols Committee has drafted the present Report (RCFP, 1951), which has since been adopted by the four Societies concerned as superseding CFP, 1937, and is now put forward as recommended practice in British scientific publications.

Since the war the correlation of the views of physicists and chemists on the use of symbols has been carried further at international level. At the Conference of the International Union of Chemistry in London in 1947, its Commission on Physico-Chemical Symbols and Co-ordination of Scientific Terminologies (P.C.S. Commission) accepted most of the general principles enunciated in CFP, 1937, and adopted, at least as acceptable alternatives, a majority of the symbols recommended for individual quantities; the conclusions of the Commission were published in the *Report* of the Conference (IUC, 1947). At its meetings in London the Commission had the

benefit of the advice of representatives of the Symbols, Units and Nomenclature Commission (S.U.N. Commission) of the International Union of Pure and Applied Physics, who were present by invitation. At the Conference of this latter Union in Amsterdam in 1948, the S.U.N. Commission took cognizance of relevant recommendations in recent reports of national and international bodies, including IUC, 1947. Its own *Report* (IUPAP, 1948) covered much common ground, but naturally extended further into the field of pure and applied physics. In the following year a Conference of the International Union of Pure and Applied Chemistry (which had then reverted to this earlier title) was held in Amsterdam, when its P.C.S. Commission revised IUC, 1947, with special regard to securing the widest measure of agreement with IUPAP, 1948. In the resulting *Report* (IUPAC, 1949) the recommendations in IUC, 1947, and IUPAP, 1948, were almost completely reconciled and co-ordinated, and recommendations in the latter referring to symbols for quantities mainly of interest to physicists were incorporated so as to provide in one *Report* the agreed conclusions of chemists and physicists.

In preparing the present *Report* (RCFP, 1951) the R.S. Symbols Committee has given special attention to the recommendations of these International Commissions and has not departed from them, except, in certain instances, by selecting from alternative symbols for a quantity the one which is most in accord with British usage and, in a few cases, by introducing other alternatives to avoid clashes with symbols for different quantities that may appear in the same equations. Such deviations from the international recommendations have thus been essentially in points of detail and have not arisen from any disagreement on matters of general principle.

In the course of its work, the R.S. Symbols Committee has also maintained close touch with the British Standards Institution, whose Technical Sub-Committee, OC/22/1, has been concurrently engaged in the revision and co-ordination of the existing British Standards *Engineering Symbols and Abbreviations* (B.S. 560–1934) and *Chemical Symbols and Abbreviations* (B.S. 813–1938). In so far as this leads to widening the scope of agreement between physicists and chemists to meet the needs of engineers—at least in respect of symbols for the more fundamental quantities of common interest—a further important step will have been taken towards removing differences of usage in the various branches of pure and applied science and thus providing a firm basis on which to develop consistent practice in more specialized fields.

RECOMMENDATIONS

I. GENERAL PRINCIPLES

(*a*) Alphabets and Founts

In order to make the best use of the limited number of readily available alphabets and founts, it is strongly recommended that the undermentioned principles, already generally approved at international level, should be adopted and strictly followed.

A clear distinction is to be drawn between:

(1) **Symbols for physical quantities** (*see* Schedule A, 1–10):

These normally consist of single letters of the Latin or the Greek alphabet (sometimes with subscripts or other modifying signs—*see* Schedule B) which are used to represent the quantities concerned, especially in equations showing relationships between them. For a particular quantity the same symbol is to be used irrespective of the units in which it is expressed.

Where letters of the Latin alphabet (capitals or lower case) are used for this purpose, they are to be printed in *italic* (sloping) type, except that for vector quantities the customary heavy-faced sans serif type may be used (*see* Schedule A, 9), and where so used for one such quantity must be employed consistently for others in the same discussion. A further permissive variation is the use of bold italic type for certain general constants (*see* Schedule A, 1); if this variation is adopted it should also be applied consistently.

(2) **Other symbols and abbreviations**, including:

(i) those denoting mathematical operations and constants (*see* Schedule C);
(ii) symbols for the chemical elements;
(iii) abbreviations for words (*see* Schedules D and E), including abbreviations (symbols) for the names of units (Schedule D).

Where letters of the Latin alphabet (capitals or lower case) are used for any of these purposes, they are to be printed in roman (upright) type.

It is not suggested that where Greek letters are involved any attempt should be made to use a sloping fount for symbols for physical quantities and an upright fount for other symbols and abbreviations, though this differentiation has been made for capital letters in the schedules to indicate the possibilities of this refinement. It is useful, however, to use bold Greek letters for certain specified general constants wherever the practice of printing letters of the Latin alphabet for these quantities in bold italic type is adopted (*see* Schedule A, 1).

By making the broad distinction between symbols for physical quantities—to be

printed in a sloping fount of type—and other symbols and abbreviations—to be printed in an upright fount of type—at least in so far as letters of the Latin alphabet (including capital letters) are concerned, the pressure on certain overworked letters is notably relieved. A further relief is secured if bold type (italic or Greek) is employed for symbols for general constants; this has the additional advantage of causing these symbols to stand out against those for variables in equations. Thus, e can be used to denote the base of natural logarithms (a purely mathematical constant—Schedule C), and ***e*** to represent the magnitude of the charge of the electron (a physical constant —Schedule A, 1), leaving *e* for physical variables. Similarly, the use of d to denote the operation of differentiation (Schedule C) leaves *d* available for physical quantities such as 'diameter', 'relative density' or 'current density at an electrode', but in this particular instance the alternative *d* is to be regarded as permissive. Again, demands on *E* for several physical quantities, of which more than one may occur in a single equation, can be partly relieved by adopting **E** for electric force or field strength.

Nevertheless, even with these provisions for the use of different founts, the number of distinctive letter symbols available for physical quantities is insufficient to enable each such symbol to be allotted to a single quantity, and alternatives are therefore required in some instances. Such alternatives are given in the schedules where a need for them is most likely to arise or, in a few cases, where alternative usages are firmly established and unobjectionable. **Where two or more symbols separated by commas are given for a quantity, these symbols are to be regarded as alternatives for which no preference is expressed; where they are separated by a dotted line, the former is the first preference.** Where it is necessary to select from alternative symbols for a quantity, or to adopt a symbol for a quantity not listed, consideration should be given to current practice by authorities in the field and to the desirability that **symbols for quantities constituting a well-defined class should, if possible, belong to the same alphabet, fount and case.** The selected symbols should be such as to permit of modification in accordance with a uniform scheme for the representation of any important series of corresponding derived quantities.

Abbreviations for words, including abbreviations (symbols) for the names of units, may be used in the text of papers and, in so far as they represent words that vary from one language to another (*see* Schedule E), they are not susceptible to international agreement. Moreover, although it is desirable to secure as wide a measure of agreement as may be readily achieved in English-speaking countries on abbreviations for words in common scientific use, failure to achieve such agreement in respect of individual words should not be regarded as so serious a matter as any disagreement on symbols for physical quantities. It is more important, however, to get agreement on **abbreviations (or symbols) representing the names of internationally accepted units** (*see* Schedule D, 1). These may consist of single letters (such as V for volt), or of several letters (such as kWh for kilowatt-hour), and **are used following (or preceding) a number** (e.g. 1·236 V; pH 5·3) **and never as symbols for the corresponding physical quantities in equations.** A single-letter abbreviation for the name of a unit which is identical with or derived from a personal name should always be a capital letter (*see also* below).

(*b*) Other General Principles

Mathematical Usages. There should be no departure from the standard practice of mathematicians in the use of signs, operator symbols, etc. (*see* Schedule C). Numbers should be printed in upright figures. A decimal point should be used to separate whole numbers from the decimals. To facilitate the reading of large numbers the figures may be grouped together in threes, but no commas should be used to separate the groups.

Use of Modifying Signs. For the use of modifying signs such as subscripts, superscripts and brackets (for examples *see* Schedule B) no rigid rules are laid down, but a satisfactory notation should fulfil the following requirements:

(i) It should be unambiguous.
(ii) It should be systematic, simple and easy to remember.
(iii) It should not be extravagant in using up more letters of the alphabet than necessary.
(iv) It should not be expensive or difficult to print.

The notation ln and log would be preferable to $\log_e$ and $\log_{10}$ respectively because of condition (iv), were it not for condition (i). The use of ln and $\log_{10}$ is encouraged for the time being in the hope that the use of ln may become universal, and it will then be safe to abbreviate $\log_{10}$ to log.

Brackets, including parentheses ( ), braces { } and square brackets [ ], should not be used around the symbol for a quantity in order to make it represent any other quantity, unless such use is consistently adopted for a whole class of quantities as in crystallography. The use of brackets or braces around a chemical formula to denote, respectively, the molar concentration or the relative activity of the substance fulfils the above general and particular requirements. Most other uses of brackets, apart from their mathematical uses, do not fulfil these requirements.

Conventions for the representation of Thermodynamic Data for Chemical Reactions. It is recommended that thermodynamic data for chemical reactions be expressed by quoting the equation for the reaction (with such specification of the physical states of participating substances as may be necessary) followed by the magnitude of the change (positive or negative) in the appropriate thermodynamic function. For example, for the heat of reaction at a constant pressure of 1 atm

$$\mathrm{CH_3OH\ (liq.) + 1\tfrac{1}{2}O_2 = CO_2 + 2H_2O\ (liq.)};$$
$$-\Delta H\ (\text{at } 298^\circ\,\mathrm{K}) = 726{\cdot}93\ \mathrm{kJ}.$$

Similarly, for the heat of the same reaction at constant volume

$$-\Delta U\ (\text{at } 298^\circ\,\mathrm{K}) = 728{\cdot}18\ \mathrm{kJ}.$$

It is preferred that quantities of heat, as of other forms of energy, be expressed in joules; where data are given in calories the corresponding values in joules should be added, with the conversion factor used. The use of a special symbol

to denote the heat *evolved* in a chemical reaction—as was formerly customary in thermochemistry—is not recommended.

Conventions concerning Abbreviations. Abbreviations for the names of units are the same in the singular and the plural, i.e. no 's' is to be added when the magnitude is greater than unity.

No definite rule is prescribed for the use of a full point after an abbreviation, but the recommendation is that such points are preferably omitted wherever this can be done without causing ambiguity (l. is used for litre in order to avoid confusion with the numeral one), and should always be omitted after single capital letters representing the names of units (*see* Schedule D). It is customary, however, to use a full point after abbreviations for words used in the text and for the names of British units.

II. SPECIFIC USAGES

A. SYMBOLS FOR PHYSICAL QUANTITIES

(*Letters of the Latin alphabet used for this purpose are to be printed in italic type, except in so far as a heavy-faced sans serif type may be employed for vector quantities.*)

1. General Constants

(*Symbols for these constants may be printed in* ***bold*** *type—italic or Greek—to distinguish them from variables. For purely mathematical constants, see Schedule C.*)

speed of light	$\boldsymbol{c}$, c	Planck's constant	$\boldsymbol{h}$, h
Avogadro's number	$\boldsymbol{N}$, N	Bohr's magneton	$\boldsymbol{\beta}$, β
gas constant per mole	$\boldsymbol{R}$, R	Rydberg's constant	$\boldsymbol{R}$, R
Boltzmann's constant	$\boldsymbol{k}$, k	Stefan–Boltzmann constant	$\boldsymbol{\sigma}$, σ
Faraday's constant	$\boldsymbol{F}$, F	gravitational constant	$\boldsymbol{G}$, G
charge of electron	$-\boldsymbol{e}$, $-e$	gravitational acceleration,	
mass of electron	$\boldsymbol{m}$, m	standard value	$\boldsymbol{g}$, g_0

2. Mensuration

length	l	rectangular coordinates	x, y, z
height	h	cylindrical coordinates	$r, \phi, z \ldots \rho, \phi, z$
breadth	b	spherical coordinates	r, θ, ϕ
radius	r		
diameter	d	angle, plane	$\alpha, \beta; \theta, \phi, \psi$, etc.
		angle, solid	ω
area	A		
volume	V, v		

3. Kinematics

time	t	velocity	v, u
period	T	velocity, angular	ω
frequency	f, ν	acceleration	$a \ldots f$
wave number	$\nu, \tilde{\nu}$	acceleration, angular	α
wave-length	λ	acceleration, gravitational	g

4. Mechanics

mass	m	Young's modulus	E
density	ρ	rigidity	G
density, relative	d	bulk modulus	K
		compressibility	κ
force	F	Poisson's ratio	$\sigma \ldots \nu$
weight	W		
moment	M	bending moment	M
pressure	p, P	torque	T
		modulus of section	Z
work	W, w		
energy	E, W	coefficient of friction	μ
energy, kinetic	T	viscosity	η
energy, potential	V	fluidity	ϕ
power (*see also section* 9)	P	viscosity, kinematic	ν
efficiency	η		
		surface tension	γ, σ
moment of inertia	I		
radius of gyration	k		

5. Thermodynamics

temperature, empirical	$\theta \ldots t$	internal energy	U
temperature, absolute	T	entropy	S
thermal conductivity	λ, k	free energy (Helmholtz function)	F
		heat function; enthalpy; total heat	H
quantity of heat	Q, q	Gibbs function	G
thermal expansion, coefficient of	α		
		partition function	Q
heat capacity per unit mass	c		
heat capacity per mole	C		
ratio of specific heats	γ		
Joule–Thomson coefficient	μ		

6. Chemical Composition and Reaction

atomic number	Z
atomic weight	A
molecular weight	M
number of molecules	N
number of moles	n
stoichiometric number of molecules	ν
degree of dissociation (*see also section* 10)	α
mole fraction	x
weight fraction	w
volume fraction	ϕ
concentration	c, C
concentration, molar, of substance X	$c_X, C_X, [X]$
molality	m
surface concentration	Γ
diffusion coefficient	D
velocity constant (of reaction)	k
activation energy (of reaction)	E
equilibrium constant (of reaction)	K

7. Chemical Thermodynamics

chemical potential	μ
activity, absolute	λ
activity, relative	a
activity, relative, of substance X	$a_X, \{X\}$
activity coefficient (*see also section* 10)	f, γ
osmotic pressure	Π
osmotic coefficient	g

8. Light

luminous flux	F, Φ
luminous intensity	I
luminance; brightness (photometric)	L, B
luminance factor	β
luminous radiance	R
illumination	E
absorption factor	α
reflexion factor	ρ
transmission factor	τ
refractive index	$n \ldots \mu$ (with subscript)

9. Electricity and Magnetism

electromotive force (*see also section* 10)	E, V
potential; potential difference	V
electric current	I
electric charge	Q
resistance	R
inductance	L
capacitance	C
electric force; electric field strength	$\mathbf{E}, E$
electric flux density; electric displacement	$\mathbf{D}, D$
magnetic flux density; magnetic induction	$\mathbf{B}, B$
magnetic field strength; magnetizing force	$\mathbf{H}, H$
permittivity	ϵ
permittivity, relative; dielectric constant	ϵ_r, ϵ
permittivity, of free space	ϵ_0
permeability	μ
permeability, relative	μ_r, μ
permeability, of free space	μ_0

magnetic vector potential	**A**, A
electric flux	Ψ
magnetic flux	Φ
current density (*see also section* 10)	**J**, J
intensity of magnetization; magnetic polarization	**M**, M ... **I**, I
Poynting vector	**S**, S
magnetic susceptibility (volume)	κ
magnetic susceptibility (mass)	χ
charge density (volume)	ρ
charge density (surface)	σ
electronic exit work function	ϕ
resistivity; specific resistance	ρ, r
conductivity; specific conductance (*see also section* 10)	σ, γ
dipole moment, electric or magnetic	μ
resistance	R
reactance	X
impedance	Z
conductance	G
susceptance	B
admittance	Y
inductance, self	L
inductance, mutual	M
inductance, self or mutual (with subscripts)	L
energy, electrical	W
power (*see also section* 4)	P
power, reactive	Q
power, apparent (or 'volt-amperes')	S
phase difference	ϕ
power factor	$\cos\phi$
dielectric loss angle	δ

10. Electrochemistry

degree of electrolytic dissociation (*see also section* 6)	α
valency of an ion (negative for anion)	z
ionic strength	I
activity coefficient (*see also section* 7)	f
activity coefficient, stoichiometric (*see also section* 7)	γ
conductivity; specific conductance (*see also section* 9)	κ
conductance, equivalent or (with subscript m) molar	Λ
ionic conductance, equivalent (with subscript)	Λ ... l
transport number (with subscript)	t, T
electromotive force of voltaic cell (*see also section* 9)	E
single electrode potential (with subscript)	E
current density at an electrode surface (*see also section* 9)	d
electrolytic polarization; overpotential	η
electrokinetic potential	ζ

B. EXAMPLES OF SUBSCRIPTS AND OTHER MODIFYING SIGNS

1. Subscripts to Symbols for Quantities

I, II ...	*especially with symbols for thermodynamic functions*, referring to
1, 2 ...	different systems or different states of a system.
A, B ...	referring to molecular species A, B, etc.
i	referring to a typical ionic species i.

u	referring to an undissociated molecule.
+, −	referring to a positive or negative ion, or to a positive or negative electrode.
p, v, T, S	indicating constant pressure, volume, temperature and entropy respectively.
p, c, a	*with symbol for an equilibrium constant*, indicating that it is expressed in terms of pressure, concentration, or activity.
G, L, S, X	referring to gas, liquid, solid and crystalline states respectively.
f, e, s, t, d	referring to fusion, evaporation, sublimation, transition and dissolution or dilution respectively.
c	referring to the critical state or indicating a critical value.
0	indicating limiting value at infinite dilution.
C, D, F	*with symbols for optical properties*, referring to particular wave-lengths.

Where a subscript has to be added to a symbol which already carries a subscript, the two subscripts should be separated by a comma.

Some of the above subscripts may sometimes be more conveniently used as superscripts.

2. Other Modifying Signs

[]	*enclosing formula of chemical substance*, indicating its molar concentration.
{}	*enclosing formula of chemical substance*, indicating its relative activity.

In crystallography it is recommended that:

Millerian indices be enclosed in parentheses, ( );
Laue indices be unenclosed;
Indices of a plane family be enclosed in braces, { };
Indices of a zone axis or line be enclosed in square brackets, [ ].

Numerals attached to a symbol for a chemical element in various positions have the following meanings:

upper left mass number of atom,
lower left nuclear charge of atom,
lower right number of atoms in molecule;
e.g., ${}^{7}_{3}\mathrm{Li}$; ${}^{2}_{1}\mathrm{H}_{2}$.

Ionic charge should be indicated by a superscript plus or minus sign following the symbol of the ion; for multiple charges an Arabic superscript numeral should precede the plus or minus sign; e.g., Na^{+}, NO_3^{-}, Ca^{2+}, PO_4^{3-}, ${}^{7}_{3}\mathrm{Li}^{-}$.

A valency state should be indicated by a superscript Roman numeral following the symbol of the element; e.g. $\mathrm{Sn}^{\mathrm{II}}$, $\mathrm{Sn}^{\mathrm{IV}}$.

In the formula of a free radical the unshared valency should be indicated by a bold-type point in the middle position; e.g., $\mathrm{H_3C}\cdot$, $\mathrm{C_6H_5}\cdot$, $\mathrm{HO}\cdot$.

C. EXAMPLES OF SYMBOLS AND ABBREVIATIONS DENOTING MATHEMATICAL OPERATIONS AND CONSTANTS

(*Letters of the Latin alphabet used for this purpose are to be printed in roman type.*)

limit of y	$\lim y$
tends to a	$\to a$
average of several values of x	$\bar{x}$
sum of	Σ
product of	Π
division by (solidus), e.g. g/cm²s	/
square root	$\sqrt{}$
nth root	$\sqrt[n]{}$
base of natural logarithms	e ... ϵ
logarithm of x to base e	$\ln x$ ... $\log_e x$
logarithm of x to base 10	$\log_{10} x$
antilogarithm	antilog
exponential function of x	$\exp x$, e^x
factorial n	$n!$
ratio of circumference to diameter of circle	π
trigonometric functions of θ	$\sin\theta$, $\cos\theta$, $\tan\theta$, $\operatorname{cosec}\theta$, $\sec\theta$, $\cot\theta$
inverse trigonometric functions	$\sin^{-1}\theta$ ... arc $\sin\theta$, etc.
hyperbolic functions of x	$\sinh x$, $\cosh x$, $\tanh x$, $\operatorname{cosech} x$, $\operatorname{sech} x$, $\coth x$
inverse hyperbolic functions	$\sinh^{-1} x$, etc.
increment or finite difference operator	Δ, δ
*differential coefficient of y with respect to x	$\frac{dy}{dx}$, dy/dx
*differential coefficient, nth	$\frac{d^n y}{dx^n}$, $d^n y/dx^n$
differential coefficient, partial	$\frac{\partial y}{\partial x}$, $\partial y/\partial x$
operator $\frac{\partial}{\partial x}$ or with single variable $\frac{d}{dx}$	D
*integral of y with respect to x	$\int y\,dx$
*integral of y from $x = a$ to $x = b$	$\int_a^b y\,dx$
*integral of y around a closed contour	$\oint y\,dx$

* See note on use of d or *d*, p. 34.

complex operator $\sqrt{(-1)}$	i, j
real part of	$\mathscr{R}$
imaginary part of	$\mathscr{I}$
modulus of complex number z	$\lvert z \rvert$
argument of complex number z	$\arg z$
vector of magnitude A	$\mathbf{A}$
scalar product of **A** and **B**	$\mathbf{A}.\mathbf{B}$
vector product of **A** and **B**	$\mathbf{A} \times \mathbf{B}, \mathbf{A} \wedge \mathbf{B}$
nabla or del, $\left(\mathrm{i}\frac{\partial}{\partial x}+\mathrm{j}\frac{\partial}{\partial y}+\mathrm{k}\frac{\partial}{\partial z}\right)$	∇
Laplacian operator, $\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)$	∇^2

D. ABBREVIATIONS (SYMBOLS) FOR THE NAMES OF UNITS

(Letters of the Latin alphabet used for this purpose are to be printed in roman type.)

1. Internationally accepted Units

(The use of small roman capitals for single capital letter abbreviations is permissible.)

metre	m
micron	μ
ångström	Å
square metre	m^2 ... sq.m
cubic metre	m^3 ... cu.m
cubic centimetre	cm^3 ... cu.cm ... c.c.
litre	l.
second	s ... sec
minute	min
hour	h
hertz	Hz
cycles per second	c/s
revolutions per minute	rev/min
gramme	g
kilogramme (mass)	kg
kilogramme (force)	Kg
dyne	dyn
newton	N
bar	b
atmosphere (pressure)	atm
poise	P
joule	J
watt	W
watt-hour	Wh
calorie	cal
kilocalorie	kcal
degree Celsius	°C
degree centigrade	°C
degree Fahrenheit	°F
degree Kelvin	°K

lumen	lm
lux	lx
stilb	sb
candella	cd
electrostatic unit	e.s.u.
electromagnetic unit	e.m.u.
Debye unit	D
coulomb	C
ampere	A ... amp
volt	V
ohm	Ω
electron-volt	eV
volt-coulomb	VC
volt-ampere	VA
farad	F
henry	H
gauss	G
weber	Wb
normal concentration	N
molar concentration	M
molal concentration	m
hydrogen-ion exponent	pH

2. Prefixes to Abbreviations for the Names of Units Indicating

Multiples		Sub-multiples	
tera ($\times 10^{12}$)	T	deci ($\times 10^{-1}$)	d
giga ($\times 10^{9}$)	G	centi ($\times 10^{-2}$)	c
mega ($\times 10^{6}$)	M	milli ($\times 10^{-3}$)	m
kilo ($\times 10^{3}$)	k	micro ($\times 10^{-6}$)	μ
		nano ($\times 10^{-9}$)	n
		pico ($\times 10^{-12}$)	p

3. Common British Units

inch	in.	ounce	oz.
foot	ft.	pound (mass)	lb.
yard	yd.	hundredweight	cwt.
square inch	$in.^2$, sq.in.		
(similarly for foot, etc.)		pound (force)	Lb.
cubic inch	$in.^3$, cu.in.	poundal	pdl.
(similarly for foot, etc.)			
		foot-pound	ft.Lb.
gallon	gal.	horse power	h.p.
grain	gr.	British thermal unit	B.Th.U.

E. SOME ABBREVIATIONS FOR WORDS OTHER THAN NAMES OF UNITS

This list is not intended to be exhaustive. The words in this list will often be given in full in the text, but where abbreviations are used the following forms are recommended.

(*To be printed in roman type*)

absolute	abs.
alternating current	a.c.
anhydrous	anhyd.
approximate (-ly)	approx., *ca.*
aqueous	aq.
atmospheric	atm.
atomic weight	at.wt.
boiling point	b.p.
calculated	calc.
centre of gravity	c.g.
coefficient	coeff.
compound	cpd.
concentrated	conc.
concentration	concn.
constant	const.
corrected	corr.
critical	crit.
crystalline, crystallized (adjective)	cryst.
current density	c.d.
decomposition	decomp.
degree	deg.
dilute	dil.
direct current	d.c.
distilled	dist.
electromotive force	e.m.f.
equation	eqn.
equivalent	equiv.
experiment (-al)	expt.
figure (diagram)	fig.
freezing point	f.p.
gram molecule	mole
horse power, brake	b.h.p.
horse power, effective	e.h.p.
horse power, indicated	i.h.p.
horse power, nominal	n.h.p.
horse power, shaft	s.h.p.
infra-red	i.r.
insoluble	insol.
latent heat	lat.ht.
liquid	liq.
magnetomotive force	m.m.f.
maximum	max.
melting point	m.p.
minimum	min.
molecule, molecular	mol.
molecular weight	mol.wt.
observed	obs.
per cent	% (or in full)
potential difference	p.d.
precipitate	ppt.
preparation	prep.
recrystallized	recryst.
relative humidity	r.h.
root mean square	r.m.s.
section, paragraph	§
soluble	sol.
solution	soln.
specific	sp.
specific gravity	sp.gr.
specific heat	sp.ht.
specific volume	sp.vol.
standard temperature and pressure	s.t.p.
temperature	temp.
ultra-violet	u.v.
vacuum	vac.
vapour density	v.d.
vapour pressure	v.p.
volume	vol.
weight	wt.

ALPHABETICAL INDEX

Of recommended symbols for physical quantities including single letters denoting mathematical constants and operations but not single-letter abbreviations for names of units or other words

(*Names of independent quantities are separated by colons; alternative names for a single quantity are separated by semicolons. Enclosure of the name of a quantity in parentheses indicates that there is an alternative symbol of equal standing; enclosure in square brackets indicates that there is another symbol which is preferred. An asterisk against the name of a quantity indicates that the specified symbol is always used with a subscript when denoting that quantity.*)

A area: atomic weight

A, A magnetic vector potential

a acceleration: activity, relative

B (luminance; brightness): susceptance

B, B magnetic flux density; magnetic induction

b breadth

C heat capacity per mole: (concentration): capacitance

c heat capacity per unit mass: (concentration)

c, c speed of light

D differential operator

D diffusion coefficient

D, D electric flux density; electric displacement

d differentiation

∂ partial differentiation

d diameter: relative density: current density at an electrode surface

E (energy): Young's modulus: activation energy: illumination: electromotive force: single electrode potential*

E, E electric force; electric field strength

e base of natural logarithms

$-\boldsymbol{e}, -e$ charge of electron

F force: free energy; Helmholtz function: (luminous flux)

$\boldsymbol{F}, F$ Faraday's constant

f (frequency): [acceleration]: (activity coefficient)

G rigidity: Gibbs function: conductance

$\boldsymbol{G}, G$ gravitational constant

g gravitational acceleration: osmotic coefficient

$\boldsymbol{g}, g_0$ gravitational acceleration, standard value

H heat function; enthalpy; total heat

H, H magnetic field strength; magnetizing force

h	height
$\boldsymbol{h}$, h	Planck's constant
I, I	[intensity of magnetization]
I	moment of inertia: luminous intensity: electric current: ionic strength
i	(square root of minus one)
$\mathbf{J}$, J	current density
j	(square root of minus one)
K	bulk modulus: equilibrium constant of chemical reaction
k	radius of gyration: (thermal conductivity): velocity constant of chemical reaction
$\boldsymbol{k}$, k	Boltzmann's constant
L	(luminance; brightness): inductance, especially self-inductance: inductance, self or mutual*
l	length: [equivalent ionic conductance*]
$\mathbf{M}$, M	(intensity of magnetization)
M	moment: bending moment: molecular weight: mutual inductance
m	mass: molality
$\boldsymbol{m}$, m	mass of electron
N	number of molecules
$\boldsymbol{N}$, N	Avogadro's number
n	number of moles: refractive index*
P	(pressure): power
p	(pressure)
Q	(quantity of heat): electric charge: power, reactive: partition function
q	(quantity of heat)
R	luminous radiance: resistance
$\boldsymbol{R}$, R	gas constant per mole: Rydberg's constant
r	radius: spherical or cylindrical coordinate: (resistivity; specific resistance)
S	entropy: power, apparent
$\mathbf{S}$, S	Poynting vector
T	period: kinetic energy: torque: temperature, absolute: (transport number*)
t	time: [temperature, empirical]: (transport number*)
U	internal energy
u	(velocity)
V	(volume): potential energy: potential: potential difference: (electromotive force)
v	(volume): (velocity)
W	weight: (work): (energy): energy, electrical
w	(work): weight fraction
X	reactance
x	coordinate: mole fraction
Y	admittance
y	coordinate
Z	modulus of section: atomic number: impedance
z	coordinate: valency of an ion

α	(angle): angular acceleration: coefficient of thermal expansion: degree of dissociation: light absorption factor
β	(angle): luminance factor
$\boldsymbol{\beta}, \beta$	Bohr's magneton
Γ	surface concentration
γ	(surface tension): ratio of specific heats: (activity coefficient, especially stoichiometric): (conductivity; specific conductance)
Δ	(increment or finite difference operator)
δ	(increment or finite difference operator): dielectric loss angle
ϵ	[base of natural logarithms]: permittivity
ζ	electrokinetic potential
η	efficiency: viscosity: electrolytic polarization; overpotential
θ	(angle): spherical coordinate: temperature, empirical
κ	compressibility: magnetic susceptibility, volume: conductivity; specific conductance, especially of electrolytes
Λ	equivalent conductance: equivalent ionic conductance*
λ	wave-length: (thermal conductivity): activity, absolute
μ	coefficient of friction: Joule–Thomson coefficient: chemical potential: [refractive index*]: permeability: dipole moment
ν	(frequency): (wave number): [Poisson's ratio]: kinematic viscosity: stoichiometric number of molecules
$\tilde{\nu}$	(wave number)
Π	product
$\mathit{\Pi}$	osmotic pressure
π	ratio of circumference to diameter
ρ	density: light reflexion factor: electric charge density, volume: (resistivity; specific resistance)
Σ	summation
σ	Poisson's ratio: (surface tension): electric charge density, surface: (conductivity; specific conductance)
$\boldsymbol{\sigma}, \sigma$	Stefan–Boltzmann constant
τ	light transmission factor
Φ	(luminous flux): magnetic flux
ϕ	(angle): spherical or cylindrical coordinate: fluidity: electronic exit work function: phase difference: volume fraction
χ	magnetic susceptibility, mass
Ψ	electric flux
ψ	(angle)
ω	solid angle: angular velocity

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30 JAN 1959

THE ROYAL SOCIETY



BRITISH NATIONAL COMMITTEE

FOR THE INTERNATIONAL GEOPHYSICAL YEAR

SOME INTERNATIONAL GEOPHYSICAL YEAR ACHIEVEMENTS

AN INTERIM STATEMENT ISSUED AT THE CLOSE OF THE OBSERVATIONAL PHASE OF THE INTERNATIONAL GEOPHYSICAL YEAR

LONDON
THE ROYAL SOCIETY
DECEMBER 1958

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SOME INTERNATIONAL GEOPHYSICAL YEAR ACHIEVEMENTS

In a foreword to the book* which described the British plans for participation in the International Geophysical Year, Sir Cyril Hinshelwood, President of the Royal Society, wrote:

'Physical phenomena occurring on the earth are subject to complex influences, partly of solar origin, the analysis and interpretation of which has hitherto been incomplete and hindered by the lack of carefully co-ordinated observations made simultaneously all over the globe. The object of the International Geophysical Year is to make good these deficiencies by a programme of observations extending over the period from 1 July 1957 to 31 December 1958.'

Although the complete assessment of the achievements of the I.G.Y. is not possible until fuller study has been made of its results, all indications at present suggest that a very high degree of success has been achieved. For a full report on the results of the I.G.Y. it is necessary to wait until all of the thousands of observations have been collected in World Data Centres and thereafter analyzed and studied, a process which will require some years in most subjects. The British National Committee being aware of the great public interest in the I.G.Y. has, however, decided to issue in general terms this brief interim statement on some of the more easily discernible trends and achievements already evident at the conclusion of the I.G.Y. At the same time the opportunity has been taken to mention some noteworthy British contributions. The reports below deal with each of the separate subject fields of the International Geophysical Year in turn.

The international co-ordination and planning of the I.G.Y. has been administered by a special committee (known as C.S.A.G.I. from the initials of its title in the French language) set up by the International Council of Scientific Unions, and in each subject field a World Reporter was appointed. At present four of these positions are occupied by British scientists. In each of the sixty-seven countries which have participated in the I.G.Y. programme there is a corresponding national organization.

The United Kingdom programme for the I.G.Y. has been supervised by the British National Committee for the International Geophysical Year, which was set up by the Royal Society in December 1952. In each of the scientific subject fields of the I.G.Y. a British National Correspondent was appointed, as shown in the following list:

I World Days and Communications	Dr R.L. Smith-Rose, C.B.E.
II Meteorology	Sir Graham Sutton, C.B.E.
III Geomagnetism	Dr J.M. Stagg, C.B., O.B.E.

(continued overleaf)

*See Section XV and footnote, p. 14.

IV	Aurora and Airglow	Mr J. Paton
V	Ionosphere	Professor W.J.G. Beynon
VI	Solar Activity	Professor M.A. Ellison
VII	Cosmic Rays	Dr H. Elliot
VIII	Longitudes and Latitudes	Dr R. d'E. Atkinson
IX	Glaciology	Professor G. Manley
X	Oceanography	Dr G.E.R. Deacon, C.B.E.
XI	Rockets and Satellites	Professor H.S.W. Massey
XII	Seismology	Dr R. Stoneley
XIII	Gravity Measurements	Dr R. Stoneley
XIV	Nuclear Radiation	Professor P.A. Sheppard
XV	Publications	Dr D.C. Martin

The other members of this Committee are Sir David Brunt, Sir Edward Bullard, Professor S. Chapman, Rear-Admiral K. St B. Collins, O.B.E., D.S.C., Sir Harold Spencer Jones, K.B.E., Professor A.C.B. Lovell, O.B.E., Mr J.A. Ratcliffe, O.B.E., Dr G. de Q. Robin, Sir James Wordie, C.B.E., and the Physical and Foreign Secretaries of the Royal Society.

Vice-Admiral Sir Archibald Day, K.B.E., C.B., D.S.O. (retd), the late Sir Nelson Johnson, K.C.B., Professor T. Gold, Dr M.N. Hill, Dr B.F.J. Schonland, and Dr R. v.d. R. Woolley, O.B.E., have also served on the committee.

During most of the planning period the Chairmanship has been held by Sir James Wordie, whose services in this regard have been of inestimable benefit to the International Geophysical Year. In the planning of the I.G.Y. in the United Kingdom, the British National Committee has been assisted by a number of subcommittees, of which the most important still functioning are the Antarctic Subcommittee, the Artificial Satellite Subcommittee, the Publicity Subcommittee and two subcommittees on the analysis of the results.

I World Days and Communications

Many of the observations made during the I.G.Y. have been concerned with phenomena which are influenced by ultraviolet rays, X-rays and streams of charged particles emitted by the sun. Solar radiation of these types is particularly intense on some days and it was considered important to make more intensive series of observations on those days when they occurred. Since it is impossible to forecast the occurrence of these outbursts of solar radiation more than a day or two ahead, it was obviously not possibly to prepare an advance calendar of the kind which was used to specify Regular World Days and World Meteorological Intervals. It is for this reason that the Special World Interval

(S.W.I.) warning system has been operated during the I.G.Y. The World Warning Centre in Fort Belvoir, U.S.A., has issued many Alerts indicating the possibility of unusual solar activity and has declared a smaller number of S.W.Is when it seemed very likely that solar radiation would be exceptionally great during the next 24 hours.

During the I.G.Y. (excluding December 1958) 38 sequences of Alerts have occurred, in the course of which 218 Alert messages have been received in the U.K. and distributed by telegram to about 30 observers in the U.K. and to U.K.-sponsored stations in Singapore, Falkland Islands, West Africa and the Antarctic. Arrangements were also made with the British Broadcasting Corporation for 'preparatory warnings' (i.e. Alerts) and S.W.Is to be notified on the Home Service at 11.03 p.m.

The Alerts culminated in 43 S.W.I. days during which many special observations were made, especially in the subject fields of the earth's magnetism, aurora, the ionosphere, cosmic rays and, of course, the observations of the sun itself using both radio and optical measuring instruments. Not all of these S.W.Is have, in fact, coincided with unusual solar activity. Nevertheless, if subsequent analysis proves that even a few exceptional outbursts have been fully observed, the effort will have been justified.

II Meteorology

The internationally planned programme of intensified and extended meteorological observations, including upper air soundings and measurements of atmospheric ozone, solar radiation and radiation balance, has proceeded satisfactorily. General distribution of world data is to be made on microcards, or otherwise, from the World Data Centre at Geneva. The Meteorological Office Library in the United Kingdom will hold a complete set of these cards.

Various nations are to share the work of producing daily synoptic charts at standard levels up to 50 mb (about 22 km) for the north and south hemispheres, the tropical belt and the whole world, and also aerological vertical cross-sections along certain standard meridians and parallels of latitude.

Large-scale systematic study of the central meteorological problem of the I.G.Y., viz. the general circulation of the atmosphere, awaits the availability in suitable form of the vast quantity of world data mentioned above. There is however some evidence from the upper air soundings made during the I.G.Y. that changes in the circulation in the stratosphere near the equinoxes occur somewhat later than had been previously recognised.

An outstanding achievement of the I.G.Y. has been the creation of an observational network covering the Antarctic region, and the likelihood of the continuation of a substantial part of this system. Provisional reports from

various sources, confirm the expectation that significant contributions to knowledge of the atmospheric circulation in high southern latitudes will be forthcoming. It is of interest to note that observations made at Royal Society Base, Halley Bay, show that the total atmospheric ozone content is fairly constant during about nine months of the year but increases sharply (though by a moderate amount) near the beginning of November and then decreases in the next two months to the general level; whereas in corresponding high northern latitudes the atmospheric ozone content rises and falls smoothly (with the minimum in October - November) and shows a greater overall variation than at Halley Bay.

Other United Kingdom contributions have been the direct measurements of ozone concentration at heights up to about 20 km by the use of Dr Brewer's electrolytic absorption apparatus on sounding balloons in England, and at Tromso, Malta and Halley Bay; and the probably unique recordings of solar radiation and radiation balance made in the North Atlantic by British Ocean Weather Ships.

III Geomagnetism

Records of the earth's magnetic field have been made at Lerwick, Eskdalemuir, Stonyhurst and Hartland in the United Kingdom, and at Argentine Island and Halley Bay in the Antarctic. At the Lerwick Observatory two subsidiary stations have made special recordings of the gradient of the magnetic field to try to measure, and define the position of, the electric currents in the high atmosphere which are responsible for geomagnetic disturbance.

The main use of the geomagnetic data which have been sent to each of the four W.D.C.s. will begin when they can be correlated with simultaneous happenings in aurora, the ionosphere and activity on the sun, and also with the world-picture of geomagnetic events as recorded at the 200 other I.G.Y. geomagnetic observatories. It is already clear that Royal Society Base, Halley Bay, has been sited most advantageously for studying these relationships. Of the 15 geomagnetic observatories on the Antarctic continent - as many as in the whole of the southern hemisphere before I.G.Y. - Halley Bay is the only station situated just outside that zone of greatest concentration of ionospheric electric currents which cause geomagnetic disturbance and which are also associated with the greatest frequency of aurora. This unique position will give observations at Halley Bay a special value.

On 13 September 1957, during one of the biggest world-wide geomagnetic storms ever recorded, the horizontal force component at Halley Bay had a range of 3950×10^{-5} gauss, equivalent to one-sixth of the average component of the field there. The incidence of irregular disturbance at Halley Bay is greatest around 3 a.m. local time on the average, and the immediate post-midday hours are usually the quietest.

IV Aurora and Airglow

In the past, the study of the geographical distribution of aurora and of the details of the changes in form and movement that occur during the progress of a great display has never been satisfactorily achieved, since it requires the organization of a vast network of observers extending over the whole globe, even into low latitudes. A great effort has been made by most of the participating nations to provide, during the I.G.Y., the necessary observers on land, in their ships and aeroplanes, and in expeditions sent to the polar regions. In the higher latitudes where aurora occurs frequently, all-sky cameras have continuously photographed the whole sky and auroral activity has been further recorded by radio-echo methods, which provide the only means of detecting daytime aurorae.

It has been the task of the World Data Centres to plot the mass of incoming data on charts in a form suitable for the study of the 'morphology' of aurora and for the investigation of correlations with solar, magnetic and ionospheric events. The Balfour Stewart Auroral Laboratory of Edinburgh University has been responsible for the collection and reduction of observations from most of Europe and from the Atlantic and Africa.

The I.G.Y. began auspiciously with an aurora playing overhead in quite low latitudes at midnight on 30 June - 1 July 1957, and activity remained at an exceptionally high level during the opening five months. Since then, there has been a quite unexpected lull with only a few well separated great displays becoming visible in middle latitudes. The all-sky camera operated at Royal Society Base, Halley Bay, Antarctica, has however provided some remarkable films showing in minute detail the development of many high latitude displays; these are certain to provide very valuable information when examined in association with the visual and radio-echo observations and the magnetic and ionospheric records.

While the fundamental studies can begin only when the Data Centres have exchanged their reduced data and thus each possesses the global information, certain not unexpected results have already come to light. Simultaneous displays of aurora australis and aurora borealis appear to progress very similarly, and near the solstices, aurora penetrates further equatorwards in the summer hemisphere. The zones of equal frequency of occurence of aurorae, which had hitherto been assumed to lie along lines of geomagnetic latitude, are more closely aligned along lines of constant magnetic inclination.

V Ionosphere

The International Geophysical Year has provided an unparalleled opportunity for studying the region of the earth's atmosphere extending upwards from about 70 km (45 miles) where the sun's ultra-violet radiation produces an ionized

medium which reflects and refracts radio waves. Over 250 observatories have co-operated during the I.G.Y. in the study of the various layers of ionization and information about irregular patches of the ionosphere and extra levels associated with disturbances on the sun will be increased accordingly.

Apart from the routine method of vertical sounding by pulsed radio signals, the I.G.Y. measurements have included studies of absorption using radio waves from radio stars and reflexions from the ionized trails created by meteors, and studies of atmospheric radio noise including that created by lightning flashes. Besides the ionospheric stations operated by the Radio Research Organization of the Department of Scientific and Industrial Research, important United Kingdom contributions to this work have been made by the Cavendish Laboratory, Cambridge; Edinburgh University; University College, Ibadan, Nigeria; King's College, London; Jodrell Bank Experimental Station, University of Manchester; and the University College of Swansea.

Interesting features of the structure of the ionosphere in high latitudes have been revealed at Royal Society Base, Halley Bay. The most striking is that the maximum ionization density in the F2 layer at noon in winter exceeds the corresponding quantity at noon in summer despite the fact that at the height of the layer the sun neither rises in midwinter nor sets in midsummer. The strong diurnal variation in winter gives electron densities at noon which are ten times those at midnight. Near the equinoxes there is a sudden change from typical winter to typical summer variations. In summer there is a slight inverse diurnal variation, the maximum density at noon being less than that at midnight. It is concluded that the variations of ionization density are mainly due to movements in the ionosphere, the direct ionizing action of the sun being relatively small. Detailed studies confirm that the layer is replenished in winter by ionization moving more or less horizontally.

The studies of irregularities in the ionosphere at the Cavendish Laboratory, Cambridge, and other stations have been extended to include data obtained from observations of the radio transmissions from artificial earth satellites. An hourly I.G.Y. index of meteor activity has been provided from measurements made at Jodrell Bank. Studies of 'sporadic E' ionization in the ionosphere have included the use of the back-scatter plan-position indicator at the D.S.I.R. Radio Research Station, Slough. One of the World Data Centres for the ionosphere is situated at this station and has already received 800,000 photographic records, graphs and tables of data from the 81 stations in the world network which send data direct to Slough or from other World Data Centres.

VI Solar Activity

The outstanding contribution of the I.G.Y. in the field of solar activity has been the successful organization of the Solar Patrol. Some 50 stations have been making observations at set times in hydrogen light for the recording of solar

flares. About half of these stations carry out their patrol visually with spectrohelioscopes; the remainder are equipped with automatic heliographs which photograph the sun's disk through Lyot-type filters at either 1-minute or 3-minute intervals. The coverage achieved, amounting to 89.7% of possible hours during the past year, has far surpassed all previous attempts at keeping the solar atmosphere under continuous observation. These observations, together with those of sunspots and the corona, will provide the basic materials for all subsequent studies in solar-terrestrial relationships during the I.G.Y. period.

The flare rocket programme carried through by the U.S. Naval Research Laboratory, Washington, in which two-stage solid-propellant rockets have been launched into the ionosphere during major flares, has shown the existence of a powerful flux of solar X-rays in the wave-band 1 to 8 Å. It is this radiation which produces the extra ionization in the D region during a flare and is, therefore, the cause of the short-wave radio fadeouts and long-wave enhancements which are known to occur at these times.

Great advances have been made in the U.S.A. and the U.S.S.R. in the detailed study of the magnetic fields in active solar regions. It has been shown, for example, that at the time of a flare the lines of force of the adjacent field undergo a sudden redistribution. It thus appears that the flare is a phenomenon in which there is a sudden conversion of magnetic energy into wave and particle radiation.

The British programme has contributed notably to the work of the Solar Patrol, by visual observations carried on in the British Isles at Herstmonceux and Edinburgh, and by film records made at the Cape of Good Hope, where a Lyot Hα Heliograph of advanced design was established at the Royal Observatory early in 1958. The latter instrument has recorded over 600 flares in its first 9 months of operation: during this period it has completed a 7-hour watch on the sun every clear day.

Continuous records of solar radio emissions have been made on many different frequencies at Cambridge and at Jodrell Bank.

VII Cosmic Rays

The most startling development in this field has undoubtedly been the discovery by Van Allen and his colleagues of the high intensity radiation belt which surrounds the earth. This radiation was detected in the course of satellite cosmic ray intensity measurements and whilst the individual particle energies are much smaller than for the cosmic rays the flux of particles exceeds that of the cosmic rays by many orders of magnitude. The origin of the radiation is still not clear but it seems likely that whilst some of it is due to cosmic ray albedo by far the greater part probably originates in the sun.

The British programme has been almost entirely devoted to the study of sea-level cosmic ray intensity variations and to the behaviour of the cosmic rays in the earth's magnetic field. The neutron component of the radiation fell to about three-quarters of its value at sunspot minimum, this change in intensity being due to the changes in the interplanetary magnetic fields of solar origin during this time. Considerable progress has been made in the elucidation of the effect of the earth's magnetic field on the primary cosmic rays with the result that it is now possible with confidence to use the earth's magnetic field as a spectrometer for measuring primary cosmic ray energies. This work is of wide application in the interpretation of cosmic ray intensity variations whether measured at sea-level or from satellites.

VIII Longitudes and Latitudes

This section is concerned largely with long-term work, on time and latitude-variation, which has been only slightly intensified during the I.G.Y.; the dual-rate moon-camera programme has been added, but has not come very fully into operation as yet. It is too early to assess the geodetic value of that programme, but it should give useful astronomical information; it will continue for a while beyond the end of 1958. In the "permanent" work a very satisfactory parallelism is now shown, both for time and for latitude-variation, between the results of the Danjon astrolabe at Paris and the photographic Zenith tube at the Royal Greenwich Observatory, Herstmonceux. In addition an apparent "diurnal" variation of latitude, which has been known for some time but has hitherto been treated somewhat arbitrarily, is increasingly demanding positive study; its cause is still obscure, but a systematic refraction anomaly seems probable, and this may have geophysical significance.

IX Glaciology

Ice covers one-tenth of the land surface; it provides a major source of cold air, and 23 countries have indicated their intention to make some contribution to the study of the earth's ice cover during the I.G.Y. This study may be divided into two parts: first that of the smaller ice masses represented by the mountain glaciers in regions such as the Alps, the Rockies, the Altai, the Himalaya, the Andes; second, that of the great polar ice-sheets of Greenland and Antarctica. For many years past, the majority of mountain glaciers in Europe and North America have been in retreat, the result of the prevailing amelioration of climate during the present century.

In glaciology, results are only to be obtained slowly and after considerable physical effort. In addition to observations at coastal and island bases, among which those of the Falkland Islands Dependencies Survey and Halley Bay may be mentioned, several nations have carried out extensive traverses over the

Antarctic continental ice and knowledge of its depth is increasing. Soviet scientists have found evidence, using seismic-shooting techniques, that the base of the ice in East Antarctica descends well below sea level at points several hundred miles within the continent, whereas French, American, British and Australian expeditions have so far reported that the rock floor stands, in the main, above sea level. The possibility that the "continent" should be regarded as a group of islands is becoming less acceptable. Borings have been made into the Antarctic ice and down to 1400 feet into the ice of northern Greenland. By applying refined but very difficult techniques, it may become possible to estimate the character of climatic fluctuations over the past 400-800 years, and to relate them to known events in the northern hemisphere. A variety of studies of the heat exchange with the atmosphere and the physical characteristics and condition of the polar ice-caps is also being made.

The United Kingdom has had a party studying the behaviour of the mountain glaciers of South Georgia in 54°S. Variations in the glaciers in this critical region on the outer margin of the Antarctic appear to agree with those round the North Atlantic, save that there may be a lag of the order of 10 to 15 years; e.g. the culmination of an advance took place about 1890 in the north and about 1900-1905 in South Georgia. This is an important finding; the meteorological implications and the relationship with variations in the amount of sea-ice are under investigation.

In the equatorial tropics the glaciers of Mount Kenya, Kilimanjaro and Ruwenzori in East Africa have all been under observation. The glaciers of Kenya and Kilimanjaro have diminished in size since they were first seen 60 years ago, but hitherto there has been a lack of exact measurements. How far these fluctuations are representative of fluctuations in the rainfall of the region in the days before European settlement remains to be established.

Most of the glacier programmes in the northern hemisphere have continued up to the autumn of 1958, and as yet very few results are available. It is however known that a considerable relationship exists between glacier behaviour and the small but significant climatic fluctuations to which Europe and America have been subject over the past few centuries. If these are found to be more or less synchronous with events in the southern hemisphere we shall gain a better understanding of these tendencies which appear to be associated with the prevailing character of the summers in any given decade. With some caution, we may envisage a possible approach to the problem of seasonal forecasting.

X Oceanography

Preliminary study of the I.GY. recordings of long-period waves has given new information about their relation to local weather and the passage of hurricanes, but most of the material has still to be examined. The emphasis on studies of mean sea level has roused much new interest in changes in the volume

of the water as well as in the bending and tilting of the land. Many of the specially sited tide gauges will be continued, and the International Scientific Unions have set up a Permanent Service to deal with the records.

The programme on ocean circulation has been particularly successful. The widely extended network of temperature and salinity observations has given much new information about the layering and movements of water masses typical of different climatic regions. British ships have made observations along 30,000 miles of track in the North Atlantic Ocean and Arctic approaches. One of the most important British contributions has been the direct measurement of deep currents using Dr Swallow's acoustic signalling float which is made to drift with the water at chosen depths. Below the Gulf Stream there was first a layer of little horizontal movement and then a countercurrent with a southward transport roughly equal to the northward movement at the surface. On the eastern side of the ocean there were deep currents of 1 and 2 miles per day, remarkably variable from place to place and time to time. Outside the Straits of Gibraltar there was a rapid westward current, $\frac{1}{2}$ knot at 1150 metres, along the northern slope, with rotating eddies some 10 miles across on its southern flank.

These observations have already done much to stimulate further theoretical and practical study of the general circulation of the ocean, and to excite expectation of useful applications to fishery and climatological problems.

XI Rockets and Satellites

Experiments with upper-atmosphere sounding rockets have been conducted by Australia, Canada, France, Japan, the U.S.S.R., the U.K. and the U.S.A. A special period for the world-wide firing of rockets was allocated in June 1958 and one of a number of successful British 'Skylark' rocket firings was made from Woomera, Australia, during this period. Valuable information about the upper atmosphere will be obtained from the results of rocket firings and this will include data derived from U.S.S.R. firings in Antarctica.

Six University groups in Britain have co-operated in the design of rocket-borne equipment and its installation in the 'Skylark' rockets has been the responsibility of the Royal Aircraft Establishment, Farnborough. One interesting phenomenon found in one of the 'Skylark' experiments has been the development of an intense luminescent cloud lasting 3 to 4 minutes from the explosion of the highest sound-ranging grenade at about 120 km. This luminescence is believed to be due to the presence of atomic oxygen in the atmosphere at this height and may help in studies of wind distribution.

The U.S. flare rocket programme has been described above in connexion with Solar Activity. Another American rocket experiment has shown that there are a number of regions of the sky from which ultra-violet radiation is emitted.

The short-wave ultra-violet light from these sources is completely absorbed by the earth's atmosphere. Such studies can therefore only by carried on from rockets or satellites and will add greatly to astronomical knowledge.

Among the most spectacular events of the International Geophysical Year have been the launchings of the first artificial earth satellites by the U.S.S.R. and the U.S.A. The enormous amount of data collected by these new scientific tools for exploring the surroundings of the earth takes many months to analyze and assimilate but the first results of these researches already indicate that there is much new knowledge to be gained from these experiments. The discovery of the Van Allen radiation described in the section on Cosmic Rays above was quite unexpected but already some explanations of it have been proposed and a choice between these has been assisted by the observations made on the radiation in the U.S. lunar probe experiments.

Observations in the United Kingdom of artificial satellites launched by the U.S.S.R. and U.S.A. have enabled British scientists to deduce new information about ionospheric structure from observations of the radio transmissions from satellites. Optical observations by kinetheodolites at Ministry of Supply establishments have been internationally acknowledged as among the most accurate of their kind. Studies by the R.A.E., Farnborough, based on this data, have led to various interesting conclusions affecting our knowledge of the frictional and electrical drag of the atmosphere and of the shape of the earth, e.g. the flattening at the poles is slightly less than previously believed.

Radio and radar observations of satellites made at the Jodrell Bank Experimental Station, University of Manchester, have included the tracking of lunar probes launched in the U.S.A. and the recording of telemetry from the latter for measurements of the intensity of the Van Allen radiation. Equipment for recording telemetry from U.S. earth satellites has been lent by the U.S. Participating Committee and operated at University College, Ibadan, Nigeria and the Radio Research Substation, Singapore. The D.S.I.R. Radio Research Station, Slough and the B.B.C. receiving station at Tatsfield have recorded telemetry signals also from U.S.S.R. earth satellites. Amateur radio observers have participated in studies of telemetry and the long-range reception of satellite signals.

Predictions for satellites crossing the U.K. were issued at first by the Nautical Almanac Office and subsequently by the Royal Aircraft Establishment, Farnborough, but responsibility for this service has now been taken over on a permanent basis by the D.S.I.R. Radio Research Station, Slough, where a World Data Centre for rockets and satellites has been established.

XII Seismology

No significant correlation has so far been established between the solar cycle and the occurrence of earthquakes. Accordingly, the efforts of seismologists during the I.G.Y. have tended in the main to be directed towards obtaining comprehensive and strictly up-to-date collections of data concerning earthquakes happening during this period. To this end, seismological stations, some temporary and some permanent, have been set up in parts of the world where the coverage was previously thin, e.g. on the Antarctic continent which had previously had no permanent stations. In addition, as many stations as possible have been invited to prepare station bulletins for speedy despatch to World Data Centres, and all those which have the necessary staff to do so have been asked to contribute regular bulletins of microseismic information.

So far as can be judged the response has been excellent. For instance, all the permanent stations in Great Britain and the British West Indies are transmitting regular seismic bulletins, and most of them are sending in microseismic information as well. Data from Royal Society Base, Halley Bay, as from other Antarctic stations, is despatched by telegram. It is too early to make comprehensive statements about the seismic activity of Antarctica, but investigations by U.S.S.R. scientists indicate that it is probably confined to the continental margin.

The I.G.Y. has stimulated a number of specialized researches. For instance, U.S. seismologists have set up long period instruments in various parts of the world to observe the long wave phase, particularly the Lg waves. U.S.S.R. investigators have combined near earthquake studies and seismic explosion work to delineate the transition from continental to oceanic structure in north-east Asia.

The net result of I.G.Y. activity in seismology will be to secure a large body of data that should be valuable both for world-wide and for regional studies of the constitution of the earth, and especially its outer layers. New problems of organization are likely to arise. Many of the stations set up during the I.G.Y. will operate permanently and the considerable increase of material may eventually call for some rationalizing of the observational network and the work done by the compilers of the International Seismological Summary.

XIII Gravity Measurements

The setting up of scientific stations in remote corners of the globe has made it practicable during the I.G.Y. to extend the measurement of gravitational forces, which vary slightly from place to place over the earth's surface, to these additional locations, e.g. to stations in Antarctica. The I.G.Y. has thus afforded an excellent opportunity to improve knowledge of the relations between the gravity networks of the different continents.

Relative gravity measurements were made by the Commonwealth Trans-Antarctic Expedition during the traverse of Antarctica and at Halley Bay. With funds from the U.S.A., the Department of Geodesy and Geophysics, University of Cambridge, has made a series of pendulum gravity observations at eight stations between Teddington and Johannesburg and a further series at stations between Washington D.C. and South America.

This section of the I.G.Y. programme has also included studies of the variation in direction of the gravity vector due to the very small displacements of the earth's crust known as earth tides. These variations have been recorded continuously during the I.G.Y. at Bidston and Winsford in Cheshire and, with the co-operation of the Institute of Geophysics of the University of California, a recording gravimeter was installed at both sites in turn for a period of about a month.

XIV Nuclear Radiation

The results of importance on the global scale arising from the nuclear radiation observations of the I.G.Y. will not become apparent for some time. There is, however, little doubt that the observations will provide valuable information on exchange processes between the stratosphere and troposphere - a field in which the more usual kind of meteorological observations does not give such direct evidence as those on nuclear radiation.

On a smaller scale, the existence of the I.G.Y. network of nuclear sampling stations in Europe enabled a detailed study to be made over that area of the dispersion of foreign material from the point source provided by the Windscale nuclear reactor accident in October 1957. This occasion is the first on which it has been possible to study atmospheric diffusion over several hundred kilometres in such detail. The meteorological situation on this occasion was such that radically new features of atmospheric dispersion were brought to light.

XV Publications

The great quantity of data accumulated during the International Geophysical Year would be of little value if it were not readily accessible to scientists all over the world. This aspect of the I.G.Y. has been the subject of careful study and a number of World Data Centres have been created. There are three or more in each subject field and while in each case one is in the U.S.A. and one in the U.S.S.R., the third and further Centres have been located in various countries according to the subject concerned, e.g. in Britain and Japan for the ionosphere. Four major centres of this third kind are in the U.K. European and N. African visual observational data on aurora are being collected in the Balfour Stewart Auroral Laboratory at Edinburgh University, ionospheric data at the Department

of Scientific and Industrial Research, Radio Research Station, Slough, glaciological data by the British Glaciological Society at Cambridge, and data based on rocket and satellite observations at Slough. Each of these centres exchanges with other centres, in its own field, so that each may have a complete set of data.

In addition a new scientific journal called Annals of the International Geophysical Year has been created and volumes already published contain manuals for I.G.Y. observations according to internationally agreed techniques. Other volumes of this publication will contain historical material and a calendar of the I.G.Y. showing days on which there were severe disturbances on the sun etc., so that specialists can choose the periods which are likely to be of greatest interest for further study. Selected data in each subject which are likely to be of interest to workers in the other subjects will also be published in the Annals.

British publications have included a book 'The United Kingdom Contribution to the International Geophysical Year, 1957-58'* and reports† prepared for the international meeting in Moscow in the summer of 1958 and the Antarctic conferences of 1956, 1957 and 1958. The Royal Society will publish, beginning in 1960, a series of volumes containing the results of the work carried out at Halley Bay, in Antarctica, by the Royal Society Antarctic expedition. Other British results, in the appropriate fields, are being and will be published in the Observatories Year Book etc., and standard scientific journals e.g. Nature, Proceedings of the Royal Society. Discussions and symposia such as that held in November 1957 by the Royal Society on 'Observations of the Russian Artificial Earth Satellites and their Analysis', will assist the study of the results.

The Polar Regions

In the First and Second Polar Years held respectively 75 and 25 years before the International Geophysical Year, interest was centred mainly on the Arctic but during the I.G.Y. an intense effort has been devoted to the study of the Antarctic continent and the surrounding seas and islands. Work in the Arctic has been carried on by Canada, Denmark, Finland, Iceland, Norway, Sweden, Switzerland, U.S.S.R. and U.S.A., and has included co-operative enterprises such as the joint Finnish-Swedish-Swiss expedition to Spitzbergen.

In the Antarctic 57 stations have been established by 12 countries: Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, South Africa, U.S.S.R., U.K., and U.S.A. The very successful trans-continental

*Published by the Royal Society at 10s. plus 1s. postage.

†Available on request from the Royal Society, Burlington House, Piccadilly, London, W.1.

journey of the Commonwealth Trans-Antarctic Expedition has caught the imagination and included many scientific observations. The fixed scientific stations, whose distribution over the Antarctic continent follows recommendations made at the I.G.Y. Antarctic Conferences, have, however, carried on the bulk of the scientific activity. The stations at the south geographical, magnetic and geomagnetic poles have been manned respectively by the U.S.A., France and U.S.S.R., while a determined attempt to reach the remote "pole of relative inaccessibility" in the centre of the Antarctic continent has been made successfully by a U.S.S.R. expedition.

The principal British scientific station in Antarctica has been Royal Society Base, Halley Bay, situated on the part of the coast of the Weddell Sea known as Coats Land, where a successful programme over a large range of I.G.Y. subjects has been completed. This success could not have been achieved without the excellence of leadership displayed by Surgeon Lieutenant-Commander D.G. Dalgliesh, O.B.E., R.N., leader of the advance party, and Colonel R.A. Smart, C.B.E., and Mr J. MacDowall, leaders of the main party during 1957 and 1958 respectively, and the devotion to duty of the other 31 members of the two parties. Further British stations in the Graham Land peninsula and adjoining islands and in South Georgia have been manned by the Falkland Islands Dependencies Survey. Some of the contributions these Antarctic stations have made to the I.G.Y. have been mentioned in the separate sections above.

International Geophysical Co-operation 1959

The International Geophysical Year is the biggest co-operative scientific enterprise that has ever been attempted, and it is natural therefore that its success should have led to suggestions that the programme should be continued in 1959. This was very carefully considered at a meeting of I.G.Y. scientists held in Moscow in the summer of 1958. Whilst first priority will be given to the study and analysis of the information accumulated during the eighteen months of the I.G.Y., observational and data-collecting activities in the geophysical and related sciences will be conducted during 1959 on the same general plan as in 1957-58, under the direction of the C.S.A.G.I. (or its successor) as far as practicable and at such level and in such fields as may be determined. This means that each country will continue during 1959 those studies which are considered to be most important, but that the prescribed schedules of the I.G.Y. will be abandoned, and many of the special investigations discontinued. However, in most countries the routine observations which formed part of the I.G.Y. activities are conducted as part of a regular service such as is provided by the Meteorological Office, the D.S.I.R. Radio Research Organization, and the National Institute of Oceanography in this country. The name 'International Geophysical Co-operation 1959' has been suggested to cover the further period of co-operation envisaged at the Moscow meeting.

The International Council of Scientific Unions has decided that C.S.A.G.I. shall cease to function as such on 30 June 1959, but a new Special Committee for Co-operation in the Geophysical Sciences (S.C.G.) has been established. In general the participating committees set up in various countries to plan their I.G.Y. activities will continue to function in the same way in relation to I.G.C. 1959.

The developments in certain fields during the planning and observational periods of the I.G.Y. have led to the creation of further special committees by I.C.S.U. These are the Special Committee on Antarctic Research, the Special Committee on Oceanic Research and the Committee on Space Research, each of which will assist in international co-ordination of work in its field of activity. A further proposal for international co-operation which is likely to bear fruit is a suggestion that a World Magnetic Survey be conducted during the next sunspot minimum for comparison with the results obtained during the sunspot maximum with which the I.G.Y. was timed to coincide.

The co-operation of the British National Correspondents in compiling this survey is gratefully acknowledged. Readers of it will have gained some impression of the extent to which the International Geophysical Year 1957-58 has fulfilled the expectations of the scientists who planned and executed this enterprise. By being timed to take place during a period of predicted sunspot maximum (which has turned out to be the highest on record) the I.G.Y. has provided them with an unparalleled opportunity for research into the effects of the sun on our planet the earth. This opportunity has been grasped to the full and the observational phase of the programme has closed with an enormous volume of work satisfactorily accomplished. The reduction and analysis of the observations will proceed during the next few years and their final interpretation will be the culmination of the I.G.Y.

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