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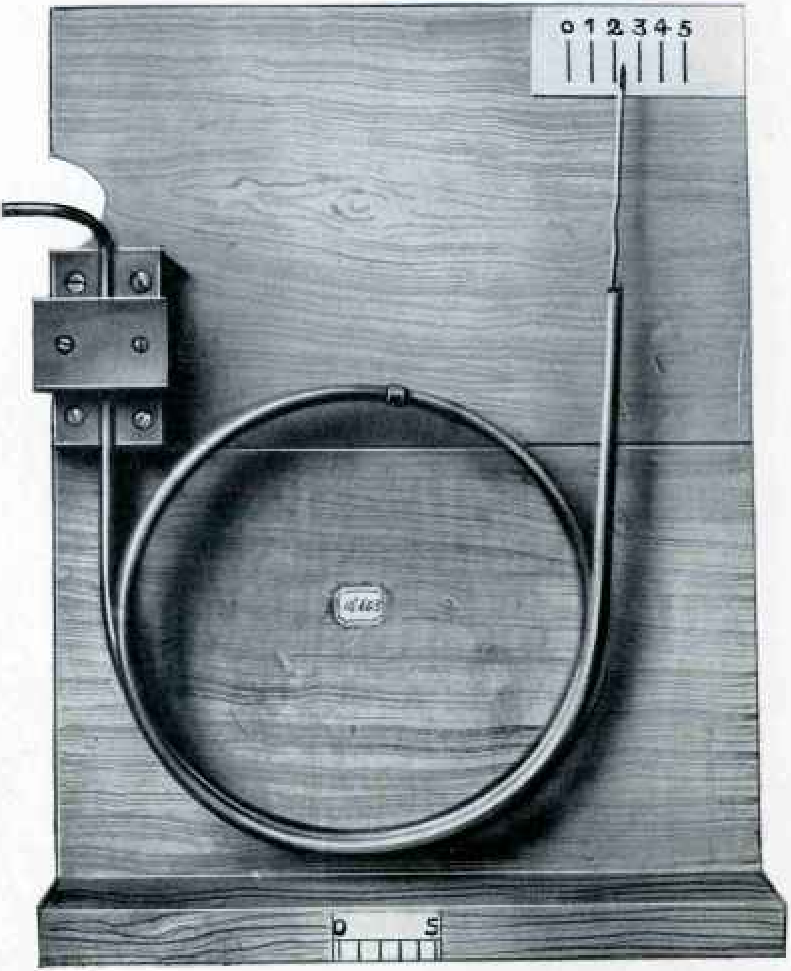

[*Courtesy Etablissements Bourdon.*

The first Bourdon tube.

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Issued by the
COPPER DEVELOPMENT ASSOCIATION
KENDALS HALL, RADLETT, HERTS.
Telephone No.: Radlett 5616

C.D.A. Publication No. 48.
Third Impression, 1955

Printed in England

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INTRODUCTION

THE history of every branch of science and technology shows that little advance is made until suitable instruments are devised to measure the quantities involved, and the accuracy of such instruments is a measure of the progress made. Without accurate measurement there is no certainty of performance, whatever the process may be. This is as true today as it was over seventy years ago when Lord Kelvin said, "When you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of *science*, whatever the matter may be."

It is not many years since the majority of industrial processes were controlled by the "know-how" of a foreman who had gained his experience in the hard way over long years of trial and error. With the increases in speed of production and the demand for greater uniformity of the products this method of control was not good enough and recourse had to be made to the use of industrial instruments, which after a slow start spread rapidly. Once having measured the variables in a process it was a logical step to introduce some form of control, but the theory of automatic control had to be built up before really successful operation was assured. That stage has been reached, and it is now possible to control automatically almost any conceivable process. The aim of this book is to show the part copper and its alloys play in industrial instrumentation and automatic control apparatus.

The title "Copper in Instrumentation" has been chosen to cover the uses of copper and its alloys in both ordinary industrial instruments and the ancillary equipment used for automatic control processes, instrumentation being commonly defined as the industrial applications of the science or technology of measurement and control. A book on instruments covering all aspects of their design, construction, testing and application could be set out in many ways; but in this publication, which deals with the more limited aspect of some of the materials used in instrument construction, it has been thought best to divide the subject into three main sections, namely, pressure- and strain-responsive instruments, electro-magnetic instruments and temperature-responsive instruments. When discussing the functions of an individual instrument or controller, it is convenient to split them into three stages: (*a*) conversion or detection stages, where the sensitive element detects the change in the variable to be measured or controlled; (*b*) intermediate stage, where the sensitive element output is amplified or transmitted; and (*c*) final or end stage, which may be the movement of a pointer over an instrument scale, a pen over a recording chart, or the initiation of a control operation. As far as possible this division of instrument functions has been followed in the present publication, although in many cases it is only the sensitive element that is considered.

No attempt has been made to deal with laboratory or purely scientific instruments, and the scope of the book has been restricted to instruments of types most commonly used in industry. The purely electronic aspect of instrumentation also falls outside the purview of this book.

Copper and its alloys are much used for instrument linkages, cases, dials, terminals, wiring and cabling, tubing, filters, etc., but in general these familiar, though essential, applications have not been dealt with in detail in this book. Of necessity, many aspects of instrument construction have also had to be left out; nevertheless it is hoped that the information given is sufficient to form a fairly complete picture of the finished equipment.

Although spiral and flat springs are used in almost every type of instrument controller, they are given only a very brief treatment here, as C.D.A. publication No. 39, "Copper and Copper Alloy Springs," deals with the matter at length. Similarly, resistance materials are fully dealt with in C.D.A. publication No. 38, entitled "Copper Alloy Resistance Materials."

It has been assumed that the reader has some acquaintance with the terminology of metallurgy; metallurgical terms used in this publication have, therefore, not been specially defined.

The Copper Development Association is indebted to many who have assisted in the preparation of this book and particularly to those mentioned in the text who have provided illustrations or blocks. The Association is a non-trading organization maintained by the British Copper Industry to collect and distribute information, to develop applications and processes connected with copper and its alloys, and to promote the extended and correct use of these materials. The Association's technical staff will be glad at all times to furnish advice or assistance, without charge or obligation, on any matter relating to copper or copper-bearing materials. A list of the Association's publications which are available on request, free of charge, to those genuinely interested will be found on page 152.

CHAPTER I

PRESSURE- AND STRAIN-RESPONSIVE INSTRUMENTS

BASIC PRINCIPLES

General

UNTIL early in the nineteenth century pressure was measured by balancing it against that of a column of liquid. Meteorology and the then new steam locomotive provided the incentive which led Fontaine-Moreau and Vidi in France to devise and patent in 1844 a method whereby a flexible metallic diaphragm was used to indicate pressure in terms of its deformation when the pressure was applied; a corresponding British patent of the same year also stands in the name of Fontaine-Moreau. Bourdon, whose name is usually associated with the arrangement, now in worldwide use, of a tube of oval cross-section bent in a curve to resemble the letter C, was working at about the same time on methods of pressure measurement. Although he himself does not appear to have taken out any British patent on the pressure-sensitive element associated with his name, a British patent of Vidi's in 1850 relates to improvements in the linkages and methods of indication of pressure-sensitive devices which are clearly of the Bourdon type. Earlier patents of Bourdon in France led to an action for infringement by Vidi; in the course of subsequent litigation it emerged that the idea of utilizing metallic deformation as a means of pressure measurement could be traced back even earlier than Vidi to the work of Conté in 1796, although he did not pursue or patent his idea. The court decided, however, that Bourdon's apparatus was based on a fundamentally different principle from that of Conté, which Vidi had applied, and the action was defeated. The same judgment was upheld in an appeal, Bourdon's invention being declared entirely original and Vidi's nothing more than an application of Conté's principles. Nevertheless, six years later, in 1858, Vidi actually succeeded in getting a reversal of this judgment and heavy damages were awarded to him, together with the entire stock of Bourdon's gauges.[1] The latter's name is, however, always associated with the familiar tubular pressure-sensitive elements to be described later in this publication.

The need for accurate indication of pressure has given rise to innumerable devices which, though essential for special applications, are not in general use. The bulk of pressure indicators used in industry today are based on the principles given by Vidi and Bourdon, namely, by the movement of corrugated diaphragms or capsules, Bourdon tubes or flexible metallic bellows. The first manometer to be made by Bourdon is illustrated in the Frontispiece, which shows clearly the principle of operation of tubes of this type.

In 1856 William Thomson[2] (later Lord Kelvin) pointed out that the resistance of a metal altered when it was stressed and gauges depending on this principle are now widely used. (Strictly speaking, all such sensitive elements are known as secondary elements, to differentiate them from primary elements which read in terms of length or mass and need no calibration, e.g. liquid manometers, dead weight piston gauges, etc.). Apart from pressure indication by means of elastic deformation of metal and change of resistivity, there are also inferential methods of pressure measurement based on the e.m.f. produced when pressure is applied to certain types of crystals, the thermal conductivity of gases, rate of ionization in a gas, movement of a conductor in an electric field, etc., but this chapter is concerned only with those methods which depend on elastic deformation or change of resistance of copper alloys with pressure or strain.

Although the subject is treated in detail later, it is convenient at this stage to note that materials for pressure-sensitive elements may be divided into two main groups:—

(*a*) Those which obtain their good elastic properties as the result of working the material in the cold stage ("strain-hardening materials").

(*b*) Those in which the requisite properties are acquired as the result of heat treatment ("heat-treatable materials").

In order that the best choice for any given application may be made, it is necessary to understand what happens to a metal when it is subjected to elastic and plastic deformation or strain and an elementary outline is given before considering the individual properties of the materials.

Elastic and plastic strain

The maximum stress which can be placed on a material without a departure from Hooke's Law ("Ut tensio sicut vis: As the stretch so the force") is known as the limit of proportionality. Hooke enunciated his law[3] in 1674, since when it has been generally accepted, although modern thought tends to the view that all metals have curved stress/strain relationships and that perfect linearity does not exist. The departure from linear law within a limited range has, however, been detected only by ultra-sensitive methods. As far as pressure-sensitive elements for industrial instruments are concerned, a linear law and a definite limit of proportionality may be taken to exist for the materials under consideration.

External forces on a body are resisted by internal stresses which are mainly electrostatic in nature. Consideration of the nature of these stresses would involve a study of recent theories of the atomic structure of metals; this subject is, however, far beyond the scope of this publication and those who wish to pursue the subject are referred to the works of Hume-Rothery,[4] Mott and Jones,[5] Wilson[6] and others.

When a material is stressed within the limit of proportionality its atoms move relatively to each other, but return to their original positions when the external load is removed. The restoring stress in the material is proportional to the factor which is usually referred to as Young's Modulus. In practice, Young's Modulus is generally obtained by measuring the slope of the stress/strain diagram and, within the limit of proportionality, does not change with change of external stress. If the material is worked at any time beyond that limit then, apart from any sub-permanent set which may occur, the value of the modulus may also be very slightly changed. In cold plastic working of the metal, such as occurs in the production of capsules, tubes, diaphragms or bellows for pressure-sensitive elements, the atoms slip along so-called "slip-planes," thus allowing the metal to be shaped into new forms. As the amount of cold-working increases, the crystals become elongated in the direction of the plastic flow. Heavy cold-working results not only in fragmentation of the crystals but gives a pronounced preferred orientation to them. The distortion of the crystal lattice results in an increase in the internal strain energy and an increase in hardness, tensile strength, etc., of the metals, which may be considered as a stored part of the energy expended in cold-working the material. Numerous theories have been advanced to account for the alteration in physical and mechanical properties, but none of them fully accounts for all the observed facts. The internal stresses in a cold-worked material, i.e. those stresses present in a material when no external forces are acting on it, are very complex and may vary considerably over a quite small section of the material.

Stress relief and annealing

Internal stresses have a very pronounced effect on the properties of metals, particularly when used for pressure-sensitive elements. As these stresses in a cold-worked material may vary in an unpredictable manner, it is essential that they be removed, or at least reduced to very low values, if dependable elastic properties are to be obtained. In the case of strain-hardening materials (i.e., those which depend for their elastic properties on the amount of cold work which has been done on them), removal of internal stresses is usually effected by means of a low temperature heat-treatment generally known as a stress-relieving treatment; on the other hand, stress-relief is to a very large extent automatically accomplished in alloys which obtain their elastic properties as a result of heat treatment (see pp. 21, 31).

As the temperature of cold-worked material is raised under carefully controlled conditions above a critical value, but to an extent not sufficient to cause general annealing, so-called "recovery" of the material takes place. This is usually manifested by an increase in the limit of proportionality and an increase in conductivity and, in certain materials, due to the relief of internal stresses, by a greater resistance to season cracking. As the temperature is further increased new crystals appear and, depending on the time/temperature relationship, annealing takes place and the whole of the metal ultimately consists of new crystals. Annealing is a time/temperature phenomenon and, provided the temperature is above a certain critical value, similar (although not identical) results will occur with a high-temperature short-time anneal as with a lower temperature long-time anneal. When the recrystallization due to annealing is complete, the effects of cold work on the specimen are removed. The temperature at which annealing starts not only varies with the composition but also depends upon the amount of cold work the metal has received; the greater the amount the lower the temperature at which annealing will commence. Thus extremely heavily cold-worked pure copper can start to anneal at comparatively low temperatures, but it is much more difficult to remove slight hardening due to small amounts of cold work. Continued increase of the temperature or time results in growth of the new grains and very large crystals can be obtained by suitable heat treatment. Grain size is an important factor when selecting sheet material for the forming of capsules and bellows. As a general rule, the larger the grain size the more ductile the material, i.e. the greater its ability to deform plastically under stress; but above a certain size the grains tend to show on the surface, producing an "orange-peel" effect, and the tendency to rupture increases. Apart from the selection of a suitable grain size, the regularity of grain size is of great importance, as material containing areas of large grain size compared with the remainder will tend to flow more readily at those areas. Jevons[7] has considered the effect of grain size on drawing in some detail. Severe preferred orientation must also be avoided in materials which are to be drawn and this can be achieved by suitable rolling and annealing technique.

Pressure-responsive elements of the elastic deformation type should be made of materials which enable the following requirements to be met:—

- (*a*) Deflection to be a linear function of the applied pressure at all working temperatures and to be consistently repeatable over long periods. (See below under *Variation of modulus of elasticity*.)
- (*b*) No appreciable time-lag between application or release of pressure and movement of element to its final position. (See below under *Elastic drift and recovery*.)
- (*c*) Element to return to zero position when pressure is released. (See below under *Zero shift*.)
- (*d*) No difference in reading under increasing and decreasing pressure. (See below under *Hysteresis*.)
- (*e*) Material for sensitive instruments to possess a high ratio of maximum working stress to modulus of elasticity.
- (*f*) Material to have a high endurance strength: this is the property which determines the maximum stress at which the pressure-sensitive elements can be used. Where maximum accuracy is required, a low working stress will be essential; this will probably be below the endurance strength also.

To meet all these requirements a metal would have to have perfect elastic properties and no such material is known, though the properties of some materials approach more closely to the ideal than those of others. In addition, the ideal material should, of course, be highly resistant to any possible corrosive attack by the fluids with which it may have to come in contact. It should also be readily available in the form required (tube, strip or sheet) and should be easy to work.

Elastic imperfections*

Several copper-base alloys meet most of the requirements; but before considering their properties in detail it is instructive to study the ways in which departures from the law of perfect elastic behaviour may occur. It is convenient to consider them under the following headings:—

- (*a*) Variation of modulus of elasticity.
- (*b*) Elastic drift and recovery.
- (*c*) Zero shift.
- (*d*) Hysteresis.

These terms have slightly different meanings in various contexts, but the definitions given here are those usually accepted in instrument practice.

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* Further information on this subject may be found in Chapter IV of C.D.A. Publication No. 39, "Copper and Copper Alloy Springs."

(*a*) *Variation of modulus of elasticity*

An ideal elastic material would exhibit a perfectly linear stress-strain relation. In fact, however, the modulus of elasticity varies very slightly with the stress and the resulting stress-strain curve is not quite linear.

Both Young's Modulus and the rigidity modulus for metals also vary with temperature, and with copper-base alloys (as with most metals, although not all), the modulus falls as the temperature rises, thus giving a greater movement of the material for a given load. Considerable work on the effect of temperature on Young's Modulus has been carried out, chiefly with regard to instruments for use in aircraft, where high degrees of accuracy are required over large ranges of temperature. For the copper alloys considered here, the modulus temperature coefficients lie between 0.03 and 0.05 per cent. per degree C. Table 11 of C.D.A. publication No. 39, "Copper and Copper Alloy Springs," gives a summary of values for various copper alloys.

The modulus of elasticity also varies with time, the phenomenon being known as "ageing." With copper-base alloys the change is usually a slight increase, but with other alloys it may in rare instances be a decrease, the variations being up to a maximum of 5 per cent. Ageing is due to release of the internal stresses arising in the course of manufacture, and may be removed by low-temperature heat treatment.

(*b*) *Elastic drift and recovery*

Drift as here considered is a slow and usually minute change in the indication given by a sensitive element after every pressure change and after the true elastic strain has taken place. Drift always occurs in the direction of the pressure change and, if the pressure remains, continues for many hours, although the rate of drift decreases rapidly. The amount of drift at the end of a pressure cycle is sometimes referred to as "after-effect." On the removal of the load, the direction of the movement reverses and in most cases recovery is eventually completed, although the process is very slow. Drift depends, to a certain extent, on the pressure changes to which the instrument has previously been subjected, although it naturally depends principally on the pressure changes last made, particularly if their magnitude is large. Before measuring drift the element should be in the rested state, which will take at least twenty-four hours to achieve.

The phenomenon of "drift" is closely associated with creep, but the term "drift" is generally reserved for the elastic portion of these effects, i.e. the portion which ultimately recovers when the stress is removed.

Elastic drift can usually be eliminated or, at least, greatly reduced in cold-worked copper alloys by low-temperature heat treatment at about 200° C. for about 2 or 3 hours and it is also advantageous in a pressure-sensitive element to subject the element to a pressure cycle in which the pressure is brought up to at least the maximum designed pressure and then released slowly, the whole process being repeated if necessary two or three hundred times. This process is referred to as "seasoning" or "cycling." The drift in copper alloys used in pressure-sensitive elements is very small, as may be seen from Fig. 1.

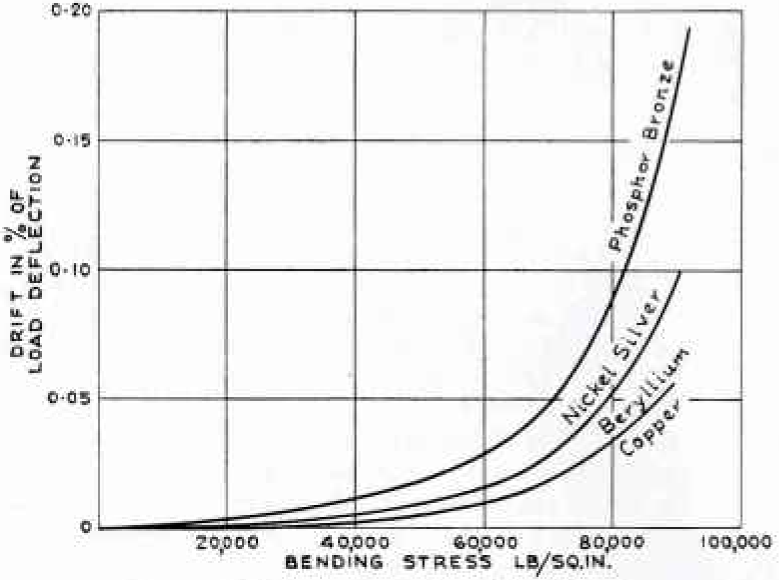


FIG. 1.—Drift in some copper-base alloys (Carson[9]).

(*c*) *Zero shift*

Zero shift is a change in the neutral position from which there is no recovery. This failure to recover the initial position distinguishes zero shift from drift, although, as with drift, it is usually shown by a change in position of the sensitive element in the direction of increase in pressure change. It is considered to be mainly due to the slow release of the internal stresses which have been induced in the material by cold-working. Pressure elements can have the zero shift greatly reduced by low-temperature heat treatment, the temperature and time of which vary with the material and are considered later under the heading "Materials." It may also be reduced by a cycling or seasoning treatment and unless so removed may take several years before it finally ceases. Alloys which obtain their hardness as the result of heat treatment show very little, if any, zero shift.

Recapitulation: Drift and Zero Shift.—Recapitulating, it may be seen that when a load is applied to a material an almost instantaneous deflection takes place, which, in the ideal case, is exactly proportional to that load. In practice, however, following on this initial deflection, if the load is maintained the material "creeps" at an ever decreasing rate to a higher value of deflection; on removal of the load a small deflection known as the "after-effect" remains. Recovery of the elastic drift then takes place, reducing the "after-effect" in the course of time to a small permanent value known as the "zero shift"; zero shift is thus seen to be the plastic component of creep, while drift, although a certain time must elapse before its recovery is complete, is the elastic component. Zero shift, under specified test conditions, is a useful method of determining the consistency of a production run of pressure-sensitive elements.

(*d*) *Hysteresis*

Hysteresis, in pressure-responsive instruments, is defined as the difference in reading at any given stress, measured when the stress is increasing and when it is decreasing, the time interval between the readings being very small. It is thus easily distinguishable from drift, which has its maximum effect after a long period.

A pressure-indicating instrument will, in general, read lower when pressure is increasing than when it is decreasing. On some instruments the speed at which the pressure cycle is made affects the reading, but not usually to any marked degree. Hysteresis can be kept to a minimum by working the material at a low stress, but generally it is more economical to use a better grade of material which, though more expensive, can be worked at a higher stress with the same degree of hysteresis. Low-temperature heat treatment or cycling does not have any very marked effect on the hysteresis value.

MATERIALS FOR PRESSURE-SENSITIVE ELEMENTS

General

Copper alloys used for pressure-sensitive elements may, as already mentioned, be divided into two main classes, (*a*) strain-hardening alloys, i.e., those which obtain their good mechanical properties as a result of cold working, such as brasses, phosphor bronze, nickel silver, aluminium bronze and Monel, and (*b*) heat-treatable alloys, i.e., those which obtain

TABLE I

Mechanical and Physical Properties of Materials Used For Pressure-Sensitive Elements

Description	Composition		Properties					British Standard
	Cu (%)	Other Elements (%)	Limit of Proportionality (Ton/sq. in.)	0·1% Proof Stress (Tons/sq. in.)	Tensile Strength (Tons/sq. in.)	Modulus of Elasticity (lb/sq. in. $\times 10^6$)	Diamond Pyramid Hardness (No)	
80:20 brass ..	80	20 Zn	2·5(A)–17(H)	4·5(A)–32(H)	20(A)–40(H)	15	65(A)–170(H)	711
Phosphor bronze, "Low tin"	96	3·75 Sn, 0·1 P	4(A)–25(H)	7(A)–40(H)	22(A)–48(H)	14·5	60(A)–210(H)	407/1
Phosphor bronze, "High tin"	93	6·75 Sn, 0·1 P	5(A)–35(H)	10(A)–50(H)	24(A)–55(H)	14·5	65(A)–260(H)	407/3
18% nickel silver	62	18 Ni, 20 Zn	5(A)–22(H)	8(A)–40(H)	24(A)–45(H)	18	75(A)–220(H)	790
Monel	29	68 Ni, 1·25 Fe, 1·25 Mn	10(A)–25(H)	15(A)*–38(H)*	35(A)–47(H)	25	120(A)–220(H)	1526
4% aluminium bronze	96	4 Al	4(A)–20(H)	8(A)–38(H)	25(A)–50(H)	18	80(A)–220(H)	—
80:20 copper-nickel	80	20 Ni	4(A)–18(H)	7(A)–30(H)	22(A)–35(H)	20	75(A)–165(H)	374
3% silicon bronze	96	3 Si, 1 Mn	4(A)–20(H)	6(A)–40(H)	23(A)–50(H)	15	70(A)–220(H)	—
2% beryllium copper	97·6	2 Be, 0·4 Co	(*a*) 6 (*b*) 35 (*c*) 40	(*a*) 10 (*b*) 50 (*c*) 60	(*a*) 30 (*b*) 75 (*c*) 85	19	(*a*) 110 (*b*) 350 (*c*) 400	—
K-Monel	25	68 Ni, 4 Al, 2 Fe, 1 Mn	—	(*a*) 25* (*b*) 45* (*c*) 55*	(*a*) 45 (*b*) 65 (*c*) 75	25	(*a*) 200 (*b*) 300 (*c*) 310	—
Copper-manganese-nickel	60	20 Mn, 20 Ni	—	(*a*) 13–16 (*b*) 60 (*c*) 60	(*a*) 35–40 (*b*) 70–78 (*c*) 70–80	21	(*a*) 130–145 (*b*) 350–390 (*c*) 450	—

In the above table the suffix (A) refers to the annealed condition while the suffix (H) refers to the most fully work-hardened condition which is usual in commercial production; for Monel, this corresponds to about 20 per cent. reduction in thickness only, though for the remaining materials a greater degree of cold-working than is represented by this figure is more usual.

In the case of the precipitation-hardening alloys the suffix (a) refers to the solution heat-treated condition, (b) to the solution heat-treated and precipitation-hardened condition, and (c) to the solution heat-treated, cold-worked and precipitation-hardened condition.

* 0·2 per cent. Proof Stress.

their properties as a result of heat treatment, such as beryllium copper, certain copper–manganese–nickel alloys and K-Monel. In this publication only such details of these alloys are given and tabulated as might be useful in connection with their use in pressure-sensitive elements and fuller general information will be found in other C.D.A. publications. Table I shows typical values of some of the mechanical properties for comparison purposes. From this it may be seen that the mechanical properties of copper-base alloys vary over a wide range and this, combined with their resistance to corrosion, makes them suitable for use in a very large number of industrial processes. Copper alloys should not, however, be exposed to the action of ammoniacal solutions, strongly oxidising acids and salts, mercuric or ferric compounds.

Brass

The word "brass" is used as a general term to cover the whole range of copper-zinc alloys. The alloys may sometimes also contain small percentages of other elements such as tin, lead, iron, silicon, aluminium, manganese and nickel. For further information on brasses reference should be made to other C.D.A. publications, especially Nos. 6, 36 and 43.

The main use of brass for pressure-sensitive elements is for flexible bellows (sometimes known as "sylphons"), although it has been and still is used to a more limited extent for Bourdon tubes and diaphragms. The brass in general use for these purposes is composed of 80 per cent. copper and 20 per cent. zinc. With this percentage of zinc the alloy consists of a uniform solid solution of zinc in copper and is known as *alpha* brass. Alpha brasses which include percentages of zinc up to about 36 per cent. combine good mechanical properties with considerable ductility, enabling them to be easily worked in the cold condition. When the percentage of zinc is in excess of about 36 per cent. a second or *beta* phase is formed in the alloy. This has the effect of considerably reducing the ductility, making it necessary to carry out forming operations in the hot state and preventing high elastic properties being obtained. Thus for pressure-sensitive elements such alloys are useless, but nevertheless these brasses find a wide use for other parts in instruments and controllers, since they can be hot stamped or die-cast, giving good mechanical properties with close dimensional tolerances, are easy to machine and have good corrosion resistance.

For pressure-sensitive elements a brass is required that can be easily rolled, pressed, drawn or otherwise fabricated to close tolerances and which combines good elastic properties with good resistance to corrosion. 80:20 brass adequately fulfils these conditions and its main properties are given in Table I. It will be noted that, although the strength of this cold-worked brass approaches that of the lower carbon steels, its modulus of elasticity, like that of other copper alloys, is only just over half that of these steels. Thus, under similar conditions and for a given stress, the deflection of brass is nearly twice that of steel, thus making a much more sensitive element, an advantage which is shared by most copper-base alloys. Fig. 2 shows the effect of cold working on 80:20 brass. For sensitive elements this composition probably provides the optimum relationship between ease of working and final mechanical properties, resistance to fatigue and corrosion. Certain brasses are subject to what is known as "stress corrosion" or "season cracking," due to a combination of corrosion attack and internal stresses. It is generally considered that alloys containing less than 15 per cent. zinc are free from the risk of season cracking. The 20 per cent. zinc alloy used in the making of a bellows is also virtually free from this risk. Above a zinc content of about 20 per cent. however, season-cracking may occur and this is one of the reasons why 80:20 brass is chosen, since bellows are widely used in connection with industrial processes where mildly corrosive conditions exist which might initiate this form of failure. The risk of season cracking is considerably reduced if the internal stresses in the material are relieved and this can be done by a suitable low-temperature heat-treatment, generally known as a "stress-relief treatment," to which reference has already been made (see p. 16). At the same time this treatment very slightly raises the limit of proportionality and tensile strength. A suitable treatment for 80:20 brass is for half an hour to one hour at 250° to 270° C. Annealing is usually carried out at 450° to 650° C. The annealing time should be such that excessive grain growth does not occur and for small articles should not normally exceed a few minutes. A suitable grain size for the applications under consideration is about 0.03 mm. to 0.04 mm.

Phosphor bronze

The phosphor bronzes are essentially copper–tin alloys, containing additions of phosphorus, generally from about 0·02 per cent. to 0·4 per cent. Two ranges of composition are usually employed in the construction of pressure-sensitive instruments, those possessing a tin content of about 3.5 to 5 per cent. and those with a tin content of about 5 to 7 per cent. In both these alloys the tin forms a uniform solid solution with the copper and both can be formed by cold work into sheet, strip, wire, rod, tube, etc. Table I gives their main properties and it will be seen that their limit of proportionality is higher than that of 80:20 brass;

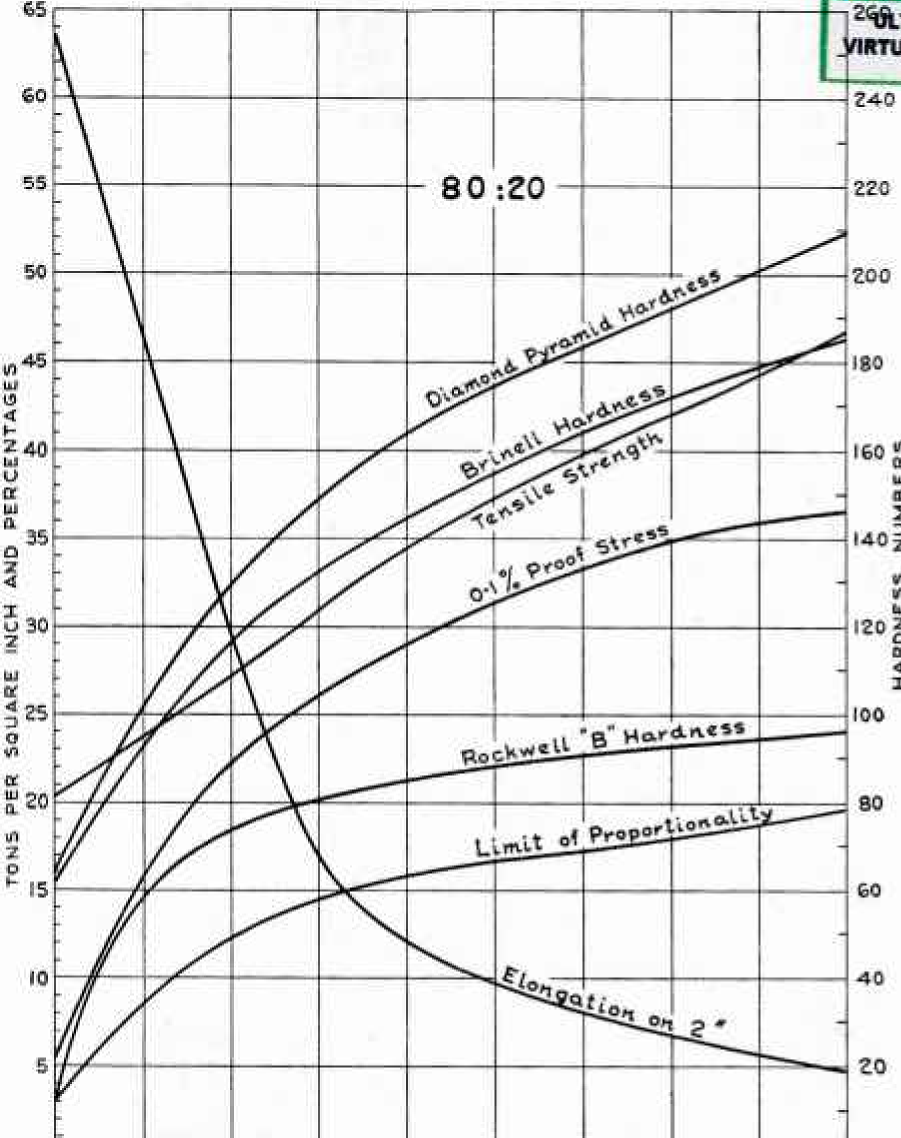


Fig. 2.—Effect of cold working on mechanical properties of 80:20 brass.

generally, also, their resistance to corrosion is somewhat better. They work-harden more rapidly than 80: 20 brass, as can be seen from Fig. 3 and, therefore, cannot be cold-worked to the same extent without inter-stage annealing. The endurance limit is higher than for 80: 20 brass, while drift and hysteresis are lower. Internal stresses can be reduced, and the limit of proportionality raised, by heating for half to 1 hour at 250° C. to 270° C.* Annealing can be carried out in the temperature range 450° C. to 650° C. Phosphor bronze is widely used for the manufacture of Bourdon tubes and diaphragms and, when the occasion demands, also for bellows.

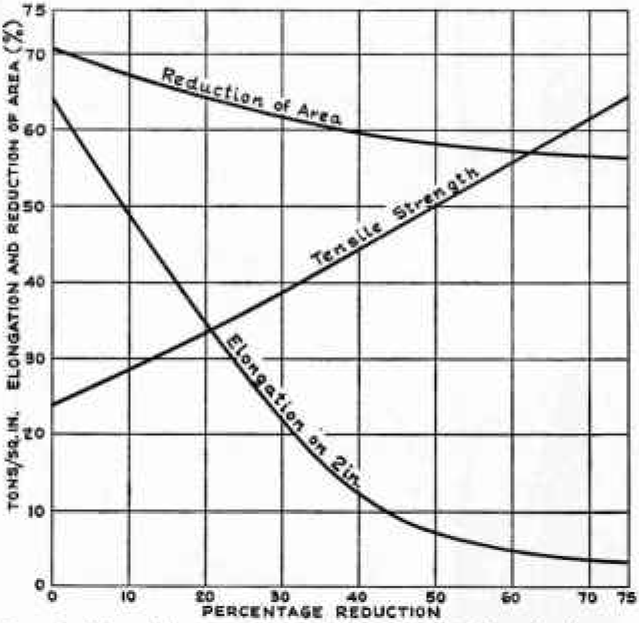


FIG. 3.—Effect of cold working on mechanical properties of phosphor bronze (6 per cent. tin).

Nickel silver

There is a wide range of copper–nickel–zinc alloys which take the name of "nickel silver" because of their silvery appearance, but those used for instrument purposes generally have a nickel content of 12 per cent., 15 per cent., 18 per cent. or 20 per cent. The copper content is usually maintained at from 55 per cent. to 65 per cent., the remainder being zinc. Nickel silver is not now often used for pressure-sensitive elements, although it was

* For optimum spring properties, a lower temperature for a longer period may be used.

quite widely used in the past. The main properties of the 18 per cent. alloy are given in Table I. Fig. 4 shows the effect of cold rolling on the mechanical properties of nickel-silver strip with 18 per cent. nickel. A typical stress-relief treatment would be to heat the components for half to 1 hour at 270° C. to 300° C. Annealing should be carried out in the temperature range 600° C. to 750° C.

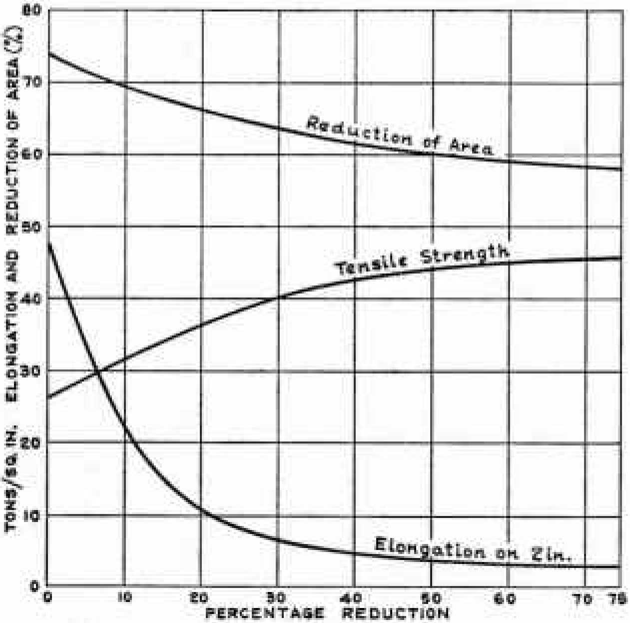
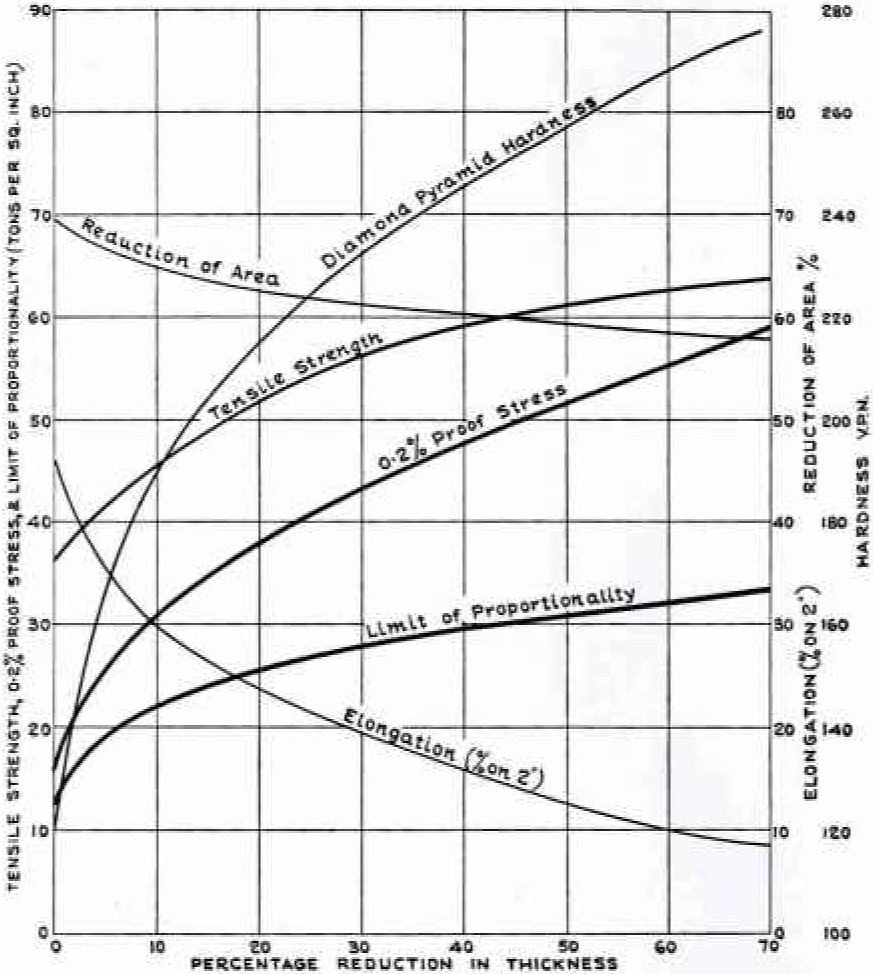


Fig. 4.—Effect of cold working on mechanical properties of nickel silver (18 per cent. nickel).

Monel

Monel is an alloy containing approximately 29 per cent. copper, 68 per cent. nickel and 1.25 per cent. each of iron and manganese. It is highly resistant to most corrosive agents, and, at the same time, possesses good mechanical properties, typical values of which are shown in Table I. It will be noted that its tensile properties are better than those of the brasses, bronzes and nickel silver previously described, while at the same time it has a high ductility. Fig. 5 shows the increase of hardness with cold working; for pressure-sensitive elements it is advisable to give a stress-relief treatment after the cold-working operation. A typical treatment would be to maintain the cold-worked material at about 300° C. to 350° C. for half to 1 hour. Annealing should be carried out at a temperature of 700° to 800° C., depending upon the degree of cold working.



[Courtesy of Messrs. Henry Wiggin & Co. Ltd.

FIG. 5.—Effect of cold working on mechanical properties of Monel.

Monel is used for pressure-sensitive elements where other materials, which would be easier to fabricate, would be prone to failure due to corrosion. Monel can also be used at rather higher temperatures than the previously described materials without appreciable softening.

Aluminium bronze

The aluminium bronzes are copper–aluminium alloys containing up to about 12 per cent. aluminium, but for pressure-sensitive elements the aluminium content would normally not exceed 7 per cent. Alloys within this range possess good ductility and have mechanical properties somewhat similar to those of the *alpha* brasses, but their superior corrosion-resisting properties enable them to be used in situations where brass would be unsuitable. The properties of 4 per cent. aluminium bronze are shown in Table I but are more fully covered in C.D.A. publication No. 31, which should be consulted for further particulars. Fig. 6 shows the effect of cold rolling on the mechanical properties of 4 per cent. aluminium bronze.

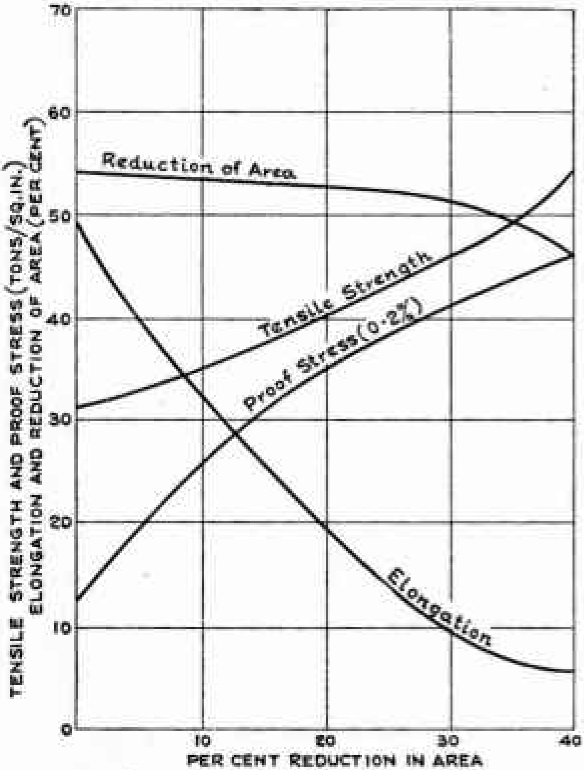


FIG. 6.—Effect of cold working on mechanical properties of aluminium bronze.

The corrosion resistance of aluminium bronze is mainly due to the formation of a surface film of aluminium oxide. With certain acid solutions, notably both hot and cold sulphuric acid in moderate strengths, the protective film permits the aluminium bronzes to be used with outstanding success.

Aluminium Brass

Although pre-eminently a marine condenser-tube alloy (see C.D.A. Publication No. 43, p. 37), aluminium brass (76 per cent. Cu, 22 per cent. Zn, 2 per cent. Al), by virtue of its high resistance to salt-water corrosion, is sometimes preferred to a straight brass for marine applications.

Cupro-nickel

The 80:20 copper-nickel alloy used in the manufacture of bullet envelopes possesses properties which make it suitable also for use in pressure-sensitive elements. Its tensile properties are similar to those of 80:20 brass, as may be seen from Table I, while it is particularly suited to heavy degrees of cold work and has good resistance to corrosion.

Silicon bronze

Where rather higher tensile properties than those of 80:20 brass are required, a 3 per cent. silicon bronze may be used. Its properties are included in Table I. It is strongly resistant to corrosion.

Beryllium copper

General.—Of the heat-treatable alloys, the beryllium coppers are probably the most important alloys for pressure-sensitive elements where extreme accuracy is required or where the conditions are particularly onerous due to high alternating stresses or corrosive influences. Owing to the ease with which production runs can consistently be made, calibration and rejects are reduced to a minimum and thus, despite an initial cost higher than that of competitive materials, the final product may ultimately be cheaper than with a lower first-cost material.

Several beryllium copper alloys are available, the most important, from the point of view of pressure-sensitive elements, probably being the alloy which normally contains about 2 per cent. beryllium with 0·3 per cent. or 0.4 per cent. cobalt or nickel. It is this ternary alloy which is considered here. Not only does the additional element effect a distinct economy of beryllium, but it facilitates heat-treatment by making the conditions under which this must be carried out rather less critical than would otherwise be the case. This alloy, which is available in any of the normal commercial forms, such as strip, wire, tube, etc., attains its good mechanical properties only after heat treatment.

Relative freedom from the elastic imperfections enumerated on page 18, combined with its high limit of proportionality and endurance strength, high resistance to corrosion (see p. 33) and freedom from directional properties, make beryllium copper a unique material for pressure-sensitive elements. So good are its properties that, after correct processing, the measurement of its departure from the law of perfect elastic behaviour is sometimes difficult. Special testing devices have, however, been developed for measuring these factors so as to assist in the selection of the optimum heat-treating conditions.

Heat treatment.—At 800° C., the solid solubility of beryllium in copper is about 2 per cent. and beryllium copper, if quenched after being held at this temperature for a sufficient time to attain equilibrium, consists of a single-phase solid solution. In this condition, the alloy is soft and ductile and can be cold-rolled into strip or drawn into wire in the same way as copper or the *alpha* brasses. The electrical conductivity, it should be mentioned, is in this condition only about 15 per cent. of that of pure copper.

At 300° C., on the other hand, the solid solubility of beryllium in copper falls to 0·2 per cent. and after sufficient reheating at this temperature nearly the whole of the beryllium is ejected from solid solution as a separate phase. When the conditions of heat treatment are such that this second phase separates from the solid solution in the form of ultra-microscopic particles distributed more or less uniformly throughout the matrix, the alloy becomes exceedingly hard and strong, while the ductility is much diminished. It can no longer be easily rolled and drawn, but possesses all the attributes of an excellent spring material. These changes are accompanied by a marked increase in electrical conductivity to as much as 30 per cent of that of copper.

Further, like most other metals and alloys, beryllium copper is also hardened and strengthened by cold work. Thus, if a sample is rendered soft and ductile by quenching from 800° C. and is then cold rolled or drawn, it will become much harder and stronger. At the precipitation-hardening temperature of about 300° C. cold-worked beryllium copper does not recrystallize or anneal and it is, therefore, practicable to superimpose the hardness and strength occasioned by the precipitation effect upon that due to cold work, and in this way to obtain the phenomenally high strengths which are a unique feature of beryllium copper.

Table I shows the typical properties of the 2 per cent. (nominal) beryllium copper alloy, but the precise thermal treatment that is given, both in the solution-annealing and in the hardening stages, may vary the properties of the material. In the production of pressure-sensitive elements it is therefore, important that, from each batch of material received, samples should be selected, formed and then heat-treated in order to ensure that the optimum conditions for the final product are obtained. Typical results of heat treatment are given in Fig. 7, which shows that the heat treatment is not the same for obtaining the optimum mechanical and electrical properties. If the best combination of hardness, freedom from drift and high limit of proportionality, such as are required in pressure-sensitive elements, is the main consideration, then a rather longer time is needed than that for obtaining the highest tensile strength, and a still longer time is required to obtain the maximum conductivity. To obtain the maximum conductivity it is usually necessary to "over-age" the material.

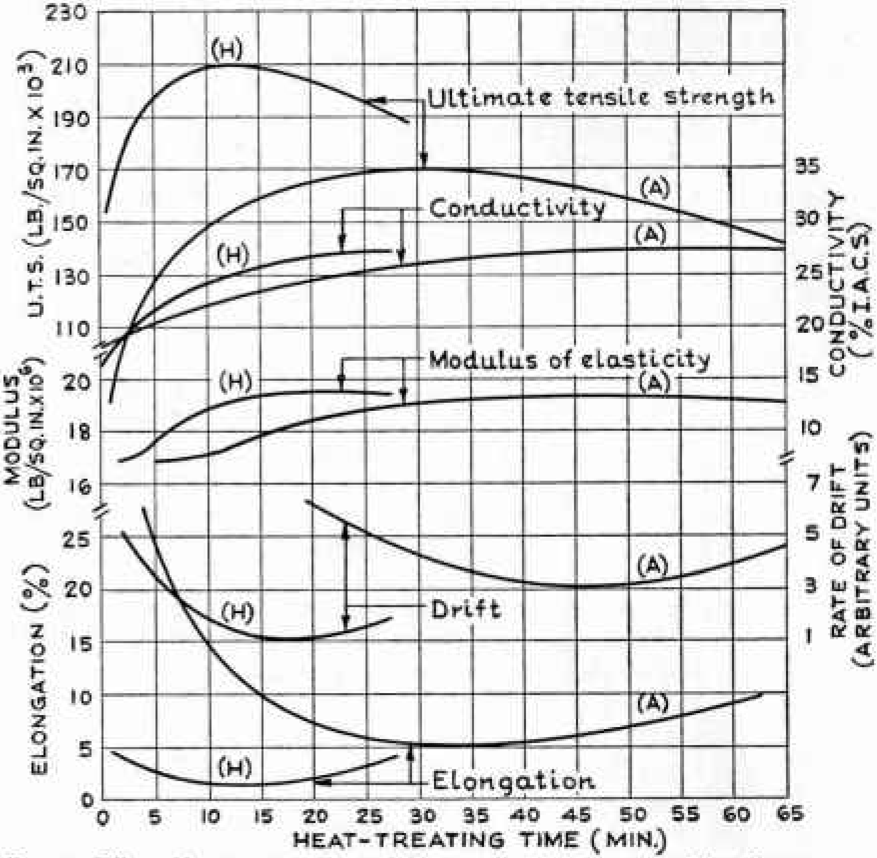


Fig. 7.—Effect of heat treatment at 350° C. on mechanical properties of beryllium copper. H= half-hard; A= annealed.

It will be noted from Fig. 7 that the heat treatment is not the same when the material is in the annealed condition as when it has received a certain amount of work hardening. The heat treatment necessary to harden the material also relieves most of the unwanted internal stresses, although for applications requiring the minimum of drift at low stresses there would seem to be some advantage in using a rather higher temperature for a shorter time.

Resistance to corrosion.—In most normal environments, the resistance to corrosion of beryllium copper is comparable with that of copper itself; it is far more resistant to corrosion than most of the steels with which it competes in the manufacture of springs and pressure-sensitive appliances.

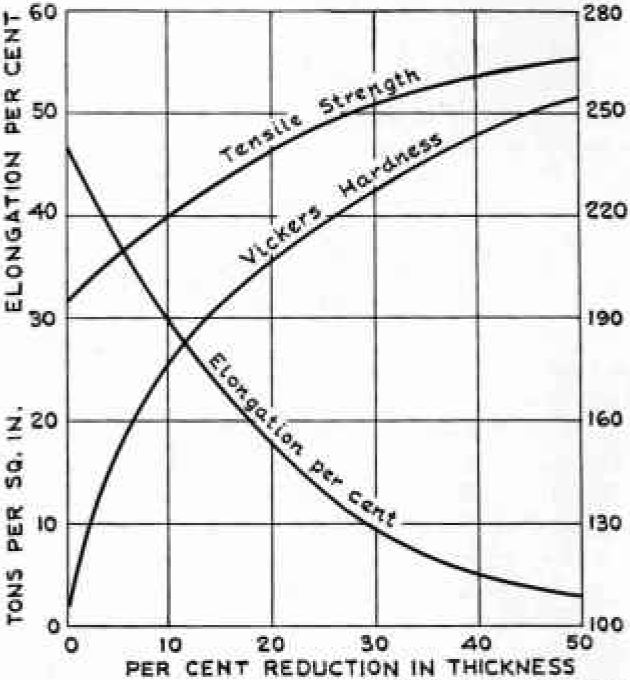
Beryllium copper is quite as resistant as copper to the corrosive effects of sea water, and its resistance to corrosion fatigue in this medium is also outstandingly high. In a salt-spray test taken in the course of an investigation into the properties of this alloy the endurance strength was ± 17·4 tons/sq. inch for 50×10^6 cycles, and beryllium copper was regarded by the investigators as superior to the best 18:8 chromium nickel steel tested.[8] (It should be noted that these tests were carried out on beryllium copper prior to its final heat treatment, the tensile strength of the specimen being 41·8 tons/sq. inch only. Heat treatment at 350° C., though having a very pronounced effect on the tensile strength, as will be observed in Fig. 7, has little effect on the fatigue limit.)

Under oxidising conditions, especially at elevated temperatures, the film of beryllium oxide formed on the surface of the material is protective and greatly retards progressive oxidation. Since, however, the temperatures at which such protection becomes apparent are those at which over-ageing occurs, the use of beryllium copper merely as an oxidation-resisting material would hardly be economical.

Beryllium copper is attacked by sulphur and certain of its compounds, particularly those which, like sulphur dioxide and sulphuretted hydrogen, are gaseous. The chloride, like other halides of beryllium, is volatile and beryllium copper is attacked by gaseous chlorides, especially at elevated temperatures.

Fabrication of beryllium copper.—No particular difficulty is found in the fabricating of beryllium copper in the soft condition, although it work-hardens slightly more rapidly than brass or phosphor bronze. About 30 per cent. reduction between anneals is generally found possible in press-work technique, and it is important to note that every anneal must be carried out at the homogenizing temperature of 800° C., followed by quenching. Wear on press tools is more severe than that with most other non-ferrous alloys, and greater spring-back must be allowed for in bending operations, especially when using work-hardened material with a view to developing the maximum hardness and strength by subsequent heat treatment.

In order to prevent distortion, heat treatment of the formed parts should be carried out in fixtures sufficiently rigid to prevent movement of the pressure-sensitive elements. In this way, the elements can be produced to within very fine tolerances and with a high degree of reproducibility.



(Courtesy of Messrs. Johnson, Matthey & Co., Ltd.

FIG. 8.—Effect of cold rolling on mechanical properties of solution heat-treated beryllium copper.

Fig. 8 shows the effect of cold working upon beryllium copper. For stampings or pressings, the material should be used in the half-hard condition if this is possible, since such material is less likely to distort during heat treatment.

The high temperature required for annealing gives rise to a certain degree of superficial oxidation unless a protective atmosphere is used in the furnace. For cleaning purposes a suitable pickling solution consists of

Concentrated sulphuric acid	2 pints.
Sodium dichromate	5 pounds.
Water	5 gallons.

K-Monel

K-Monel has a composition basically similar to that of Monel, except that small percentages of aluminium and silicon are added which enable it to be heat-treated to give improved mechanical characteristics. K-Monel has a higher limit of proportionality and proof stress than Monel and, if required, the heat-treatment can be carried out after cold working. The heat treatment temperature is sufficiently high to relieve any unwanted internal stresses. Heat treatment is usually carried out on the finished object at a temperature between 530° C. and 580° C., the times varying from 6 to 16 hours. After this, the material should be quenched in water or in a solution of approximately 2 per cent. by volume of denatured alcohol in water, to minimize oxidation. Where annealing is required, this may be carried out by heating to a temperature of approximately 870° C. to 980° C. for one to five minutes. Table I shows typical mechanical properties. Apart from its excellent corrosion-resisting properties, which enable it to be widely used in the chemical industry, K-Monel can be employed at both high and low temperatures without exhibiting any seriously imperfect elastic characteristics. Thus, it may be used for pressure-sensitive elements down to temperatures of –79° C. and up to 500° C. K-Monel is non-magnetic, but it should be free from any oxide scale, since this scale is slightly magnetic.

Copper–manganese–nickel

There is a considerable range of heat-treatable alloys composed of copper, manganese and nickel. By a suitable selection of composition and treatment, the hardness of the material in strip form can be varied between 90 and 450 D.P.N. and the 0·1 per cent. proof stress from 13 to 60 tons per square inch, with an ultimate tensile strength of from 35 to 80 tons per square inch. For pressure-sensitive elements an alloy with a composition of 60 per cent. copper, 20 per cent. manganese and 20 per cent. nickel has been suggested as being suitable. Like beryllium copper, this alloy (typical properties of which are shown in Table I) is soft and ductile after quenching from 800° C., and can easily be formed into required shapes; but its electrical and thermal conductivities in this condition are low. A hardening heat treatment then follows. In contradistinction to other heat-treatable alloys, the hardening does not depend upon the presence of an accurately controlled percentage of an added element; the hardening effect appears to be due not to precipitation but to an ordering of the crystal structure. The improvement in mechanical properties is obtained by heat treating in the temperature range of 400° C. to 425° C. for a time depending upon the hardness required. Fig. 9 shows typical results.

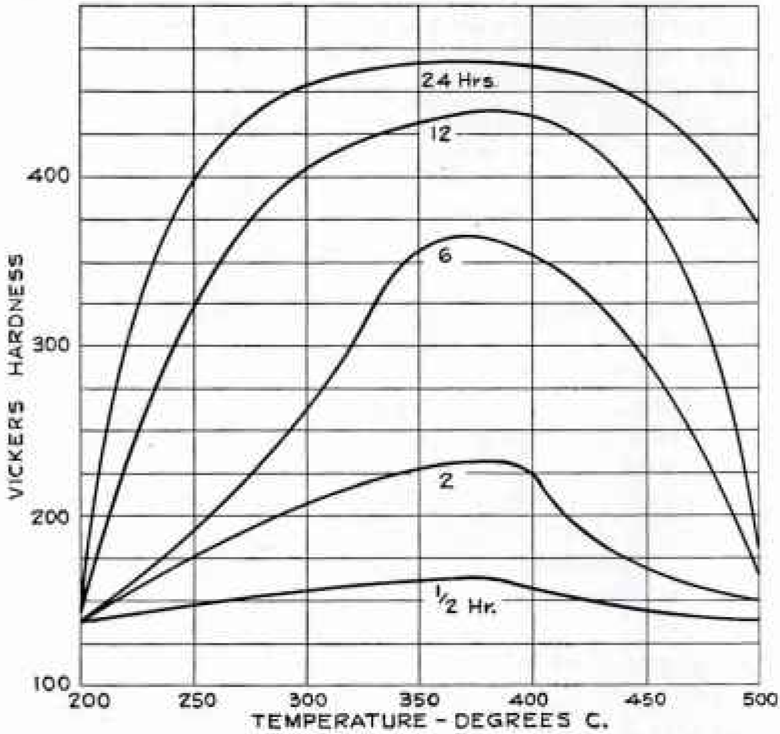


FIG. 9.—Effect of heat treatment on hardness of copper-manganese-nickel.

The material in the soft condition is quite ductile; reductions up to 80 per cent. can be effected and the forming techniques used with other copper alloys are generally applicable.

In common with most other heat-treatable copper-base alloys, it may be cold worked and the heat treatment superimposed; this gives properties superior to those obtained by heat-treating the material in the soft condition. From an inspection of Fig. 9, it will be noted that there is very little risk of over-ageing, even if the heating is prolonged. However, to ensure consistent properties, the heat treatment of all material in a batch should be identical. The heat-treated material can be softened by heating to a temperature of approximately 800° C. and quenching. Superficial oxidation will take place if the heat treatment is carried out in air and to overcome this it should be performed in an inert atmosphere or a salt bath.

There is very little risk of distortion during heat treatment, although where a considerable degree of accuracy is required it is advisable to use jigs to ensure consistent shapes.

THE JOINTING OF COPPER ALLOYS

General

Before proceeding to describe the various types of pressure-sensitive elements, it is convenient to include at this stage a few brief notes on the jointing of copper alloys. More detailed information on the subject is provided in C.D.A. Publication No. 47, "The Welding, Brazing and Soldering of Copper and Its Alloys."

Most copper alloys can be jointed easily and the following methods are in general use:

(1) Assembly by mechanical means such as riveting, bolting, screwing, and welting.
(2) Soft soldering, e.g. with tin-base solders.
(3) Brazing and silver soldering, e.g. with alloys such as those specified in B.S. 1845.
(4) Welding—
    (*a*) Resistance welding, e.g. butt, flash, spot and seam welding.
    (*b*) Gas welding, e.g. oxy-acetylene welding.
    (*c*) Arc welding, e.g. metal arc welding, carbon arc welding and inert gas shielded arc welding.

When riveted, bolted or similar joints are made, the properties of the metals are rarely affected to any appreciable extent. Most cold-worked copper alloys can be soft-soldered also without causing annealing to take place, since the soldering temperature is usually below the annealing temperature and the period of time involved is comparatively short.

On the other hand, it is practically impossible to avoid a certain amount of annealing when copper alloys are brazed or welded, on account of the high temperatures reached. However, in certain cases, heating is sufficiently quick to prevent annealing taking place except locally close to the joint. This applies particularly to resistance and induction brazing and to resistance welding.

Owing to the relatively poor elastic properties of jointing or filler metals in the cast condition, they should not be applied to highly stressed portions of pressure-sensitive elements; otherwise, hysteresis is likely to result.

Soft soldering

Most copper alloys are easily soldered. This applies particularly to the tin bronzes, gunmetals, cupro-nickels and brasses. Precautions are sometimes necessary when soldering highly stressed high-zinc brasses, due to the risk of penetration by the solder and consequent weakening of the metal. Such materials should first be given a low-temperature heat treatment and should not be stressed during the soldering process.

Though it is often claimed that the soft soldering of beryllium copper presents no difficulty, certain precautions are necessary if consistently good joints are to be obtained. It is of primary importance that the surfaces to be soldered should be free from beryllium oxide. Since soft soldering must clearly be carried out after the final heat treatment—the melting point of solder being lower than the precipitation-hardening temperature—it is evident that superficial oxide arising from both the high and low temperature heat treatment will be present on the surface, unless special precautions are taken to remove it. Though much beryllium oxide may be formed during the solution heat treatment, the precipitation-hardening treatment is rather less detrimental from this point of view. It is, however, expedient to remove the oxide film between the two heat treatments, since the second of these tends to make any beryllium oxide previously present less easy to eliminate. Where possible it is desirable to adopt abrasive or mechanical cleaning, using a file, emery paper or even metal polish; but in many cases, as in the mass production of minute components, this is hardly practicable. Such articles should be pickled between the two heat treatments in the solution described under "Fabrication of beryllium copper" (see page 33). In obstinate cases it may be necessary to repeat the pickling process after the final heat treatment, but it will generally be found that ordinary soft soldering fluxes based on zinc chloride effectively combat any traces of oxide which may be reformed at this stage. It has been shown that more cuprous oxide than beryllium oxide is formed at the temperatures in the precipitation-hardening range, and it is well known that cuprous oxide is removed by zinc chloride fluxes. Resin-base fluxes are relatively slow in their action, but it may be necessary to use fluxes of this type for articles which cannot be subsequently washed to eliminate the more corrosive zinc chloride.

Aluminium bronzes and silicon bronzes may be fluxed either with orthophosphoric acid of specific gravity not less than 1·75, or with an aqueous (25 per cent.) solution containing equal quantities of hydrochloric acid and zinc chloride, in order to prevent the formation of the oxides of aluminium and silicon.

Brazing

Copper alloys are usually brazed with silver solders or copper–phosphorus alloys. The use of a fluoride flux is generally advocated in conjunction with silver solders but no flux is required with copper–phosphorus alloys, which are self-fluxing. When brazing alloys containing more than about 2 per cent. of aluminium, a mixture of alkali chlorides and alkali fluorides should be present in the flux.

In the case of beryllium copper, if the surfaces are oxidised badly they should be cleaned mechanically before brazing, and if they are coated with oil or grease, solvent degreasing is recommended. If mechanical cleaning is not sufficient, the articles may be pickled in a solution as described under "Fabrication of beryllium copper" (see page 33).

Brazing should be carried out quickly and is necessarily restricted to material in the solution heat-treated condition, since, at the temperatures reached, the effects of previous precipitation-hardening would be destroyed. It is, however, an advantage that brazed articles can subsequently be hardened and strengthened by heat treatment in the usual way, without affecting the joints.

Welding

Practically all copper alloys can readily be joined by welding methods.

Resistance welding is perhaps more applicable to instrument manufacture than gas or arc welding, since the heat applied when jointing by these last two methods usually results in a general annealing of the metal, whereas with resistance welding the annealing can be restricted to metal immediately adjacent to the weld. For further details, reference should be made to C.D.A. Publication No. 47.

TYPES OF PRESSURE-SENSITIVE ELEMENTS

BOURDON TUBES

General description

Pressure-gauges operated by means of a Bourdon tube are the oldest and most commonly used in industry, the preference for them over other methods of industrial pressure measurement being due to their relative cheapness and reliability. A typical gauge is shown in Fig. 10.

Operation

A tube of elliptical or oval section, when subjected to internal fluid pressure, tends to become circular, and if such a tube is bent into an arc of a circle any increase in internal pressure tends to straighten the tube as the cross-section becomes more circular. This effect was generalized by Bourdon[10] in 1851 in his paper to the Institution of Civil Engineers, by the statement that a surface which is curved in two planes at right angles cannot have one curve increased without decreasing the other and *vice versa*. Later Gauss's theorem on the bending of surfaces was applied

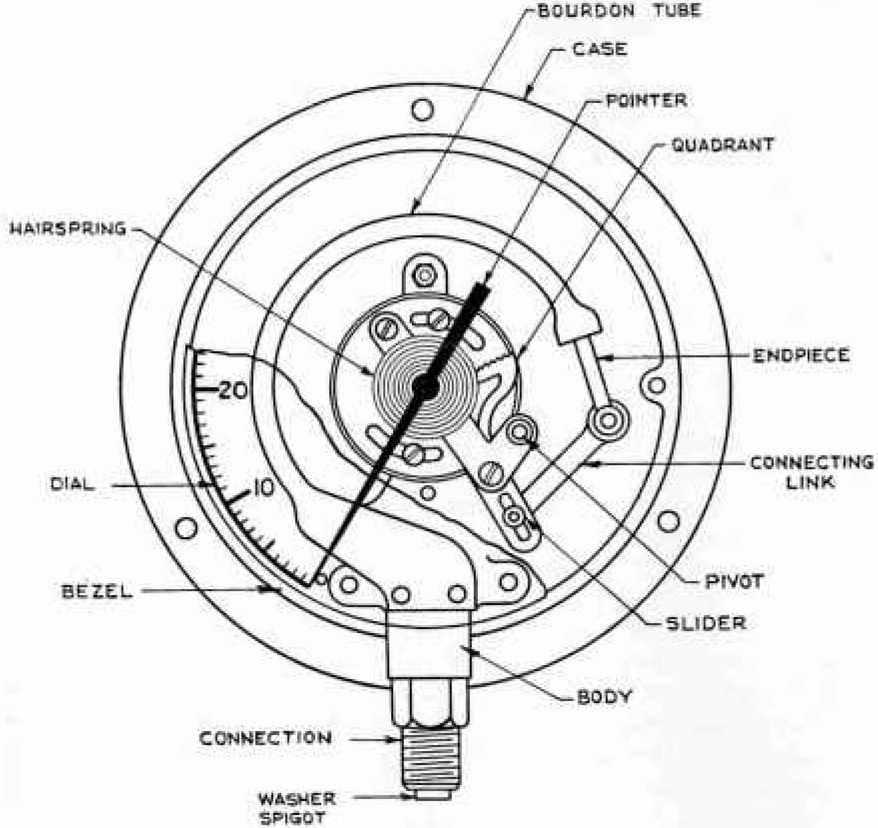


Fig. 10.—Typical Bourdon tube gauge.

by Lord Rayleigh[11] to give a quantitative explanation of this phenomenon. A considerable number of papers has been published on the theory appertaining to this type of deformation, as applied to Bourdon tubes, and the most important of these are given in the bibliography [12-16].

The movement of the free end or tip of the Bourdon tube when subjected to an internal pressure is very complex and none of the theories so far advanced takes into account all the variables involved, such as the stress-concentration where the tube is joined to the boss and the continual change in curvature during its deflection. The theories do show, however, that within close limits the change in angle subtended at the centre by the tube segment is proportional to the change of the pressure in the tube; and within the limit of proportionality of the material employed, the movement of the tip of the tube may be shown to bear a linear relationship to the applied pressure. Thus a uniform scale can easily be obtained.

A reasonable indication of the deflection of a Bourdon tube, however, can be obtained from the formula derived by Lorenz[12] and given in a slightly modified form by Rolnick[14]. This formula should be used, however, only when the minor axis of the elliptical cross-section of the tube is considerably less than the major axis.

$$\frac{\theta}{\theta_0} = \frac{1\cdot16\, pr^2}{tEb}$$

where θ = angular measure of the rotation of the tip of the Bourdon tube (degrees).

θ_0 = angular measure (or total number of turns, in case of helix) of the tube (degrees).

p = excess of internal over external pressure (lb./sq. in.).

r = radius of the helix or tube (ins.).

t = wall thickness (ins.).

E = elastic (Young's) modulus of the material (lb./sq. in.).

b = minor axis of the tube measured from the middle of one wall to the middle of the other (ins.).

Generally the shape used in practice is such that the major axis is large compared with the minor axis. The ratio between the major and minor axes of the oval shape into which the tube is formed will depend on the application for which the instrument is designed. A large ratio will give a sensitive instrument but the tube itself will be weaker. Stresses are reduced with decrease of major axis.

Another way of considering the movement of the tube tip[13] is to regard each of the flattened walls of the tube section as a beam fixed at its ends and subjected to a uniform load, the wall deflection for a given pressure then being given by the usual beam deflection formula. It is still necessary, however, to find by experiment the movement of the tip for a given wall deflection, but when a fair amount of such data has been accumulated further designs can be predicted with reasonable accuracy.

A convenient nomogram method of Bourdon tube design, based on dimensional analysis of the tube parameters, numerical values being obtained empirically from readings on a number of tubes of geometrically similar form, has also been developed[16].

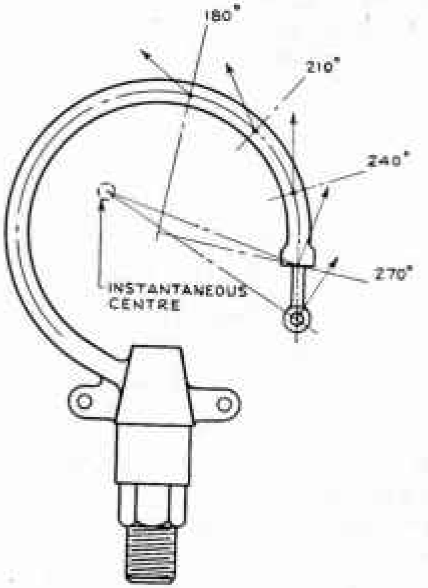


FIG. 11.—Path of travel of tip of Bourdon tube.

Fig. 11 shows the path of travel of a Bourdon tube.

Construction

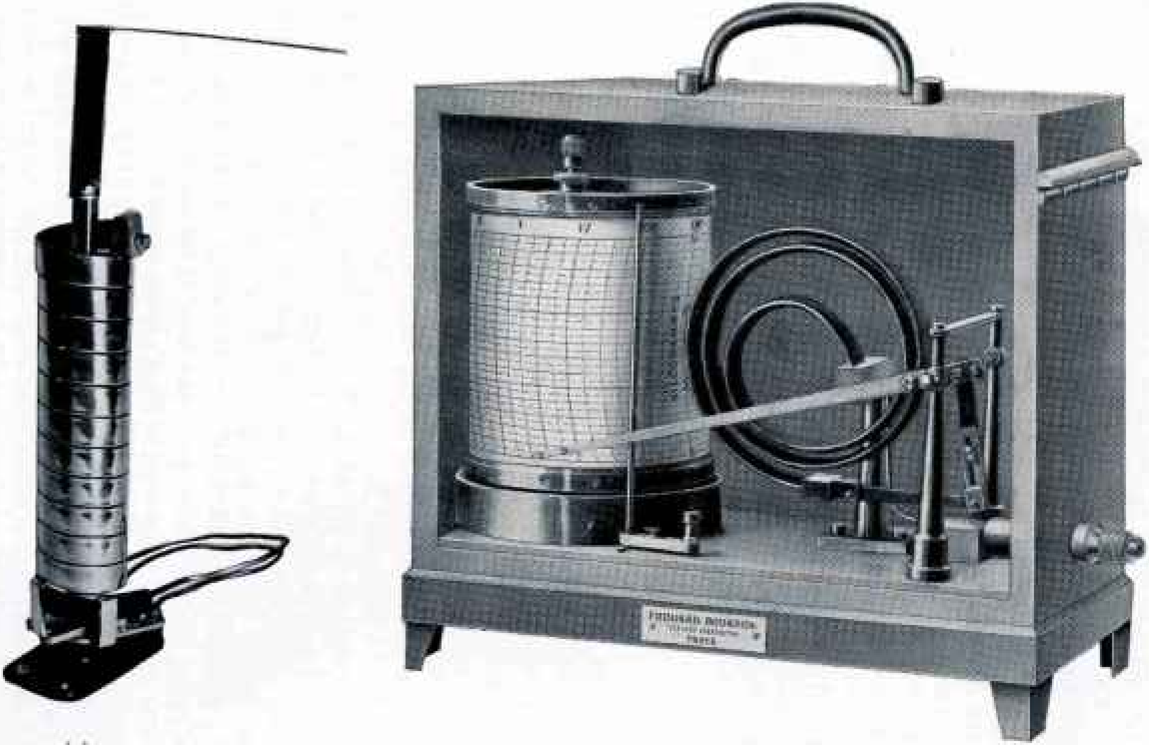
The sensitive element is a tube, normally of oval section, bent in the form of an arc of a circle (usually 270°), one end of which is hermetically sealed and the other end connected into a boss to which the pressure is applied. The end which is sealed is connected by an amplifying system of linkages and gearing to a pointer. The gearing usually consists of a pivoted quadrant which meshes with a pinion to which the pointer is secured; thus, the linkage system plus the gearing converts the linear motion of the tip of the Bourdon tube to a rotary motion of the pointer, at the same time amplifying the movement.

A small spiral spring, usually of phosphor bronze or beryllium copper, is secured between the pointer spindle and the body of the gauge to take up any backlash which may exist in the mechanism. The backlash is taken up by virtue of the spring pressure causing constant engagement between the teeth of the quadrant and the pinion on the pointer shaft. A variety of linkage systems exists, and the choice of a particular system will depend on whether fluctuating or steady pressures are to be measured, on the scale required and on general economic considerations. Whatever type of linkage is used, however, it is usual to mount the whole of the movement on the boss or socket which communicates with the source of pressure, so that any deformation of the outside case does not derange the sensitive mechanism. The movement of the free end of the Bourdon tube is small and in some cases, to get maximum sensitivity, wall thickness is reduced until the maximum working stresses are very close to the limit of proportionality of the material. This procedure, however, should not be adopted where accurate indication is required, as it introduces the risk of increased hysteresis and drift, apart from early failure due to fatigue.

Bourdon tubes are generally used for pressure ranges which vary from about 5 lb./sq. in. to about 15,000 lb./sq. in., and for precision work, such as the calibration of sub-standards, are made with an accuracy of a quarter to one half of 1 per cent.

Normally the arc length of the Bourdon tube is restricted to approximately 270°, but where greater tip movement of the tube is desired it can be wound into a spiral of several turns (usually not more than 5), which has the effect of increasing the tip movement in proportion to the increase in the angle subtended at the centre. Bourdon tubes are generally made with a major axis of about ¾ in. and wall thickness between 0·006 in. and 0·010 in., the dimensional tolerance being about ± 0.001 in.

Another method of increasing the tip movement is to use the helical type of Bourdon tube. The pointer in this case is actuated by a central shaft contained within the helix. Both spiral and helical types are illustrated in Fig. 12; they are normally employed only in conjunction with recording gauges or control equipment. A pressure gauge is sometimes required to register pressure below as well as above atmospheric pressure, in which case it is known as a compound gauge. Pressures below atmospheric are usually marked on the scale in a counter-clockwise direction,



(a) (b)

FIG. 12.—Spiral and helical Bourdon tubes.
(a) Spiral Bourdon tube; (b) Helical Bourdon tube.

pressures above atmospheric in a clockwise direction. In some installations, it is convenient for two different sources of pressure to be read on the same dial, in which case the gauge is known as a duplex pressure gauge. The internal mechanism of a compound gauge is the same as that of the normal pressure gauge, but that of a duplex gauge is rather different and is illustrated in Fig. 13.

Where high gas pressures are being measured, it is good practice to have the gauge case divided by a partition so that the Bourdon tube is one side, the scale, pointer and glass on the other. This greatly reduces the risk of the glass being blown out, should a tube failure occur.

(Courtesy Messrs. David Harcourt & Co., Ltd.

FIG. 13.—The mechanism of a duplex Bourdon gauge.

Materials

The materials most commonly employed for pressure gauges (in addition to steel) are brass, phosphor bronze, beryllium copper and K-Monel, the properties and fabrication of which have already been dealt with on pages 21 to 37. For general purposes phosphor bronze and steel predominate, but beryllium copper is becoming increasingly popular.

Phosphor bronze is used generally for pressures up to about 800 lb./sq. in., steel or beryllium copper above this pressure. For gauges where accuracy is important, beryllium copper is in general use. Brass is usually employed at low pressures only. K-Monel is used where severe corrosion conditions occur, such as in the chemical industry, with hydrogen sulphide, hydrofluoric acid, aluminium chloride, aluminium fluoride, ammonium sulphate, carbon tetrachloride, sodium fluoride and many other materials.

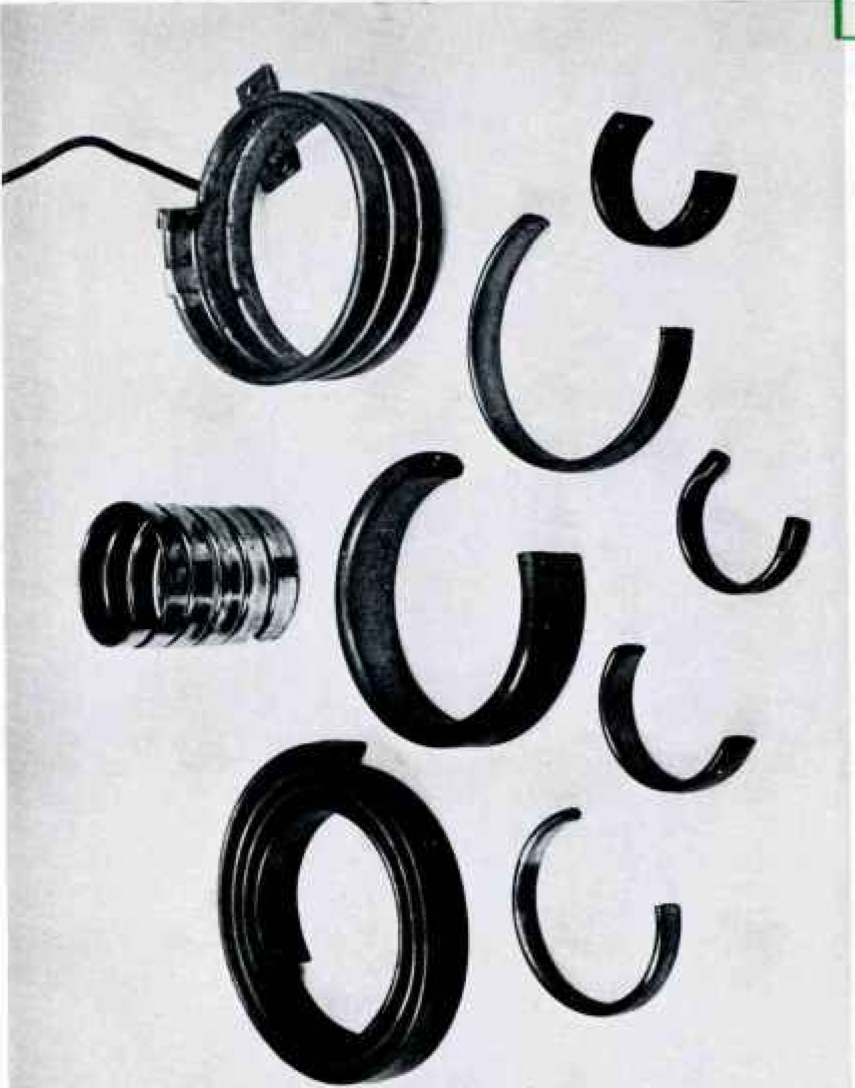
When a copper-base alloy comprises the tube element, the boss is a hot brass stamping, except when Monel is used for the tube, in which case the boss is ordinarily also of Monel. The gearing and linkages are generally of a special brass and this aspect is dealt with on page 110.

As Young's Modulus for all the materials for Bourdon tubes decreases with increase of temperature, it is desirable to compensate for this on accurate instruments. This can be done by connecting to the tube tip a spring which has the opposite temperature coefficient to that of the tube material, so that the resultant virtual modulus is unchanged; alternatively a bimetallic strip may be employed.

Manufacture

The Bourdon tube is first made by producing cylindrical tubes, usually in fairly short lengths to obtain consistent qualities, and then either by hollow sinking or rolling to get the desired elliptical or oval section. Some manufacturers test the tube when flattened for wall thickness, hair cracks, etc., by means of an electronic tester. The term oval is used as this describes most of the cases encountered. In some cases, however, the tube is almost completely flattened, the actual shape depending on individual manufacturers. Fig. 14 shows typical sections. Considerable care has to be exercised in the manufacture of the Bourdon tube if a sensitive and accurate instrument is to result. Jigs are used to bend the tube and to prevent distortion. The bending must be accurately carried out as this operation influences the elastic properties of the material, except when heat-treatable alloys are used. The tube is generally filled with a low-melting-point alloy during bending, or flexible laminated mandrels may be inserted into the tube. A typical low-melting-point alloy, sometimes known as Wood's metal, consists of lead, bismuth, tin and cadmium, with a melting point of 70° C. After bending, and removal of the alloy, the tubes are thoroughly cleaned in a pickling bath, one end then being brazed, or soft- or silver-soldered into the boss, and the other end brazed, silver-soldered or welded to a plug.

It is generally found that initial loading of the tubes gives rise to



[Courtesy Messrs. Johnson, Matthey & Co., Ltd.

Fig. 14.—Typical forms of pressure-sensitive elements of the Bourdon tube type.

non-elastic extension and that the modulus of elasticity and the limit of proportionality increase. To ensure that during calibration all extensions are elastic, a pressure in excess of the maximum scale pressure is usually applied for a few minutes and repeated a number of times to "season" the tube.

Installation

The Bourdon tube pressure-gauge is a robust instrument, but a few simple precautions should be taken during its installation. Fluctuations of pressure not onlymake exact readings impossible, but they also produce wear on the moving parts and reduce the life of the instrument by setting up fatigue stresses in the material. These troubles are overcome if a suitable "choke" or "snubber" is installed close to the base of the instrument, so that the gauge reads the mean pressure if the frequency of the fluctuation is high, but still reads the maximum pressure if that pressure is maintained constant for a reasonable period. The size of the choke must be determined by experiment, but if a cock is fitted at the point where the gauge is installed the opening of the cock can be adjusted so as to reproduce the same effects as a suitably sized choke. Sintered bronzes are sometimes used to provide an appropriate choke.

If the copper pipe connected to the pressure gauge is subject to considerable vibration, then the pipe should be coiled before reaching the instrument so as to absorb this vibration. If the fluid operating the gauge is at a high temperature, the thermal effects will tend to make the gauge inaccurate, because the modulus of elasticity varies with temperature. If the pressure of fluids such as steam is being measured, it is advisable to form a syphon coil in the pipe. If the pressure of inflammable fluids is being measured, care should be taken to see that no soldered joints are employed in the instruments, since the ignition of any escaped fluid due to a small leak would jeopardise the whole joint.

Pressure gauges are covered by B.S. 1780: 1951.

SEAMLESS METALLIC BELLOWS

General description

A metallic bellows, or a "sylphon," consists of a flexible seamless metal tube with corrugated walls, which by suitable end fittings can be hermetically sealed and will allow movement parallel to the axis of the tube. Fig. 15 shows some typical examples of metal bellows.

The end corrugations of a bellows do not play any major part in the movement and are usually referred to as "inactive corrugations," the

[Courtesy The Drayton Regulator & Instrument Co., Ltd.

FIG. 15.—Typical seamless metallic bellows.

remainder of the corrugations being "active." The stiffness of the bellows is inversely proportional to the number of corrugations per unit length.

Although such a device was envisaged in the early patents mentioned on page 12, no method was available at that time for making a satisfactory bellows, and it was not until about 1900 that a pressure-sensitive device, based on this method, became a commercial proposition.

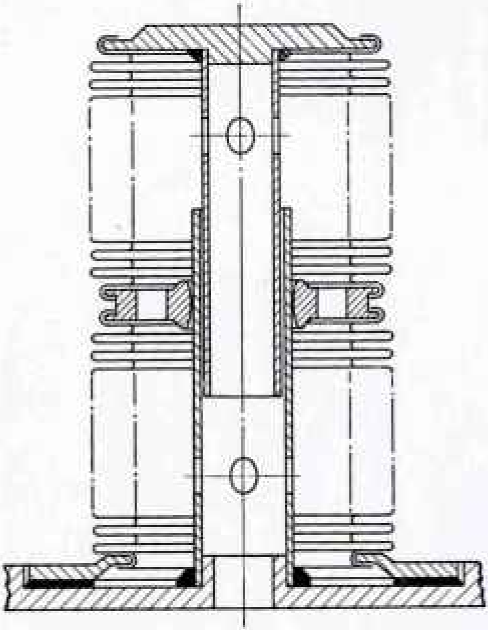


FIG. 16.—Composite bellows showing use of internal guide (end stops not shown).

Operation

The action of a bellows is very similar to that of an ordinary helical compression spring, and within the limit of proportionality of the material equal load increments give equal deflections. For a given load the deflection is proportional to the square of the outside diameter and to the number of active corrugations. It is also inversely proportional to the modulus of elasticity of the material and to some power (about 3) of the wall thickness. As the wall thickness is very small, usually ranging from 0·004 in. to 0·10 in., a slight variation in the thickness of the material causes relatively large changes in the deflection and therefore the thickness of the strip used for bellows manufacture must be held to within very close limits.

The pressure applied in service must, of course, be less than that necessary to cause the stresses in the material to exceed the limit of proportionality and in practice such stresses are much less than this, to ensure long life and freedom from elastic imperfections such as drift and hysteresis (see p. 18).

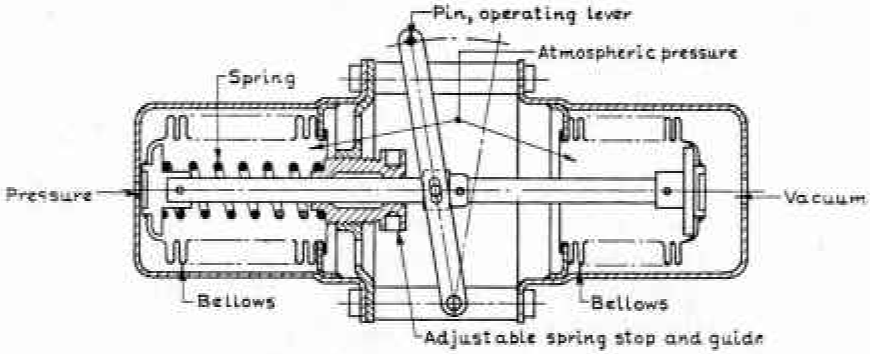


FIG. 17.—Composite bellows with stiffening spring for differential pressures.

A bellows should preferably be used in compression, i.e., so that movement is such that the corrugations tend to touch, although it may be used for small extensions in the opposite direction. Usually it is possible to compress a bellows until the corrugations actually do touch without causing any permanent set, but the normal deflection of a bellows is about 10 per cent. of its free length, and the ratio of the length to diameter should not be much in excess of unity. If it is desired to obtain greater flexibility than this ratio of dimensions allows, it is possible to use an internal guide to resist the tendency to buckle and sometimes it is necessary to employ two bellows in this manner, as shown in Fig. 16. On no account should an external guide be used to resist buckling and wherever possible the pressure should be applied externally, although there are many occasions on which this is not practicable. The deflection characteristics of a bellows are greatly modified if it is used in conjunction with a spring and in this connection a bellows with a maximum flexibility should be chosen and the stiffening obtained by means of the spring. These springs may be applied either internally or externally, depending on the operating requirements. An example is shown in Fig. 17.

A nickel-iron spring with a positive modulus-temperature coefficient can also be used to compensate for change of modulus with temperature. Alternatively, a second bellows filled with a suitable gas, usually nitrogen, may be employed to compensate for change of modulus with temperature; this may be determined from the relationship

$$\frac{(H-h)S}{\left(H-h\frac{T}{T_R}\right)S_T}=\frac{E_R}{E_T}$$

where E_R = Young's Modulus at temperature T_R (lb./sq. in.)
E_T = Young's Modulus at temperature T (lb./sq. in.).
S = Area in square inches of bellows at reference temperature T_R, external pressure H, internal pressure h.
S_T = Area in square inches of bellows at reference temperature T, external pressure H, internal pressure $H - hT/T_R$.
T_R = reference temperature (° K.).*
T = temperature (° K.).
H = external pressure at which compensation is made (lb./sq. in.).
h = gas pressure in bellows at reference temperature (lb./sq. in.).

The actual value of the stress is not the only factor involved in the life of a bellows, for the rate at which it is varied is also an important factor. Fig. 18 shows a chart issued by one manufacturer for predicting the working life of a typical 80 : 20 brass bellows of the hydraulically formed type. In many applications, bellows are subjected to alternating stresses for the larger part of their working life; thus the risk of fatigue failure is always present and in the interests of long life the maximum stroke should not be used with the maximum permissible pressure.

Materials

The vast majority of bellows are made from brass consisting of 80 per cent. copper and 20 per cent. zinc. This material has the necessary ductility to enable it to be formed into the complicated shapes required and at the same time develops adequate mechanical properties during the process.

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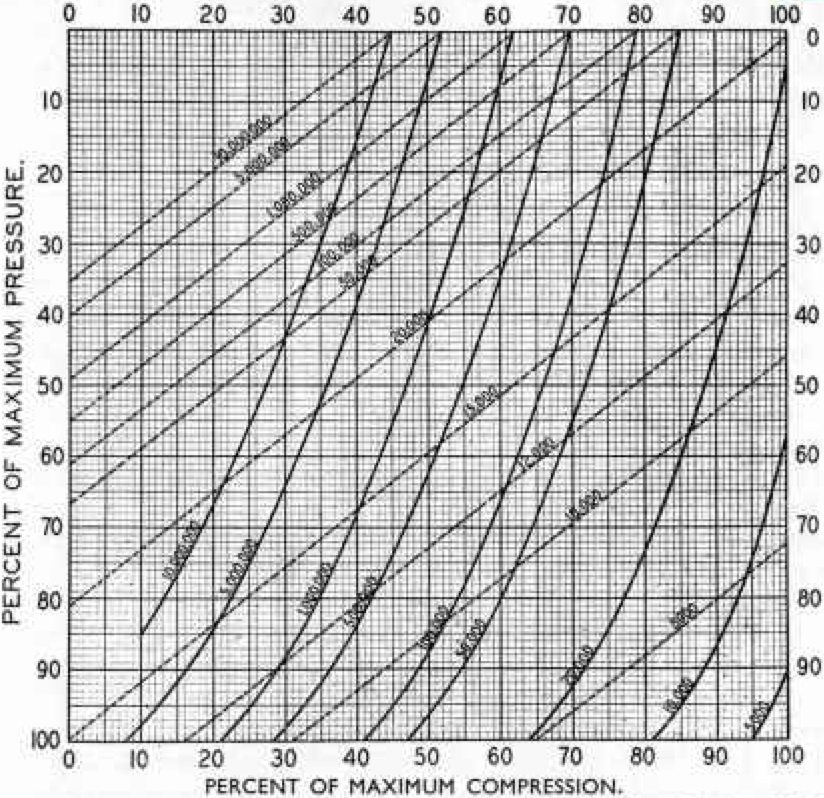
* See page 115.

It is also highly resistant to many forms of corrosion and, provided it is given a stress-relieving treatment, it is almost immune from season cracking. Bellows are also made, where corrosion or mechanical



[Courtesy The Drayton Regulator and Instrument Co., Ltd.

FIG. 18.—Chart for predicting life of 80 : 20 brass bellows, for number of cycles indicated on curves.

The full-line curves should be used when the pressure remains constant throughout the entire stroke of the bellows (maximum frequency 200 cycles per minute) and the dotted curves when the pressure varies from zero to the specified figure with each stroke of the bellows (maximum frequency approximately 20 cycles per minute.)

conditions demand it, from phosphor bronze, cupro-nickel, aluminium bronze, aluminium brass, silicon bronze, Monel, K-Monel, beryllium copper and copper-manganese-nickel, the last three materials being heat-treatable alloys.

When, in order to obtain certain mechanical properties, a material has to be used which would be attacked by the fluids with which it is employed, bimetallic bellows are adopted, the material of the bellows in contact with the fluid being suitably corrosion-resistant and that remote from the fluid having the requisite mechanical properties. This is a laminated construction; a plated finish would not generally be satisfactory. A bimetallic bellows of given wall thickness is suitable for approximately the same pressure as a single bellows of the same total wall thickness, but the spring rate (see page 56) of the bimetallic bellows is less and the permissible stroke greater.

Manufacture

The tube for making bellows is usually formed by means of a drawing and cupping operation from discs blanked from strip. The material is generally annealed and pickled between each drawing operation, there being about six operations. The side walls, which are from about 0·004 in. to 0·010 in. thick, are corrugated by hydraulic pressure or by a rolling and spinning technique. Both methods can be made to give excellent results. In the case of the rolled and spun bellows, both ends are open, but with the hydraulically formed type one end can be made integral with the corrugations. Normally the diameter of the tube used in making the rolled bellows is intermediate between the inside and outside diameter of the finished bellows and, therefore, the elastic properties of the material are developed by cold working on both inner and outer radii of the corrugations. The rolling technique burnishes the outer surface, giving a smooth, hard finish which, it is claimed, reduces the tendency to fatigue cracking during the working life. The rolling also orientates the crystals so that the majority are elongated in a direction at right angles to the axis of the bellows.

With the hydraulic forming process, the tube material flows outwards into the forming die and thus most of the cold working of the metal takes place on the outer radii. The die consists of a series of plates (split to accommodate the tube) equal in number to the number of corrugations. Once the tube is inserted, a system of levers enables the two sets of half-plates to be brought down on the tube. Initially, they are held apart axially by the pressure of light leaf springs, retractable spacers ensuring equidistant axial separation. Internal hydraulic pressure is then applied, causing the metal to flow transversely between the plates at the same time as an axially applied thrust causes the tube to collapse endwise and the dieplates to be pressed up together as the spacers between them are withdrawn; the bellows are thus formed in one continuous operation. The root diameter of the corrugations corresponds to the initial diameter of the tube, the latter being in contact with the die plates throughou the operation. The outside remains unrestricted. The depth of corruga formed, therefore, depends on the initial spacing of the die plates and on the pressure.

The forming pressure is a guarantee of the strength of the bellows, as the pressure used is considerably greater than that at which the bellows will work in service, and it is generally easier to guarantee the consistency of the wall thickness when the hydraulic technique is used. The normal limits on wall thickness of the finished bellows are about ± 0.00025 inch.

The remarks regarding the development of elastic properties referred to above do not, of course, apply when any of the heat-treatable alloys such as beryllium copper, K-Monel, and copper–manganese–nickel are being used. Improvement in elastic properties is obtained in these alloys, as in the strain-hardening alloys, by cold work, but the final effect is obtained by heat treatment after the forming operations have been carried out.

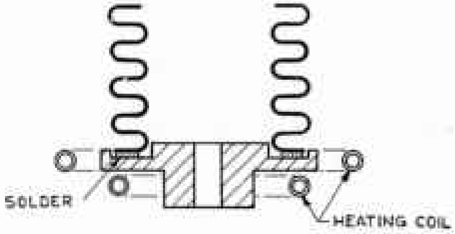


Fig. 19.—End fixing of bellows by means of induction heating.

End fixing

As has been stated, in the case of hydraulically formed bellows one end is closed during forming, but in the rolled type both ends are open. The situation in which the bellows is to be placed often determines what the end fixings are to be; but in general, since they can materially affect the working of the bellows, it is best that the end fixings should be supplied complete by the bellows manufacturer. The end fixings are relatively thick compared with the walls and any soldering must be carried out with great care. It is generally agreed that as far as possible the solder should be relieved from taking any of the working stress, so the joints should wherever practicable be mechanical, i.e. the bellows should be rolled or crimped on to the end plate. The solder is then used merely to form a hermetic seal, but this is not possible in all cases. Great care must be taken in the sealing to avoid annealing the material and in this connection induction heating can usefully be employed as shown in Fig. 19. Precautions must also be taken that no corrosive fluxes are employed and on no account should a flux which contains ammonium chloride be used with brass, as this may weaken the grain boundaries, causing rapid failure. In order that the temperature may be kept as low as possible, a eutectic alloy of tin and lead (63 per cent. tin, 37 per cent. lead) is preferable as a solder, but is slightly more difficult to use than a 50 per cent. tin, 50 per cent. lead alloy.

Performance

The performance of a bellows is best expressed in terms of the following factors:—

(1) *Spring rate.*—The spring rate is the force in pounds necessary to produce a deflection of 1 in. It is determined experimentally and expressed in pounds per inch per corrugation.

(2) *Flexibility.*—Flexibility is a calculated figure which gives the deflection per unit pressure and is normally expressed in inches per pound per square inch.

(3) *Equivalent or effective area.*—The equivalent or effective area of a bellows is used to predict its performance under a distributed load when its spring rate is known. It is the ratio of the concentrated axially applied load to the pneumatic or hydrostatic pressure which gives the same deflection. It may also be considered as the area of a piston to give the same force as the bellows when the same pressure is applied. For practical purposes it may be taken as the area of a circle the diameter of which is midway between the inside and outside diameters of the bellows; it is thus given by the formula

$$\text{Effective area} = \frac{\pi}{4}\left(\frac{D+d}{2}\right)^2$$

where D = outside diameter
d = inside diameter.

Manufacturing tolerances

The flexibility of a bellows varies directly as the number of convolutions and as the square of the outside diameter, and inversely as the modulus of the material and as the cube of the wall thickness. The importance of manufacturing tolerances (especially that of wall thickness) will, therefore, be appreciated. As a consequence of the above relation, the overall variation in flexibility or spring is about ± 20 per cent. even with the close tolerance on wall thickness given on p. 55.

DIAPHRAGMS AND CAPSULES

General description

Diaphragms and capsules are in general use for the measurement of low pressures, owing to their sensitivity, simplicity and the small space they occupy.

A metallic diaphragm for a pressure-sensitive element consists of a thin membrane separating spaces having different pressures, the characteristics of the membrane and its method of support being such that an appreciable elastic deflection is obtained. In certain instruments "limp" diaphragms are used, but these are outside the scope of this publication.[17] A "capsule" may be considered as two diaphragms joined together around their peripheries; a "capsule stack" consists of several capsules joined together. Capsule and diaphragm instruments are in general use where small differences of pressure have to be measured or where they produce movement. Such instruments are compact, cheap and relatively simple to produce, and, with suitable materials, very good pressure/deflection characteristics may be obtained. Since the pressures are small compared with the elastic moduli of the materials which are suitable for membranes, the thickness of the latter must be very small in order to obtain reasonable deflections. Larger pressures cannot be accurately measured by using thicker diaphragms and in such cases it is necessary to connect capsules in series. A reasonable deflection is considered to be about 1/50th of the diameter. Fig. 20 shows a selection of typical diaphragms.

Operation

The theory of this type of sensitive element is very complex and is part of the theory of thin elastic shells. While this latter theory is fairly well developed for small deflections, it has not been fully developed to cover larger movements such as are encountered in pressure-sensitive elements. When a thin elastic membrane is deflected there are in general two forms of deformation, extensional, in which the neutral plane of the shell is altered, and inextensional in which there is no movement of the neutral plane.[18]

For a given deflection, the stresses set up by extensional deformation are very much larger than those set up by inextensional deformation, and thus the latter form of movement is that best suited for diaphragms. It has not been found possible, however, to remove all extensional deformation, but by the suitable choice of shape it can be reduced to small value. With this end in view it is usual to apply concentric corrugations to the

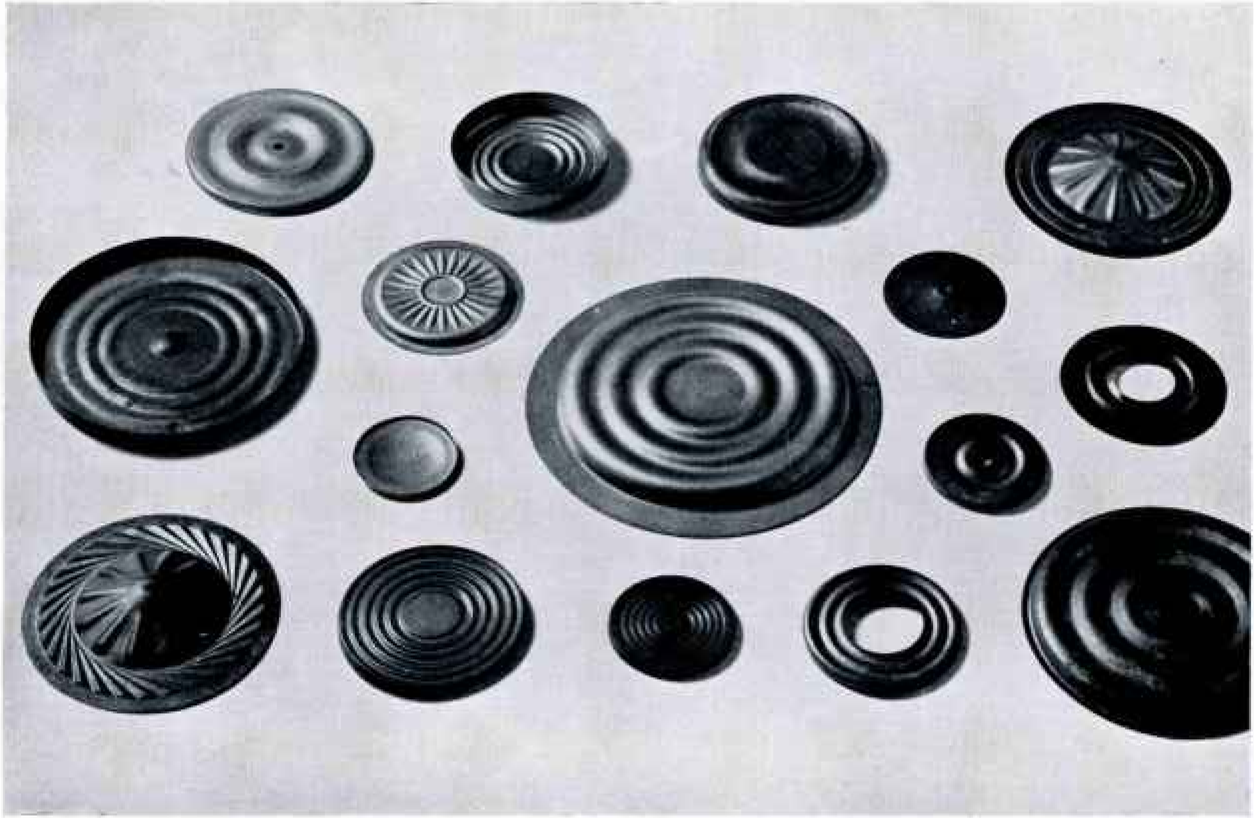
[Courtesy "Machinery"

FIG. 20.—Typical metal diaphragms.

diaphragm; this gives a more linear response over a greater amplitude than a plane disc. The load/deflection curve can also be modified by suitable

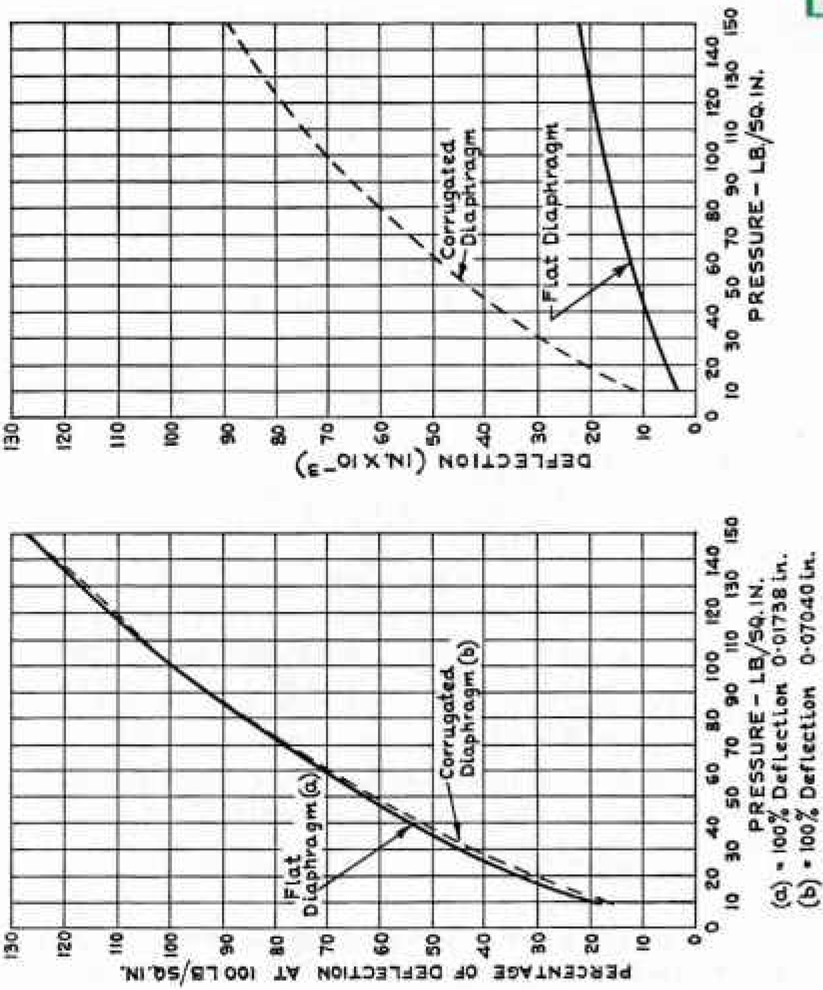


FIG. 21.—Relative movements of flat and corrugated diaphragms.

choice of corrugation. Fig. 21 indicates the relative movements of flat and corrugated discs under similar conditions.[17]

Since the function of the corrugations is to relieve the stress due to the expansion of the surface when the deflection is appreciable, the depth of the corrugation, according to Griffith (loc. cit.), should be greatest in that portion where the slope of the disc is a maximum and should decrease towards the centre and outer edges, where the slope is zero. If stiffening of the diaphragm is required, radial ribs are employed. Depth and state of corrugation must be held within close limits, ± 0·0003 in. being a typical figure. The "rate" of a diaphragm (see page 56) is dependent upon the shape of corrugation and upon the modulus of elasticity of the metal used.

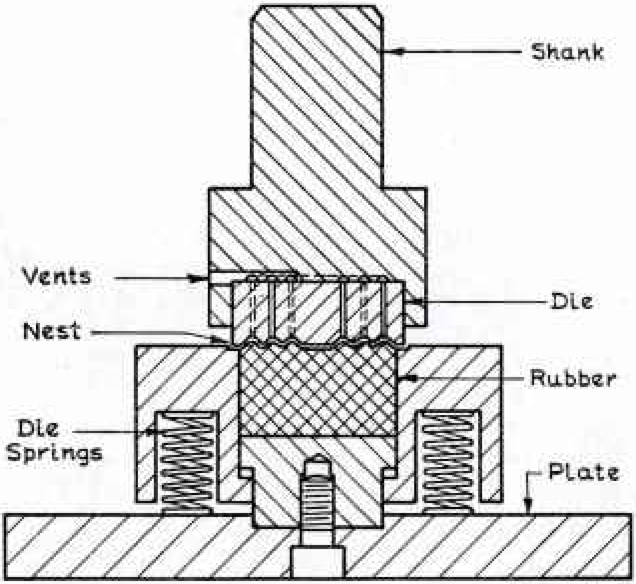
The mounting of the diaphragm is most important and the design should be such that the stress is a minimum at the mounting flange, or the pressure/deflection characteristics will be impaired. A mechanical mounting is probably best, permitting a stress-free zone at the flange, in which case solder may be used to form the seal. Soldering is also satisfactory, however, if the working stress at the joint is low, in cases where mechanical support is not provided. Heat-treatable material formed in the soft state can be brazed or welded to the mounting prior to the final heat treatment.

In order to secure the amplifying linkages from the diaphragm to the pointer, it is usual to solder a copper or brass reinforcing disc of about 0·03 in. thick to the centre of the diaphragm. Provided that the proportions of this disc are suitably chosen (its diameter should be not greater than one-fourth of the diameter of the diaphragm), it does not interfere with the linearity of the pressure/deflection characteristic. In passing, it may be mentioned that for certain instruments, though not industrial instruments, where the deflection of the diaphragms is small, an optical lever is used which consists of a beam of light projected on to a polished surface on top of the diaphragm.

It has not yet been found possible to derive rational design formulae for predicting the performance of diaphragms, although useful indications can be given and, once a particular size has been made, dimensional analysis can be used in predicting the performance of other sizes; but obviously this method is rather limited.[19] Some interesting mathematical computations of stresses in diaphragms have also been carried out, using brittle lacquer coatings as an experimental check on these theories. Diaphragm and capsule instruments have errors very similar to those experienced with the Bourdon tube type of instrument, due in general to imperfect elastic properties, the chief errors being hysteresis and drift (see p. 18). To attain a high standard of accuracy, it is necessary to ensure that the stress is kept well below the limit of proportionality. A carefully controlled manufacturing technique must also be employed.

Materials

The materials required for diaphragms and capsules must have go and consistent elastic properties, as previously described, and must be available in strip form to close dimensional tolerances. They must be easily formed, have good resistance to corrosion by the working fluids and be free from excessive directional properties. The materials normally employed are brass, phospor bronze, nickel silver, beryllium copper, Monel, K-Monel and stainless steel. A copper–manganese–nickel alloy (60 : 20 : 20) would, from its characteristics, also appear to be very suitable.



[Courtesy Beryllium Corporation

FIG. 22.—Typical die set for forming a metal diaphragm.

Manufacture

Diaphragms are formed by spinning, stamping, or by pressing, usually with hydraulic presses. The last-mentioned process is considered the most suitable as the structure of the material is kept more uniform thereby, since the forming is slower and the pressure can be accurately controlled, the method also lends itself to quantity production. Tests[20] have shown that the amount of cold work is quite small and about equal to a 10 per cent. reduction in thickness of the material. Thus the heat cycle for heat-treatable alloys can be the same as for annealed material.

Dies for making the pressings are relatively simple; normally only the top half of the die has to be made, the bottom half being a block of rubber. A typical half-die and rubber set is shown in Fig. 22. The edges of the diaphragm are usually soldered, provided the stress at the mounting flange is kept low, as stated on page 60.

Applications

Apart from the aneroid barometer and other familiar applications, many examples of diaphragm instruments are to be found among aeronautical instruments, for example, altimeters, air-speed indicators, boost gauges, Mach meters, etc.

A sensitive altimeter mechanism is shown in Fig. 23. The diaphragm assembly in this particular case consists of beryllium copper diaphragms soldered together at their edges, the space between them then being evacuated. The mechanism consists of a rocking shaft, assembly calibration arm, sector multiplying gear train and hand staff. A beryllium copper spring is anchored to the mechanism plate and secured to a member of the gear frame to remove backlash from the mechanism. The diaphragms and mechanisms are balanced in all positions by an assembly which is connected to the rocking shaft by means of a link. A temperature-responsive bimetallic element composed of brass–Invar (see page 128) is also included to compensate for the variation with temperature of the elastic modulus of the diaphragm material.

Diaphragm gauges are also widely used in industry for both indication and controlling purposes. Fig. 24 shows an unusual application of diaphragms in which small movements of objects for microscopic examination can be obtained.

RESISTANCE-TYPE PRESSURE- AND STRAIN-SENSITIVE ELEMENTS

General description

As mentioned at the beginning of this Chapter (page 15), Kelvin[2] appears to have been the first to have discovered and recorded the fact that when a material is stressed either in tension or compression its resistance is altered, the change not being that which would be expected from a change in the physical dimensions of the material. He discovered this phenomenon when measuring the resistance of copper and iron wires to which were attached various weights and made use of it to measure the depth of parts of the Atlantic Ocean in connection with the laying of the early trans-Atlantic telegraph cables. In more recent times use has been made of

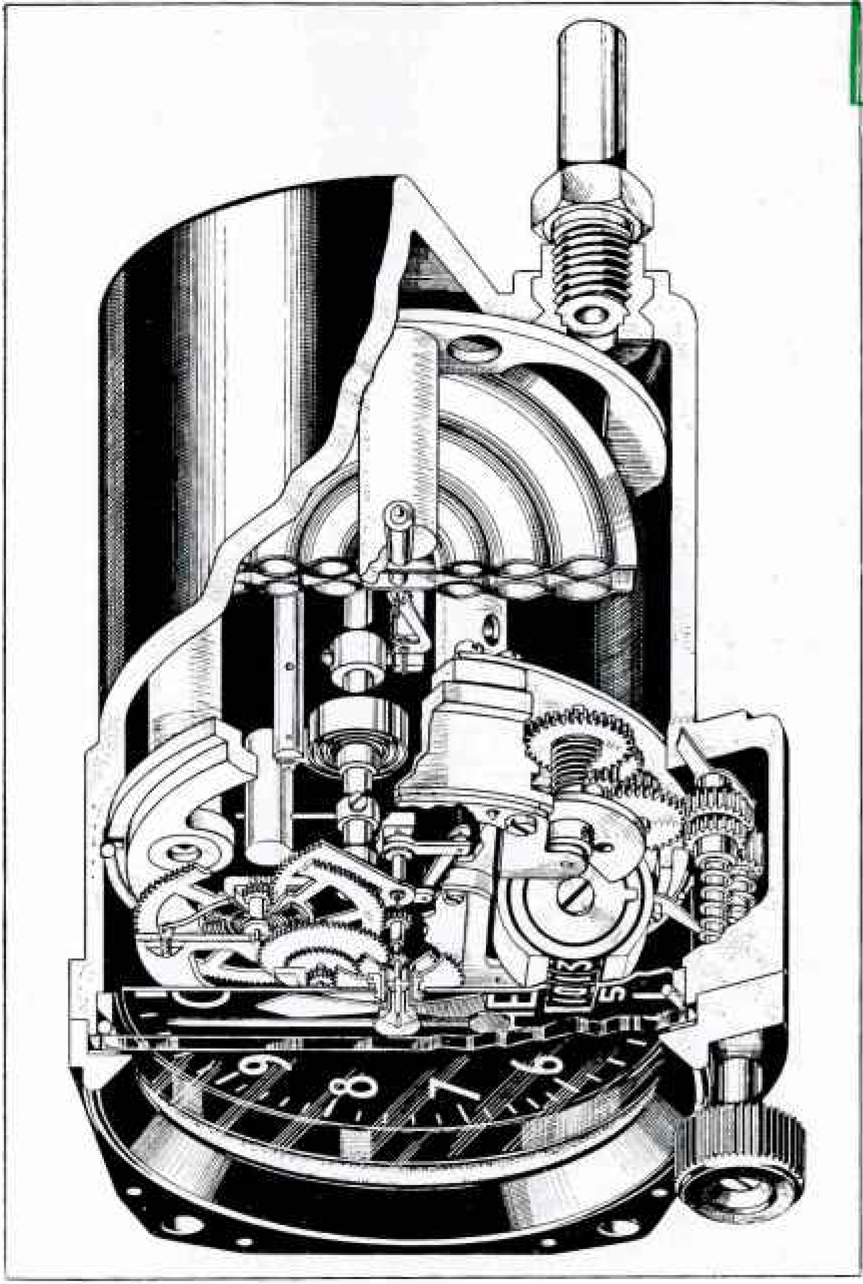
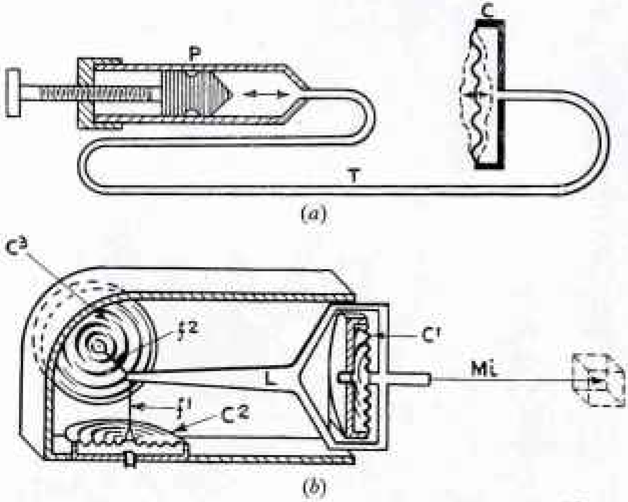


FIG. 23.—Sensitive altimeter mechanism.

the phenomenon to measure compression strains in reinforced concrete, the elements used being known as "strain gauges" of the resistance type. The development of the strain gauge into its modern practical form was due mainly to the work of Clarke and Simmons of the California Institute of Technology and Professor Ruge of the Massachusetts Institute of Technology.

Strain gauges enable both static and dynamic stresses in structures to be determined by measuring the change in resistance of a material with strain, and this type of gauge can also be adapted to determine vibration, acceleration and weight. Strain gauges can be used both in tension and compression and are particularly valuable for tensile tests on foil. Bridgeman's work[21] on high pressures is well known and the Manganin wire-resistance pressure gauge, which he developed for work with pressures of 500 atmospheres and above, is now accepted as the standard gauge. The properties of Manganin are fully described in C.D.A. Publication No. 38.



[Courtesy "Discovery"

FIG. 24.—A micro-manipulator.

(*a*) Showing the principle of transmission of movements in the pneumatic micro-manipulator. P = pump, C = discoid metallic membrane, T = rubber tube.

(*b*) Arrangement in the receiver of the three capsules (C1, C2, C3), the movable rod (L) to which movement is imparted from C2 and C3 by filaments f1 and f2, and which may carry a dissecting instrument (Mi) to which the micro-movements are imparted.

The present widespread use of the strain gauge is due to the fact that it is accurate and cheap and may easily be fixed to any structure. The results are easy to record, although the determination of stresses from strains may sometimes involve rather laborious calculations. The accuracy is normally within ± 2 per cent., although a much closer degree of accuracy can be achieved if special precautions are taken. The strain gauge has negligible inertia and is suitable for the determination of both dynamic and static stresses, and it is free from many of the disadvantages of the mechanical type of strain-measuring devices.

The associated circuits can easily be arranged so that a warning is given or preventive action taken when the strain in a member exceeds a predetermined limit; further, by suitable selection and arrangement of the gauges it is possible to read stress directly, but the conditions under which these means can be employed are rather limited. Strain gauges also form a convenient method for the determination of residual stresses.

Principle of operation

If wire is stressed so that its length L is changed by δL and the resistance R changes by δR, then the relationship between the two can be expressed by

$$S = \frac{\delta R}{R} \div \frac{\delta L}{L}$$

which is dimensionless and is nearly constant over a wide range of strain; it is known as the sensitivity or gauge factor.* Typical values of this dimensionless constant are given in Table II. Little is known, however, about its fundamental nature. It seems likely that there are two separate factors that cause the change of resistivity in a strained material, one of which is dependent on Poisson's ratio and the other on some as yet unknown property of the material. Work by Weibull[22] on Copel (a copper-nickel alloy of the Constantan type—see pp. 66, 125) seemed to indicate that the specific increase of resistance was approximately equal to twice the

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* As $\frac{1}{L} = \frac{d\,(\log L)}{dL}$

and $\frac{1}{R} = \frac{d\,(\log R)}{dR}$

this expression may sometimes be seen in the form

$$S = \frac{d\,(\log R)}{d\,(\log L)}$$

and is so expressed in Table IV, page 77.

TABLE II

Properties of Strain-Gauge Materials[24]

Material	Composition (%)	Resistance (ohms/yd. for 0·001-in. dia. wire)	Temp. coeff. of resistance* (per °C. $\times 10^{-6}$)	Sensitivity	Thermal e.m.f. vs. copper (microvolts per °C.)	Coeff. of linear expansion (per °C. $\times 10^{-6}$)	U.T.S. annealed (tons/sq.in.)	Ease of manufacture
Minalpha ..	Cu 85–Mn 12–Ni 3	732	± 3†	0·5–2·1	0·3	17	27	Fairly easy
Advance ..	Cu 55–Ni 45	—	—	—	—	—	—	
Copel Constantan Eureka	Cu 60–Ni 40	850–500	± 20	2·0–2·1	—	—	—	
Ferry ..	Cu 56–Ni 44	—	—	—	43	13·7	28	
Brightray Nichrome	Ni 80–Cr 20	1914	70	2·1–2·3	3·8	12·5	50	Easy
Chromel "C"	Ni 64–Fe 25–Cr 11	1900	180	2·5	—	—	—	Slightly difficult
Glowray ..	Ni 65–Fe 20–Cr 15	1986	140	—	0·9	12·5	48	
Iso-Elastic..	Ni 36–Cr 8–Mo ½–(Mn, Si, Cu, V) 3½–Fe 52	2040	300	2·8–3·5	—	—	—	Difficult
Nickel ..	Pure	—	—	12·1	—	—	—	

* Over range 0–100° C.

† Over range 10–40° C.

specific elongation or strain, if above the yield-point, and he deduced from this that when stressed over the yield-point the changes of electrical resistance of a material were really due to geometrical changes and not to changes of resistivity; but insufficient work has been done as yet to determine precisely the causes of the apparent changes of resistivity.

The desirable properties of a strain-gauge material are

(a) High tensile strength.
(b) High strain sensitivity.
(c) Good thermal stability.
(d) Negligible resistance/strain hysteresis.
(e) Freedom from "resistance creep" under load.
(f) Ease of jointing.
(g) High resistivity.
(h) Freedom from corrosion.
(i) Low temperature coefficient of resistance.
(j) Low thermal e.m.f. against copper.

Swainger[23] has drawn attention to the suitability of Minalpha for large degrees of strain (up to 8 per cent.) and to the importance of avoiding any strain in the joint between the gauge-wire and lead-out wire. He has also shown that changes in sensitivity occur throughout the range of strain, becoming approximately constant at strains greater than 2 per cent.; at the low values of strain at which commercial types of gauge are generally used, however (up to, say, 0·6 per cent. strain), the sensitivity may be considered constant.[24]

Some of these properties are mutually incompatible, but certain copper-base alloys meet the majority of the requirements and are very widely used in practice. Table II shows the main properties of some materials.

In the above desiderata of strain-gauge materials a low temperature coefficient of resistance is mentioned, but it is important to remember that there are, in fact, two temperature factors to be taken into account, the change of resistance with temperature, and the different thermal expansion or contraction of the material of the gauge and the material in which the strains are being measured. Thus, a gauge material ideally suited for use on one substance may have large temperature errors on others. A strain gauge could be made with characteristics to suit the material under test, or could be made of composite materials, so that the changes in one balanced out the changes in the other. Modern practice is to use a gauge material the coefficient of expansion of which is nearly the same as that of the material under test (see Table II) and to use a dummy gauge subjected to the same temperature changes, but not subjected to any strain, to balance out the change of resistance due to temperature. This effect is very much more serious when determining prolonged static stresses than when testing dynamic loads.

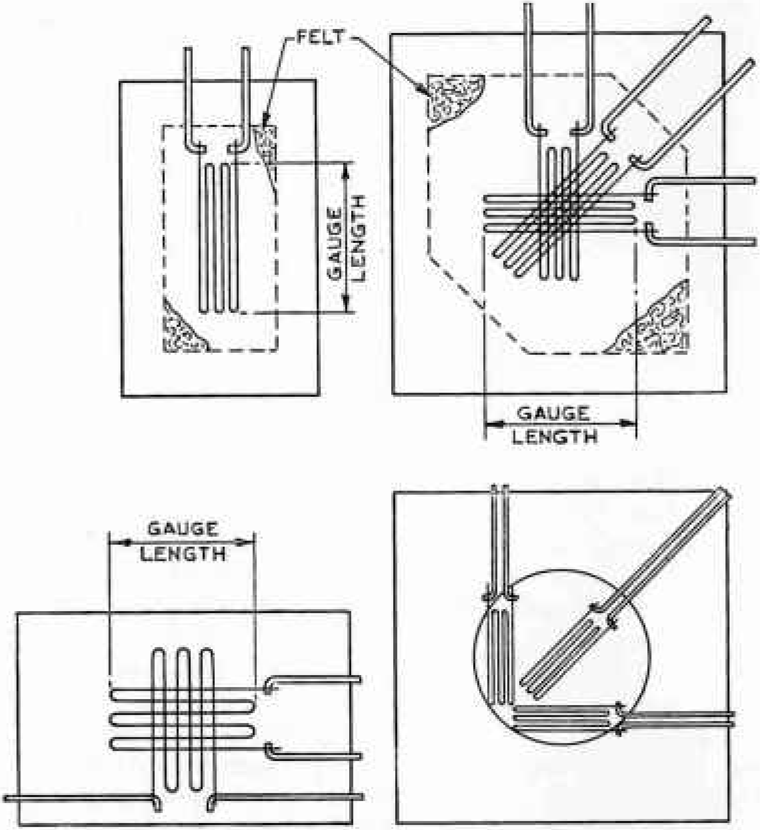

Fig. 25.—Typical arrangements of strain gauges (Dobie & Isaac[21]).

Construction

For measuring strain, two distinct types of gauge are used, one in which the stress is applied to a straight filament, and the other in which the filament is secured to an insulating backing and then stuck on the surface of the material in which it is required to measure the strain. The latter method is more widely employed than the former, since it can be applied to actual structures and machinery, whereas the former is more suitable for experimental work.

The bonded strain gauge consists of a fine wire either wound round a suitable former of insulating material (usually rice paper), and then flattened, or wound zigzag up and down the paper and kept in position by a suitable adhesive. Another type has the wire in a zigzag form and interwoven with rayon. On top of this there is usually a small piece of felt to protect the wire from sudden changes of temperature. Fig. 25 shows typical examples.

The base length of a strain gauge can be varied between wide limits; it may be as short as $\frac{1}{8}$ in. or as long as desired, but it should be borne in mind that the gauge length in a resistance wire gauge does not have the same meaning as gauge length in a mechanical extensometer. If the gauge length of the latter is increased, the sensitivity is also increased, but unless the resistance of the former is increased in proportion to the gauge length no overall increase in sensitivity is obtained. The diameter of the wire used for strain gauges varies from about 0·0305 in. to 0·002 in., but the finer sizes of wire are preferable; since it is important that the axis of the wire is as close as possible to the surface of the material in which the strains are being measured, otherwise a false result is obtained.

Attachment of leads

It is essential that the strain imposed upon the gauge is not transmitted to the junction of the gauge wire and the lead-out wires; this can easily be arranged by making a junction outside the area of the gauge which is attached to the specimen under test.

The wires are generally of copper, although sometimes cupro-nickel wires are used. They are fixed either by soldering or spot welding.

As the wire of the gauge itself is normally as fine as 0·001 in. diameter, it is not robust enough to be attached to the measuring circuits and therefore a heavier gauge lead-out wire is necessary.

Operating current

For maximum sensitivity, it is desirable to employ as large a current as possible, since for a fixed value of resistance this gives the greatest output. The temperature rise must, however, be limited so as to minimize the undesirable thermal effects which arise. The current rating for a suitable temperature rise depends on the thermal insulation surrounding the gauge, the resistance of the gauge material and the spacing of the wires themselves. The circuits in which the gauge itself is incorporated are usually of the Wheatstone bridge type.[24]

Attachment and waterproofing

The greatest care is necessary in cementing the gauge to the structure under observation, while means must also be provided to prevent the insulation resistance (which is effectively in "shunt" with that of the gauge itself) being affected by humidity changes.[24] These important aspects of the subject are, however, rather outside the scope of this publication.

Foil Strain Gauges[25]

Many of the above difficulties may be overcome by the use of gauges of the foil type, produced by the "printed circuit" technique. A layer of foil is bonded on to a thin lacquer film. A roller then inks the gauge pattern—a grid of strips—on the foil and an acid dip removes the unwanted metal. The cross-sectional area of the strips is rather greater than that of the earlier used wire types, the ends being still further widened, thus aiding the transmission of the strain. The high ratio of contact area to volume makes possible a higher operating temperature; the operating current may therefore be higher (about ten times higher than that used in wire-type gauges), with consequent increase in sensitivity. Tags may be made integral with the strip, thus greatly facilitating the attachment of leads. Special arrangements of foil strain gauges are available for measurements of stress in metallic diaphragms of the type described on page 57; these take the form of a double spiral distributed over the surface of the diaphragm and may thus be used for pressure readings. Another form—the "herring-bone"—is suitable for torque measurements on shafts.

The sensitivity of gauges of this type (the grid material of which is usually a 50 per cent. copper-nickel alloy) is so great that the amplifying equipment normally required in strain-gauge work may often be dispensed with, the gauge terminals being connected direct to the recording galvanometer.

CHAPTER II

ELECTRO-MAGNETIC INSTRUMENTS

BASIC PRINCIPLES

ALL electro-magnetic instruments employ coils and windings in various forms and copper is universally used in their construction. Copper is chosen for its high electrical and thermal conductivity (exceeded only by that of silver), the ease with which it can be accurately drawn into wire of the required sizes, its resistance to corrosion, its ability to be soldered, brazed, welded, or otherwise jointed and the fact that it can be readily wound into coils of any desired shape. Some of its basic properties will now be briefly reviewed.

RESISTIVITY AND CONDUCTIVITY

Although resistivity is defined as the resistance between the opposite faces of a unit cube of a material, a considerable number of units, mainly American in origin, have become common. There is now a tendency for the unit of resistivity to be expressed in ohm-cm. For many years the expression "ohm per cm. cube" has been in wide use and has led to some misconceptions; the name "ohm-cm." is to be recommended since it is dimensionally correct, as is also the more complete but clumsier expression, "ohm-cm.^{2} per cm.":—

$$\begin{aligned}\text{Resistivity} &= \text{resistance} \times \frac{\text{area}}{\text{length}} \quad \left[\frac{\text{ohm-cm.}^2}{\text{cm.}}\right] \\ &= \text{resistance} \times \text{length} \quad [\text{ohm-cm.}]\end{aligned}$$

Conductivity, which is the reciprocal of resistivity, is widely used and is probably more informative than resistivity when comparing a number of materials; it may also be expressed on a percentage basis (see p. 73).

It follows from the foregoing that the units of conductivity must be ($\text{ohm}^{-1}\text{cm.}^{-1}$), but the term "mho per centimetre" is also employed. Resistivity and conductivity can be expressed either on a volume or a mass basis, but the former is that generally employed.

High Conductivity copper

Copper for electrical purposes must be of the highest purity and is usually designated "High Conductivity" copper. The term "High Conductivity" (H.C.) appears to have been introduced by Kelvin in 1865.

when (as Sir William Thomson) he was responsible for the design of the first successful trans-Atlantic cable. Most of the high conductivity copper used in this country is of a type known as "tough pitch," which designation indicates that it contains a small percentage (usually about 0·04 per cent.) of oxygen in the form of globules of cuprous oxide, which are distributed throughout the body of the copper. In this form the oxygen does not have any appreciable effect on the conductivity. For special purposes oxygen-free copper of high conductivity is made (from cathode copper) by carrying out the necessary melting and casting operations in an inert atmosphere, or by sintering and extruding copper from brittle cathodes; but such material is not normally used for coil winding. Deoxidised copper is widely used for non-electrical purposes and is made by adding deoxidising agents to the molten metal; but in general the conductivity is depressed to such an extent as to make it unsuitable for electrical purposes. High conductivity deoxidised copper can be obtained by using deoxidants such as boron, etc., which do not have a marked effect on the conductivity, but close control is necessary to achieve this objective.

High conductivity tough-pitch copper can be produced from crude copper by a combination of electrolytic and fire refining or by fire refining alone, the appropriate British Standards for the two types of material products being Nos. 1036 and 1037 respectively. There is no very important difference between the products of these two methods as far as copper wire for electrical purposes is concerned.

The main physical properties of high conductivity copper are given in C.D.A. publications Nos. 12 and 36 (see p. 152).

Resistance standards

The International Electro-Technical Commission[26] established certain standards for high conductivity copper; these are:—

(i) At a temperature of 20° C. the resistance of a wire of Standard Annealed Copper one metre in length and of uniform section of one square millimetre is 1/58 ohm (0·017241 . . . ohm).

(ii) At a temperature of 20° C. the density is 8·89 grammes per cubic centimetre.

(iii) At a temperature of 20° C. the "constant mass" temperature coefficient of resistance is $0{\cdot}00393 = 1/254{\cdot}45\ldots$ per ° C.

(iv) At a temperature of 20° C. the resistance of a wire of uniform section one metre in length and weighing one gramme is $1/58 \times 8{\cdot}89 = 0{\cdot}15328\ldots$ ohm.

The following resistance figures for high conductivity annealed copper are derived from those given in the I.E.C. Standard:

Annealed Copper		At 20° C.	At 60° F.
Centimetre cube	(microhms)	1·7241	1·6939
Inch cube	(microhms)	0·67879	0·66689
Per foot per sq. in.	(microhm)	8·1455	8·0026
Wire, 1 metre long, weighing 1 gm. ..	(ohm)	0·15328	0·15062
Wire, 1 mile long, weighing 1 lb. ..	(ohm)	875·20	860·04
Wire, 1 ft. long, weighing 1 lb.	(microhm)	31·393	30·850

The resistance at 60° F. of an H.C. annealed copper conductor of uniform cross-section may be calculated with reasonable accuracy from the following empirical formula:—

$$\text{Resistance in microhms} = \frac{8 \times \text{length in feet}}{\text{cross-sectional area in sq. ins.}}$$

Copper which has a resistance equal to that given above is said to have 100 per cent. conductivity*. High conductivity annealed copper as supplied commercially may have a conductivity approaching 102 per cent.

It will have been noted that the International Electro-Technical Commission's resistance figures are based on high conductivity copper in the annealed condition at 20° C. The effect of impurities, temperature, strain and magnetic fields on the conductivity will now be considered.

Effect of impurities

The effect of various elements on the conductivity of copper is shown in Fig. 3 of C.D.A. publication No. 12, "Copper Data." The extent of this effect depends on the type and concentration of the added element. Elements such as phosphorus, silicon, arsenic, etc., are most deleterious, whereas silver and cadmium in small quantities have but little influence in reducing conductivity values. Oxygen (not included in the above-mentioned graph) has been shown to be of negligible importance from a conductivity point of view, at least in the amounts in which it is encountered in commercial grades of copper.[27] Lead, selenium and tellurium have little effect in depressing conductivity. Except for special work the effect of very small percentages of impurities is not usually of great importance.

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* The conductivity of any material may be expressed in this manner, i.e., a conductivity of x per cent. I.A.C.S. means that the resistivity in microhm-cm. is $1\cdot7241 \ldots \times 100/x$.

Effect of temperature

The electrical resistance of copper, as of all pure metals, varies with temperature. This variation is such as to reduce the conductivity of H.C. copper at 100° C. to about 76 per cent. of its value at 20° C.

If the resistance of a piece of copper be R_0 at 0° C., the resistance R_t at any other temperature t° C. can be found from the formula

$$R_t = R_0\,(1 + \alpha_0\, t)$$

where α_0 is the "constant mass" temperature coefficient of resistance at 0° C.

If the resistance is known at a temperature t° C. ("reference temperature") and it is required to determine it at some higher temperature t'° C., the new value can be calculated from the formula

$$R_{t'} = R_t\,[1 + \alpha_t\,(t' - t)\,]$$

where α_t is the temperature coefficient at the reference temperature t. Substituting for R_t from the former of these two formulae, it may readily be shown that α_t and α_0 are interrelated by the formulae

$$\alpha_t = \frac{1}{\dfrac{1}{\alpha_0} + t} \text{ or } \alpha_0 = \frac{1}{\dfrac{1}{\alpha_t} - t}.$$

Now the reference temperature adopted by the I.E.C. is 20° C., at which temperature α_{20} is taken as 0·00393 per °C. By substitution of this value, the value of α_0 is

$$\alpha_0 = \frac{1}{\dfrac{1}{0{\cdot}003\,93} - 20} = \frac{1}{254{\cdot}45\ldots - 20} = \frac{1}{234{\cdot}45\ldots} = 0.004\,265 \text{ per °C.*}$$

Multiplier constants and their reciprocals, correlating the resistance of copper at 20° C. with the resistance at other temperatures, may be obtained from tables which are included in many British Standards.

The foregoing remarks assume that the resistance of copper is a linear function of the temperature; this is not strictly correct, but the departure from linearity over temperatures up to 100° C. is so small as to be of negligible practical importance.

Temperature coefficient of volume resistivity

If the resistance of a piece of copper of known dimensions is required at some temperature other than that at which its volume resistivity is

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* To four significant figures.

known, the latter must be adjusted by the use of the volume resistivity temperature coefficient. This is related to the "constant mass" temperature coefficient by the formula

$$\beta = \alpha + \gamma$$

where β = constant volume temperature coefficient.
α = constant mass temperature coefficient.
γ = coefficient of linear expansion.

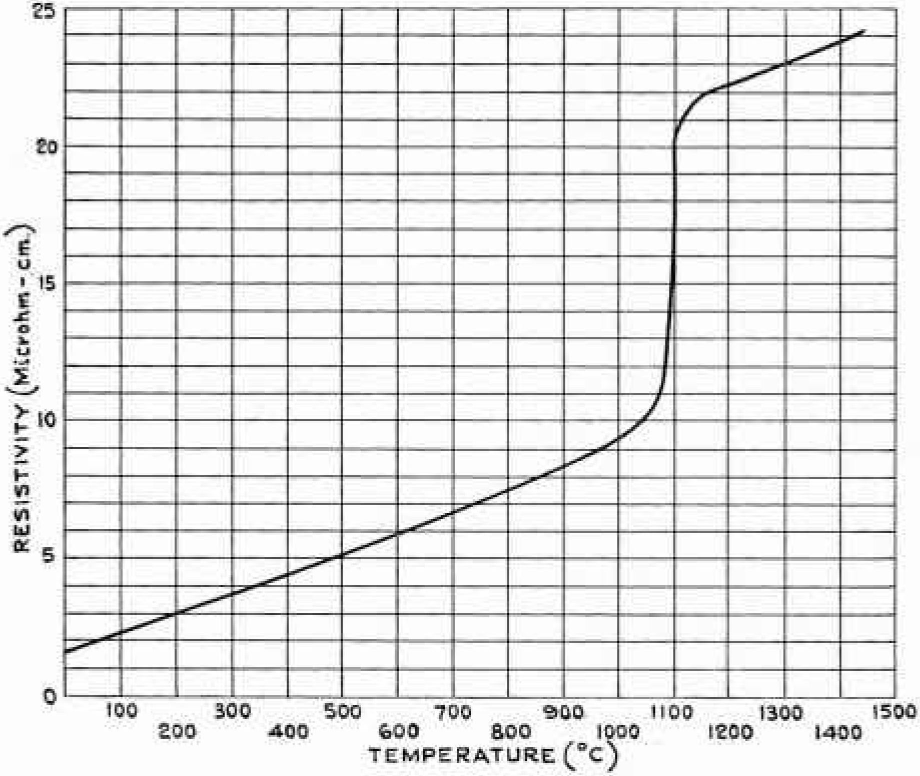

FIG. 26.—Resistivity of high conductivity copper from 0° C. to 1400° C. (Northrup[28])

The resistivity at any temperature t° C. is related to the resistivity at 0° C. by the formula

$$\rho_t = \rho_0 (1 + \beta_0 t)$$

and the resistivity at a temperature t' is determined from the resistivity at a temperature t by the formula

$$\rho_{t'} = \rho_t [1 + \beta_t (t' - t)]$$

Thus, strictly speaking, the volume resistivity temperature coefficient at any temperature t (β_t) and its value at 0° C. (β_0) are interrelated in exactly the same way as are α_t and α_0 (see above); in practice, however, γ is so small in comparison with α that no modification to its value with change of reference temperature is warranted: it is sufficient to take $\beta_t = \alpha_t + \gamma$ at any reference temperature t. The value of γ adopted by the I.E.C. is 0·000 017 per °C.

Hence $\beta_{20} = 0{\cdot}003\,93 + 0{\cdot}000\,017 = 0{\cdot}003\,947$ per °C.
$\beta_0 = 0{\cdot}004\,265 + 0{\cdot}000\,017 = 0{\cdot}004\,282$ per °C.

Fig. 26 shows the variation of the resistivity of high conductivity copper with temperature from 0° C. to 1400° C.

The temperature coefficients given above only apply to the material when the conductivity is 100 per cent. The conductivity may be less than this, due to the presence of impurities or to the effect of cold work on the material. The effect of impurities does not in general follow any recognizable law, though small quantities of certain impurities would appear to alter the temperature coefficient of resistance and the resistivity in such a manner that their product is a constant; but much more work is necessary on this question before any definite statement can be made.* The effect of cold working on the temperature coefficient of resistance is shown in Table III.

TABLE III

Effect of Cold Working on Resistivity (ρ) and Temperature Coefficient of Resistance (α) of Copper

State	Tensile Strength (Tons/sq. in.)	ρ (microhm–cm.)	α (per °C. at 20° C.)
Annealed	14	1·7241	0·003 93
Hard	30	1·778	0·003 81

Effects of physical condition

Elastic strain

As mentioned in Chapter I, Kelvin discovered the variation of resistance of copper with elastic strain, by hanging a series of weights on copper wire and measuring the resistance. The fundamental theory concerning this change of resistance is not yet fully understood; Table IV shows the

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* See, e.g., reference No. 65 of the Supplementary Bibliography, p. 145.

minute effect of strain within the elastic range upon the resistivity of copper and should be compared with the values ("sensitivities" or "gauge factors") given for various alloys in Table II, page 66.

TABLE IV

Change of Resistivity of Copper with Elastic Strain[29]

Strain (%)	Resistivity (microhm-cm.)
0	1·7241
0·1	1·7290

Notes:—(i) In the case of copper wires the general relation between resistance R, and length L may be expressed as

$$\frac{d\ (\log R)}{d\ (\log L)} = 2{\cdot}9$$

(ii) The value of 0·1 per cent. strain is actually greatly in excess of the *elastic* strain which could be experienced by annealed copper and is included here merely to illustrate the principle.

Plastic strain

If copper is worked in the cold condition (strictly speaking, at any temperature under recrystallization temperature), then the crystal structure of the metal is distorted; this increases the hardness and reduces the conductivity of the copper. An empirical rule, which expresses the increased resistivity of high conductivity copper due to cold working with sufficient accuracy for most purposes, is that within the range of 20 to 30 tons/sq. in. tensile strength the percentage increase in resistance can be expressed by

$$p = T/10$$

where p = the percentage increase in resistance of the cold-worked copper over its resistance when annealed, and T = the tensile strength in tons/sq. inch.

Effect of magnetic field

Copper, in common with other metals, exhibits the phenomenon known as "Hall's effect." When a current flows along a copper conductor, across which there is a magnetic field, a difference in potential is generated between the sides of the conductor.

The factors involved are related by the following expression, appropriate units being assumed:—

$$e = R\,(HI/t)$$

where R = Hall's coefficient
H = Field strength
I = Current
t = Thickness of the bar
e = e.m.f. produced.

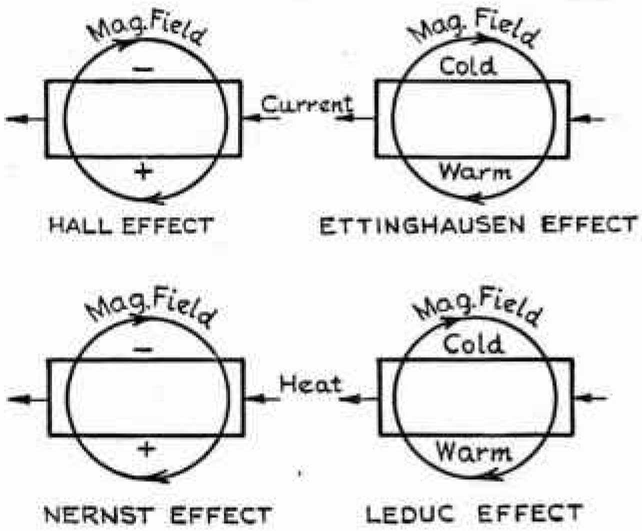

Fig. 27.—The four magnetic tranverse effects in copper (E. H. Hall.[30]), showing direction of flow of electric current or heat to give the potential or temperature difference shown, with direction of field as indicated by "corkscrew rule," i.e. vertically downwards through plane of paper.

A similar effect occurs when heat flows along the bar and there are four magnetic transverse effects which have been studied by Hall.[30] Fig. 27 shows these effects and the names normally associated with them, but reference should be made to Hall's original paper for fuller details.

Before going on to the production of copper wire and its use in instrument construction, it is convenient at this point to deal with the general phenomenon of magnetism as found in copper and its alloys, with particular reference to its influence in instrumentation.

MAGNETISM IN COPPER AND COPPER ALLOYS

All materials can be divided from a magnetic point of view, into three classes, namely diamagnetic, paramagnetic and ferromagnetic.

A diamagnetic substance is one which when placed in a magnetic field becomes weakly magnetized, the induction within the substance being less than that of the field, i.e. its permeability is less than unity and its susceptibility negative; such a substance aligns itself with its longer axis at right angles to the applied field. Both paramagnetic and ferromagnetic substances align themselves with their longer axes parallel to the magnetic field; the former become weakly magnetized (permeability slightly greater than unity, susceptibility positive) and the latter strongly magnetized by the field.

(Susceptibility is a measure of the ease with which a substance can become magnetized and is usually defined as the magnetic moment —per unit volume or per unit mass—divided by the field strength. Permeability is the total induction within the substance divided by the field strength.)

There is not a great deal of published work dealing with the magnetic effects of copper and its alloys when used in instruments, but it is an important problem with certain specialized instruments. There are two main factors to be considered: (*a*) the effect of magnetism in copper wire when it is wound into coils for moving-coil instruments, and (*b*) the effects of magnetism in copper alloys which are used in the construction of instruments the sensitive element of which is affected by small changes in the magnetic field.

Copper in its pure form is very slightly diamagnetic, having a mass susceptibility of the order of $-0 \cdot 7 \times 10^{-6}$; for most purposes, however, it can be considered as a non-magnetic material. Reekie and Hutchinson[31] have carried out experiments with copper of the highest available purity in which the iron content was less than 0·0005 per cent. Their experiments showed that the magnetic susceptibility of copper decreases with cold working and that magnetic self-recovery takes place at temperatures below that at which recrystallization can occur.

Influence on instruments

Effects such as those observed by Reekie and Hutchinson in the experiments mentioned in the preceding paragraph are, however, too small to cause appreciable errors even in ultra-sensitive instruments; but the percentage of iron in commercial copper is usually somewhat larger than that in those experiments and can cause unacceptable errors.

C. S. Smith[32] and others have shown that when small amounts of iron are in solid solution in copper, the resultant material is not ferromagnetic. Heating to approximately 650° C. and then cooling causes the iron to be precipitated in a non-ferromagnetic form. If, however, the iron-bearing copper is now cold worked it becomes magnetic. It is considered that when first precipitated the iron is in the face-centred cubic form, but after cold working it is in the body-centred cubic form, which is known to be the form in which iron is ferromagnetic.

Even if the copper, as cast, is free from ferrous impurities, it must not be forgotten that copper wire, in the course of its manufacture (see page 83), is frequently in contact with steel parts, so that a superficial ferrous deposit tends to be formed on the finished wire, rendering it ferromagnetic. This gives rise to the following errors in moving-coil instruments:—

Zero error.—The first is a zero error which arises because the iron retains a certain amount of magnetism from the field in which it was last placed, i.e. remanent magnetism. The interaction of this magnetism with the main field will produce a couple which, when the instrument is switched out of circuit, will give a zero point depending on the last applied field strength. If the field strength in an instrument were perfectly uniform, once the instrument had been calibrated no further alterations would be necessary. It is not possible, however, to obtain an entirely uniform magnetic field and in certain instruments, notably those having a non-linear scale, the magnetic field strength is purposely made non-uniform and large zero errors can arise.

Parasitic couple.—The second error arises from the parasitic couple which is set up and which, in combination with the main directional couple, gives a varying torque which destroy the linearity of the scale.

For most applications, effectively non-magnetic copper wire can be achieved by using good quality high conductivity copper, from which the surface contamination is removed by an acid dip. In some cases, however, a sufficient supply of suitable wire may be obtained by selection from normal supplies of other grades of copper, as generally only very small quantities of this type of wire are used. Moerel and Rademakers[33] suggest that if a suitable wire of one gauge is obtained, but requires redrawing, the following precautions should be taken:—

(*a*) The dies (diamond) should be reserved exclusively for the drawing of iron-free copper wire; instead of steel only bronze tongs, forceps, etc., should be used;

(*b*) Only distilled water should be used in the pickling baths and for rinsing;
(*c*) The atmosphere should be kept free of dust;
(*d*) The wire should not be touched, even with clean hands.

It is, of course, not only the wire that has to be carefully selected, but also the former upon which the wire is wound and the insulating material, as tests have shown that various insulants such as silk and enamel can have a magnetic effect as great, if not greater than, that of the wire itself.

It must again be emphasized that this special non-magnetic wire is only required in ultra-sensitive instruments, and in the normal form of moving-coil instruments standard high conductivity copper wire is quite suitable and no special precautions need be taken.

Effect of alloying elements

Copper alloys are extensively used for the construction of instruments and, where small changes in magnetic field strength have to be detected, it is necessary to ensure that the magnetism of the constructional materials is kept sufficiently low and remains constant. The magnetic moment and the susceptibility of the material have been found to be a good criterion for deciding whether or not a material is suitable. The magnetic properties arise from the presence of iron as an impurity. Butts and Reiber[24] have published results on nineteen copper alloys which contain small and varying percentages of iron. A selection of data from their tests is given in Fig. 28, page 82.

Their work showed that although the presence of iron is a major factor, the form in which it is present also has a decisive influence. The state in which the iron exists depends not only upon the mechanical and thermal treatment which the material has received, but also upon the effect of other elements which may be present. Thus, in brass, zinc tends to decrease the magnetic effects of iron until the beta phase is reached, after which the magnetism greatly increases; and in general it can be stated that the appearance of a second phase in any copper alloy when iron is present gives rise to a rapid increase in magnetism. With copper-base alloys, the magnetic properties initially increase slowly with rising iron content, but eventually the rise becomes rapid. Quenching from a temperature sufficiently high to retain most of the iron in solid solution greatly reduces the magnetic properties (although it has little effect on nickel silver) and, in general, annealing increases the magnetic properties. Aluminium bronze with an iron content of less than

0.1 per cent. and having about 8 per cent. aluminium has been found to be one of the best wrought alloys to use where the magnetic moment and the susceptibility must be kept down to a low level. Nickel silver is also good from the non-magnetic point of view, provided, as is almost always the case, that the nickel content does not exceed 38 per cent.

Permanent magnets are dealt with on page 93.

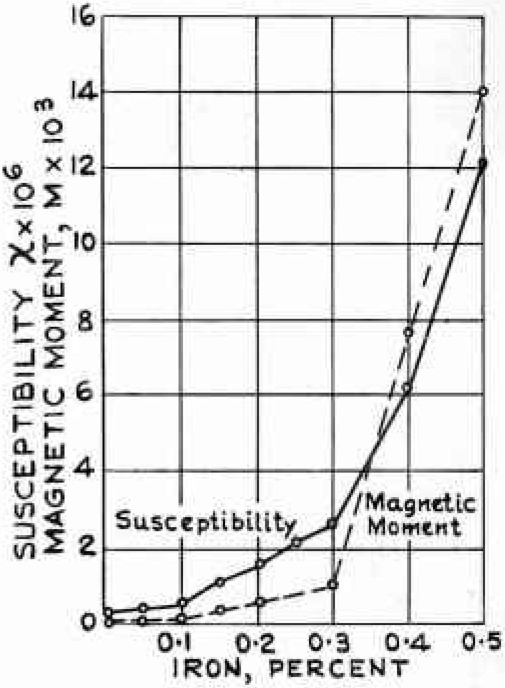

FIG. 28.—Variation of magnetic susceptibility and residual magnetic moment with iron content in various copper alloys, after cold rolling and as cast, viz.:—

A.S.M.T. Ref.	Composition (per cent.)
B 145—4A	85 Cu, 5 Sn, 5 Pb, 5 Zn.
B 145—5A	81 Cu, 3 Sn, 7 Pb, 9 Zn.
B 146—6B	67 Cu, 1 Sn, 3 Pb, 29 Zn.

CONSTRUCTION OF ELECTRO-MAGNETIC INSTRUMENTS

Introduction

The construction of electro-magnetic instruments is best dealt with by detailed consideration of the component parts comprising such instruments, viz.:—

(1) Coils.
(2) Shunts.
(3) Multiplier resistors.
(4) Permanent magnets.
(5) Thermo-magnetic elements.
(6) Copper/cuprous oxide rectifiers.
(7) Glass/metal seals.
(8) Movements.

The indispensable rôle which copper and its alloys play in the construction of all these components will be seen in the following sections. Since, however, much of the copper used is in wire form, some details relating to the manufacture of this product will first be given.

Copper wire

*Rolling and Drawing**

After refining, copper is cast into either vertical or horizontal moulds to produce wire bars. A wire bar is usually about 4 ft. long and has an approximately square cross-section about 4 in. × 4 in. Bars normally weigh about 250 lb., though much heavier ones are made for special purposes.

The relatively high percentage of oxygen in the superficial layers of a horizontally cast bar is sometimes removed by machining to produce a "scalped" bar. Vertically cast bars have only a small set surface at one end which is removed before the bar is further processed.

In the first stage of converting a wire bar into wire, it is heated to about 900° C. and passed hot through a series of grooved rollers which gradually reduce its cross-sectional area and alter its shape until it finally emerges as a roughly formed round wire rod about ¼ in. or 5/16 in. diameter.

After removal of the oxide scale by pickling in an acid bath and washing, the rod is ready for drawing into wire. For special purposes the rod may be passed through a cutting die which shaves off the surface before drawing.

The wire rod in the cold state is then passed through a series of dies of decreasing size until the required diameter is reached. A suitable lubricant is used to minimize die wear and to give a good surface finish to the wire. For large sizes of wire, tungsten carbide dies are most commonly employed, but diamond dies for finer wires (i.e. below about 0·05 in.). To produce fine wire to small dimensional tolerances, it is necessary that the diamond die be made to a very high degree of accuracy with smooth contours and a high degree of polish. The shape of the die

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* See also reference No. 63 of Supplementary Bibliography, p. 145.

is critical and is not the same for a copper wire as for a copper alloy wire. It will be appreciated that the cost of a die is high and if fine tolerances are specified (i.e. smaller than in the appropriate British Standard) the die life will be shortened and thus the price of the wire will be considerably higher per lb. than for the standard product. On the other hand, a small variation in diameter on a fine size of wire can be very serious from the instrument designer's point of view, since it is generally necessary to get a definite number of turns in a given space and with a specified resistance.

The drawing process, being a form of cold working, hardens the material, increasing its tensile strength and diminishing its elongation or ductility. The wire has, therefore, to be annealed before covering or winding. This can be done either in batches or by running the wire continuously through a tubular type of furnace. In order to produce a bright and oxide-free finish an inert atmosphere must be used, such as burnt cracked ammonia or burnt town's-gas, during the annealing process. For annealing in batches, a temperature of approximately 450° C. is used for about two hours.

Measurement of wire diameter

On wire having a diameter of approximately 0·006 in. or greater, little difficulty is experienced in accurately measuring the diameter of the wire with an ordinary hand micrometer, but on wires smaller than about 0·006 in. diameter, the stresses set up in the copper produce deformation sufficiently large to affect the readings.

Carson[35] has carried out some tests to show the amount of stress and deformation which occurs in annealed copper wire when tested between anvils of various diameters and with varying anvil pressures. Table V

TABLE V

Stresses produced in Annealed Copper Wire between Anvils (¼-inch diameter)

Wire dia. (in.)	Anvil pressure (oz.) and stress (lb/sq. in.)			
	2 oz.	8 oz.	16 oz.	32 oz.
0·020	2,200	6,000	9,000	14,000
0·010	3,500	9,000	14,000	22,000
0·005	5,500	14,000	22,000	35,000
0·002	11,000	26,000	41,000	65,000
0·001	16,000	41,000	65,000	102,000

summarizes his results, while Fig. 29 shows maximum pressures which he recommends for various sizes of anvil when used on wires up to 0·02 in. diameter.

For measuring the diameter of fine wires, a bench micrometer can be used with one anvil stationary and with an anvil diameter of not less than ¼ in. with a ratchet set to give a load of 4 oz. Although this method will not give absolute values to a high degree of accuracy, it does enable repeatable results to be obtained. The electronic micrometer is a very suitable method for determining wire diameters accurately, since no anvil pressure is involved. Optical and projection methods are not very suitable for determining the diameter of small round wires. It is usual to determine the diameter at three points around the same cross-section and take the mean of these values. In certain cases, the weight of a given length of wire is determined by means of an accurate balance and from the known density the average diameter can be calculated. In other cases, the resistance of a given length is measured and from the known resistivity the average diameter calculated, but neither of these methods can give a true diameter unless the density or resistivity is known for the particular samples to a high degree of accuracy.

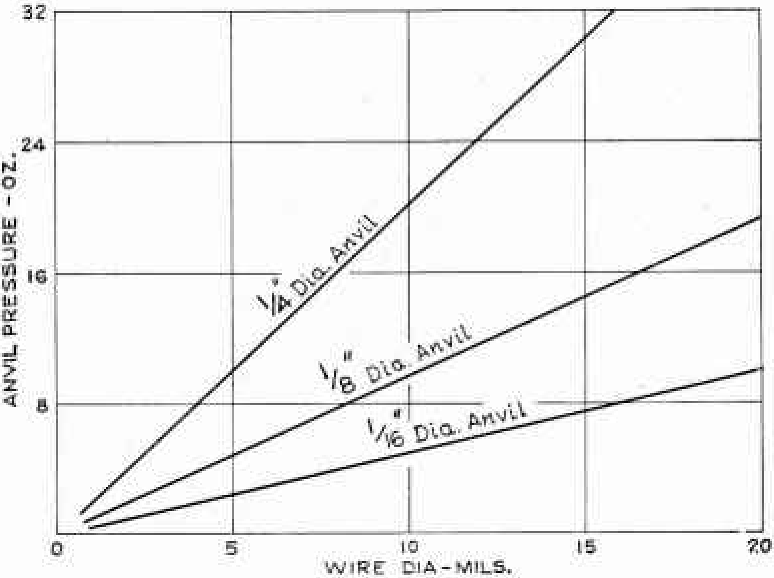


FIG. 29.—Maximum safe anvil pressure for measuring the diameter of soft copper wire.

Covered wire

For most electrical purposes round copper wire is used and is normally supplied in the annealed condition. The British Standard for this material in the bare condition is No. 128. Copper strip which is used for heavier current windings is covered by B.S. 1432. Coil windings are normally insulated with enamel, cotton, silk, rayon, glass, paper or a combination of these, the appropriate British Standards being Nos. 156, 1791, 1815, and 1844.

The majority of coils are, however, insulated with enamel, the chief advantages of which are that it is non-hygroscopic, has a high dielectric strength and a good resistance to abrasion, and that coils wound with enamelled wire have a small space factor. Attempts have been made both in this country and abroad to form an insulating oxide coating on the wire, but although patents have been taken out none of the processes appears to have been adopted commercially. Enamelled copper wire for winding electric coils should comply with British Standard No. 156; this Standard prescribes the various mechanical, electrical and chemical tests to which the wires must be submitted. The thickness of the different forms of insulation for a range of conductor sizes is given in the various tables included in the above-mentioned Standard.

The principles of design and the materials used in the various component parts of electromagnetic instruments (viz. coils, shunts, multiplier resistors, permanent magnets, thermo-magnetic elements, rectifiers and movements) will now be described.

Coils

Winding

Although enamelled copper wires are reasonably robust, a few simple precautions should be taken if damage is to be avoided. The wire may be allowed to unreel by rotation of the spool or may be removed over one of the flanges by means of a suitable spinner. Whatever method is adopted, it is essential that the wire be removed and wound with the minimum possible tension in order to prevent elongation. This is not difficult when winding round coils, but is less easy to achieve when rectangular coils are being wound; in this case the rate at which the wire is removed from the reel varies rapidly during each revolution of the coil, and high rates of acceleration may be experienced. The tension in the wire is proportional to the acceleration and mass of the wire and spool, and thus, unless care is taken, high stresses may be induced, causing excessive elongation or bad coil shape.

Impregnation

Coils are usually varnish-impregnated in order to seal the winding against the ingress of moisture, to improve the thermal conductivity and to increase the dielectric strength of the insulation. The process must be carried out with great care, since a breakdown between turns, while not important on a d.c. coil (provided only a small percentage of the total turns is affected) would produce large circulating currents by transformer action in the case of an a.c. coil. A booklet issued by the Covered Conductors Association[36] describes the impregnation process and includes details of the varnish solvents most commonly used and the types of varnish with which they are most likely to be associated.

Coil design

Basic requirements

Coils are used for many purposes in instruments and their associated equipment and they vary greatly in shape, size and function. The construction of relays, electro-magnets, solenoids, etc., is outside the scope of this book, though references to the subject are included in the bibliography. The main steps in the design of coils suitable for such pieces of apparatus are, however, dealt with briefly.

Whatever its use, and whether for a.c. or d.c. operation, the main requirement of a coil is to produce a definite magneto-motive force, which is measured in ampère-turns per unit length. The problem, therefore, is to embody these ampère-turns in a definite space without exceeding a certain specified temperature. Copper wire is universally used for this purpose, owing to its high conductivity, both electrical and thermal, its high specific heat, the ease with which joints can be made, and its resistance to corrosion. This latter point, which is particularly important, is often overlooked. Fine wires are in general use and small pits due to corrosion will reduce the cross-section considerably, producing local heating due to the increased resistance, and thus giving favourable conditions for further increased corrosion. Although coils are generally impregnated, they "breathe" during temperature changes, and without hermetic sealing it is extremely difficult to ensure that no moisture or gas penetrates into the coil.

Space factor

One of the earliest requirements in the design of a coil is to know how many turns can be wound in a given space. The turns, if evenly wound, will form either as (*a*) or (*b*) of Fig. 30. The space factor, sometimes known as the "activity coefficient," is defined as the ratio of the copper section to the coil section. In the case of (*a*), it may be shown that the space-factor is equal to $0{\cdot}785\left(\frac{d}{D}\right)^2$ and in the case of (*b*) to $0{\cdot}906\left(\frac{d}{D}\right)^2$. Practice generally is to take a figure between the two space factors.

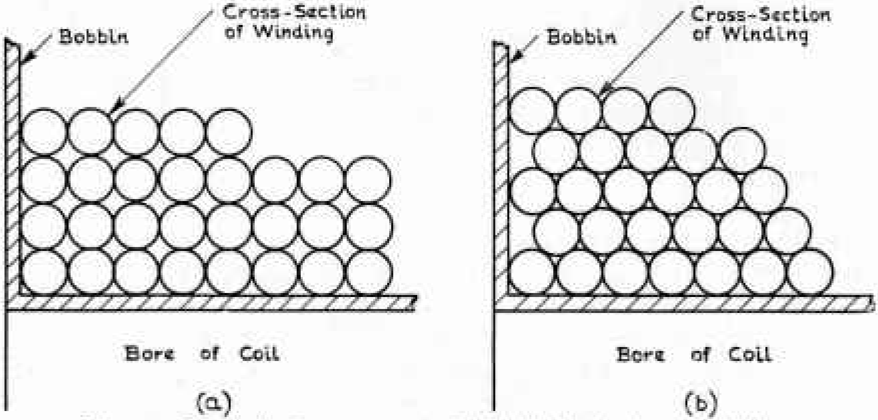


FIG. 30.—Methods of arrangement of individual wires in coil winding
(*a*) "Vertical" [Space factor = $0{\cdot}785\ (d/\mathrm{D})^2$]
(*b*) "Bedded" [Space factor = $0{\cdot}906\ (d/\mathrm{D})^2$]
where d = diameter of bare wire and D = diameter of insulated wire.

The above figures do not, of course, take into account any compression or deformation which may take place. The space factor is small for fine wires and increases as the wire diameter increases, as may be appreciated from the above formulae.

Coil design procedure

In many cases, coils are designed on the basis of previous experience and methods of construction, but the following procedure[37] gives an outline of the general method of approach:—

(1) As the space to be filled and the voltage are normally known for a cylindrical coil with copper conductors, the wire diameter can be found as a first approximation by

$$d = \sqrt{\frac{IT}{V}(D_1 + D_2) \times 1{\cdot}17 \times 10^{-8}}$$

where D_1 = outer diameter of coil (cm.)
D_2 = inner diameter of coil (cm.)
d = wire diameter (mm.)
I = current (ampères)
T = number of turns
V = voltage applied to coil terminals.

(For a rectangular coil, D_1 and D_2 are the diameters of the equivalent circles the circumferences of which are equal respectively to the outside and inside girths of the coil.) Having determined the size of the wire, the nearest standard size is selected and the insulation chosen.

(2) The number of turns obtainable is then calculated, taking into account the space factor. The resistance of the coil is determined from the length of the mean turn and the number of turns; the ampère-turns are calculated from the formula

$$\text{ampère-turns} = \frac{VT}{R},$$

where R is the resistance of the coil in ohms.

It is now necessary to check that the temperature rise of the coil is within the limits laid down for the particular type of insulation selected. The temperature distribution in the coil is far from uniform and depends on the depth of coil, type of impregnation, etc. Heat, in most cases, is dissipated by radiation, but conduction will also play a part if the coil is in good contact with an iron core. The watts per square inch of coil surface that can be dissipated from the normal shapes of coil in air vary from about 0·35 to 0·8 and, until specific design data for the type are available, a figure of about 0·5 is often chosen.

Coil temperature

The temperature rise of a coil will depend upon the power expended in the coil and the temperature will continue to rise until the watts generated are balanced by the watts dissipated. The temperature distribution through the coil will depend upon the type of winding, insulation and impregnation. The surface temperature is usually measured by means of a mercury thermometer or, if a variable magnetic flux is present, an alcohol thermometer. The thermometer must be in intimate contact with the coil surface and B.S. 587: 1940 recommends that the thermometer bulb should be covered with tin foil and the remainder covered with some form of thermal insulation to prevent the introduction of a fresh radiating area.

The surface temperature will, of course, be well below that of the hot spot temperature and a better idea of the average temperature can be obtained by measuring the resistance of the coil cold and when it has reached its final steady temperature. The temperature rise is then given by the following formula:—

$$t = \frac{1}{\alpha_0}\left(\frac{R_t}{R_0} - 1\right)$$

where R_0 = resistance cold (ohms)
R_t = resistance hot (ohms)
α_0 = temperature coefficient at the lower temperature (per °C.)
t = temperature rise (°C.).

Shunts

Theory

Moving-coil instruments are usually designed to operate with a maximum current of a few milliampères; for larger currents it is necessary to divert from the instrument a definite proportion of the current. This is achieved by means of a suitable standard resistance, across which the instrument is connected. The normal voltage drop across a shunt when carrying its full rated current is 0·075 volts and B.S. 89: 1937, specifies that if a voltage drop other than this is obtained, it must be marked on the shunt. The required resistance for a d.c. shunt is determined very simply from the following considerations:—

Voltage drop in instrument = Voltage drop in shunt

$$iR = I_s r$$

$$\therefore\ r = \frac{i}{I_s}R$$

$$= \frac{i}{(I_t - i)}R$$

$$= \frac{1}{\frac{I_t}{i} - 1}R$$

where I_t = total current (ampères)
I_s = current through shunt (ampères)
i = current through instrument (ampères)
R = instrument resistance (ohms)
r = shunt resistance (ohms)

The expression $\frac{I_t}{i}$ is generally called the multiplying power of the shunt.

Materials

The most suitable materials for the construction of instrument shunts are the Manganin type of copper–manganese–nickel alloys, a typical composition of which would be 85 per cent. Cu, 12 per cent. Mn, 3 per cent. Ni ("Minalpha"). Alloys of this type are characterized by a low (or even negative) temperature coefficient and a resistivity of about 43 microhm-cm. (The curve of resistance with temperature is parabolic in shape, reaching a maximum value between 25° C. and 30° C.; hence the average temperature coefficient (say from 0° C. to 100° C.) would be negative, while over a lower range of temperature it could be positive.) The thermal e.m.f. against copper is also very low (about 1 microvolt per degree Centigrade or even less). These properties, together with high stability over long periods, make alloys of the Manganin type eminently suitable for use in the construction of standard resistors or shunts. Reference should be made to C.D.A. publication No. 38, "Copper Alloy Resistance Materials," for fuller details of this group of alloys.

Construction

Shunts are usually constructed of alloys of the Manganin type in the form of strip, rod or tube, but the strip type predominates. The strips are usually mounted in copper blocks designed to fit into the appropriate circuits. The end lugs of large shunts require a considerable amount of machining and, in this connection, tellurium copper is very suitable. Tellurium copper consists of copper with the addition of approximately 0·5 per cent. tellurium and has a conductivity of about 96 per cent. I.A.C.S. together with the free-machining properties of *alpha* brass. Since it is essential that the machining be carried out accurately if a permanently low-resistance joint is to be obtained, this material permits of considerable economies, as compared with normal high conductivity copper. Where a large number of shunts of the same type has to be made, it is usual for the end lug to be cut from lengths of suitably shaped extruded sections.

Various difficulties encountered in the construction of Manganin shunts and how they may be overcome are mentioned on page 15 of C.D.A. publication No. 38.

At least one manufacturer casts the copper lugs around the strips to ensure a permanent low-resistance connection between the resistance material and the copper.

With large currents considerable heating takes place; this determines to a great extent the physical dimensions of the shunt, since the surface area must dissipate sufficient heat to limit the temperature-rise to the specified amount, although a certain proportion of the heat will be conducted away and dissipated by other parts of the circuit. As shunts are normally constructed from strip, they should be designed so that the strips are mounted to ensure the maximum possible ventilation. The lugs must also be so dimensioned as to enable them to be connected to the conductor system in such a manner as to give a permanently low-resistance joint. Drilling centres and sizes of bolts are given in B.S. 89: 1937. This specification recommends that the current per bolt for each contact surface should not exceed 500 amps. for shunts up to and including 4,000 amps., and 625 amps. for shunts over 4,000 amps. and up to 5,000 amps. It further recommends that either one or two faces of the shunt lug can be regarded as contact surfaces for currents up to 1,000 amps., but for currents above this value both faces should be used. For further information regarding the jointing of copper bars, reference should be made to Chapter V of C.D.A. publication No. 22, "Copper for Busbars."

As with all accurate low resistances, the potential terminals on a shunt are separate from the current connections. The potential terminals should be symmetrically disposed on the centre line of the shunt and the relationship between current and potential terminals should be such that the current is uniformly distributed across the section. B.S. 89: 1937 states that the main terminals of the shunt shall be so constructed that slight variations in the method of connecting to the circuit shall not alter the indication of the instrument for a given current by more than 0·25 per cent. It is also stated that the construction and arrangement of the leads shall be such that at its rated current any thermoelectric effects do not alter the indication by more than 0·25 per cent. The size of connecting leads to the instrument is largely determined by the fact that their resistance should not exceed 0·025 ohm.

Multiplier resistors

Theory

In most moving-coil voltmeters only a fraction of the voltage to be measured is impressed on the moving coil itself; the remainder is dropped across a suitable resistance. A suitable selection of resistance values enables a multi-range instrument to be produced. The resistance material for this purpose must have a low temperature coefficient of resistance and a reasonably high resistivity, but within fairly wide limits the thermal e.m.f. of the material against copper is not particularly important.

Materials

A range of copper-nickel alloys, manufactured under such names as Constantan, Ferry, Advance, Eureka, Copel, is very suitable for the construction of resistance multipliers. Such alloys are fully described in C.D.A. publication No. 38, "Copper Alloy Resistance Materials," to which reference should be made for details.

Resistance tolerance

B.S. 115: 1938 requires that wires of 0·012 in. diameter and up shall not vary in resistance by more than ± 5 per cent. from the declared value. Larger tolerances are permitted for smaller sizes up to a maximum of ± 15 per cent. for wires from 0·001 up to but excluding 0·002 in. diameter. With strip the tolerance is ± 5 per cent. In addition to these restrictions there is a rather closer tolerance on the resistance variations in any one batch of material. For wires it is ± 5 per cent. on sizes from 0·001 in. diameter up to but excluding 0·002 in. diameter, decreasing to ± 2 per cent. for sizes of 0·012 in. diameter and upwards. For sheet and strip the value is ± 5 per cent. from the value declared by the supplier. In all industrial processes the manufacture of the final product is facilitated by uniformity of the raw materials and the construction of resistance units is no exception. Closer limits than those required by this British Standard are therefore often called for and can be met, though not always without some increase in cost. For example, greater uniformity is particularly required in high-value fine-wire coil-wound resistances, which have to be constructed on a mass-production basis to close total resistance limits. B.S. 1117: 1943, Fine Resistance Wire for Telecommunications and Similar Purposes, gives closer tolerances than B.S. 115.

Permanent magnets

Application

Permanent magnets have a wide and increasing use in instruments and ancillary equipment; almost all forms of electrical indicating instruments require the production of a magnetic field, for which a permanent magnet is most suited. In addition, permanent magnets are used for special types of motors and generators in automatic control equipment, to transmit motion without physical contact, to give a snap action to bimetallic switches, for suspension bearings (see Fig. 33, p. 99) and similar applications.

Theory

Permanent magnets are used either with a fixed or variable air gap, but in most of the applications considered here the former class predominates. Design formulae are available for calculating most simple cases, but the main difficulty is in estimating the leakage flux, which is always present.[38] Nomograms or graphs have been evolved for certain cases, which greatly facilitate the work of calculation.[39] When choosing a "hard" magnetic material (i.e. one with a high value of remanence) for a specific purpose, its demagnetization curve will give most of the required information, since the general principle is to provide a given field in an air gap of specified volume in the most economical manner. The demagnetization portion of the curve is used, since an air gap in a magnetic circuit is always tending to demagnetize the magnet. The total energy of a permanent magnet is proportional to BHV where B is the flux density, H is the field strength and V is the volume of the magnet. Thus for economical as well as space-saving reasons (an important consideration in many instrument applications), the product BH should be a maximum, as far as is consistent with other requirements. The point on the demagnetization curve at which the magnet operates is known as the working point and this point should be kept as close as practicable to the BH maximum for the material. In practice all parts of the magnet cannot work at the same point owing to flux leakages, and the magnet must be considered as working over a small range of the demagnetization curve. Watson[40] has shown how the BH maximum value may be simply obtained from the demagnetization curve.

The dimensions of a magnet for a given purpose are determined from the consideration that the cross-section must be large enough to supply the flux to the air gap, and the length sufficient to supply the required magnetomotive force (*M.M.F.*). These two quantities are related to the reluctance of the circuit by the expression

$$\text{Flux} = \frac{\text{M.M.F.}}{\text{Reluctance}}$$

Permanent magnets are so designed that the cross-section varies inversely as the residual induction or remanence and the length inversely as the coercive force.

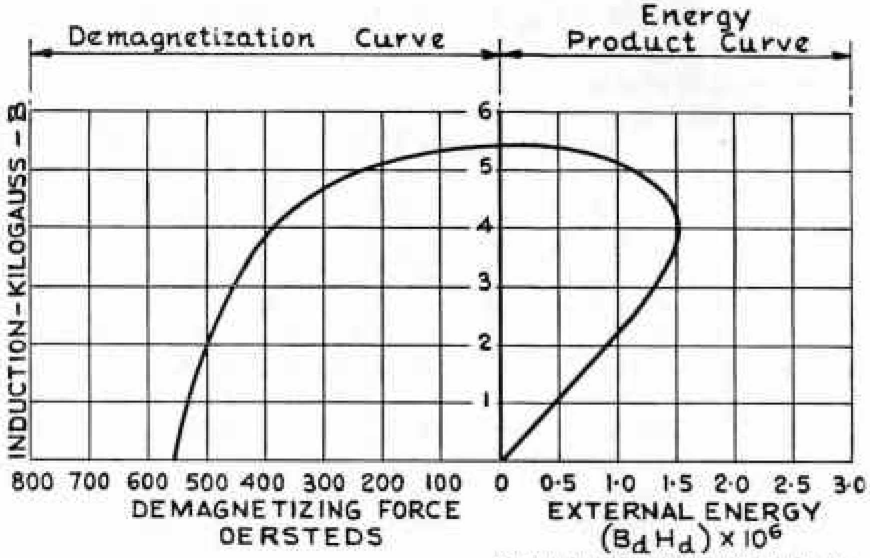
Modern "hard" magnetic materials are usually magnetized by enclosing them in the field of a single turn of copper bar or rod, through which very heavy currents are passed. The strength of a magnet falls off somewhat after it has been magnetized, fairly rapidly at first and then more slowly, the amount depending upon the thermal and mechanical treatment that the magnet receives or the presence of stray demagnetizing fields; but for most instrument applications, stability of the magnet system is essential and this can be achieved by artificially demagnetizing the magnet by about 5 to 10 per cent. by means of an alternating magnetic field, the process being known as "ageing."

Copper, which is only very slightly diamagnetic, would not appear to be a very promising ingredient for a permanent magnet alloy, but it is, in fact, used in most permanent magnet materials and is a major constituent in some of them. The Alnico, Alcomax and Ticonal range of alloys usually contain between 3 and 6 per cent. of copper. In this case the copper is used to make less critical the rate of cooling of the alloy necessary to obtain the desired degree of hardness. Almost all of these materials are, however, hard and brittle, cannot easily be machined and have to be produced by casting or sintering. The properties of the alloys, although well suited for many applications, leave much to be desired in specialized fields. There exists a wide potential use for a magnetic material that can easily be machined, drilled and tapped, or formed into complicated shapes by rolling, spinning, drawing or swaging. It is in this field that copper-base permanent magnet alloys are most useful.

For many years the Heusler alloys, some of which contain 60 to 70 per cent. of copper, have been well known for their magnetic properties, but they have never found a wide field of use, as their coercive force is too small and they are in general of purely scientific interest. There have, however, been developed in Germany and America two types of copper-base alloys with magnetic properties which make them very suitable for certain instrument applications. They are known as Cunife and Cunico.

Cunife has a nominal composition of 60 per cent. copper, 20 per cent. nickel and 20 per cent. iron and can readily be drawn, punched, spun, swaged, and machined, even in the precipitation-hardened condition in which it is ordinarily used. It is generally made in the form of wire, but can easily be rolled into strip and similar shapes. To obtain the maximum magnetic properties, a high degree of cold working is necessary and, for this reason, magnets of small cross-section are normally made only from wire, which is generally of ¼ in. diameter or under. Cunife has strong directional properties and should be magnetized in the direction of cold working. Typical properties are given in Table VI, and Fig. 31 shows the demagnetization and energy-product curves. Cunife requires a magnetization force of approximately 4,000 ampère-turns per inch.

Cunico has a nominal composition of 50 per cent. copper, 21 per cent. nickel and 29 per cent. Cobalt and, like Cunife, is easily machined, screwed and worked by normal processes. Cunico is heat-treated by keeping it for a considerable period at 1110° C. and then quenching and tempering to a final hardness of approximately 200 Diamond Pyramid Number. It can be produced in the form of strip, wire or rod, or it can be cast. It has no directional properties like Cunife and can be magnetized in any direction. Generally the maximum cross-section when in rod form is about 1 in. diameter and it is not generally used below ¼ in. diameter. Typical properties are given in Table VI and demagnetization and energy-product curves in Fig. 32. Cunico is best suited to conditions where magnets having a reasonably large cross-sectional area to carry the necessary flux are required, as its high coercive force means that normally shorter lengths are required than with most other magnet materials. Cunico requires approximately 6500 ampère-turns per inch for complete magnetization.



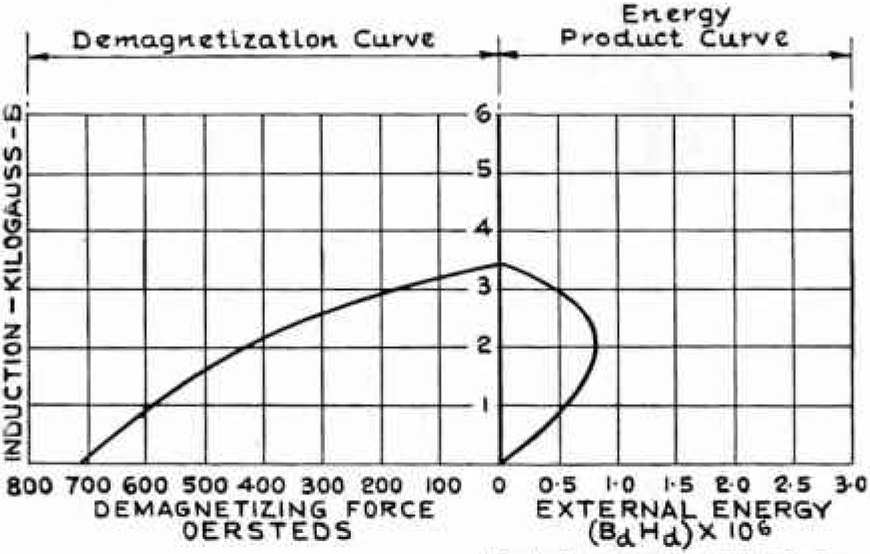
[Courtesy International General Electric Co., Inc.

FIG. 31.—Demagnetization and energy-product curves for Cunife.

TABLE VI
Properties of Some Copper Alloy Permanent Magnet Materials

Name	Composition (Per cent.)	Remanence B_r. (Gauss)	Coercivity, H_c (Oersted)	Energy Prod. $B_r \times H_c$ max. (Gauss–Oe. $\times 10^{-6}$)	Density (gms./cm.^{3})	Resistivity (Microhm-cm.)	Tensile Strength Lb/sq. in.	Diamond Pyramid Hardness Number
Cunife I	60 Cu, 20 Ni, 20 Fe	5400–6000	590–350	1·0–1·85	8·1	18	100,000	200
Cunife II	60 Cu, 20 Ni, 17·5 Fe, 2·5 Co	7300	260	0·78	8·6	18	100,000	200
Cunico I	50 Cu, 21 Ni, 29 Co	3400	660–710	0·8–0·85	7·8	—	100,000	200
Cunico II	35 Cu, 24 Ni, 41 Co	5300	450	0·99	7·8	—	100,000	200

It has been used for magnets in many aircraft instruments, and for transmitting motion showing liquid levels, etc., to the outside of sealed tanks. It has also been used for gear trains which are not in physical contact. An interesting example of the use of Cunico is as the top suspension bearing of a watt-hour meter rotor. A concentric form of construction is used as shown in Fig. 33 and is arranged so that the weight of the rotor system, giving a downward displacement, results in an upward magnetic restoring force. Provided that concentricity is maintained, no radial forces operate. Cunico magnets for this application are readily machined from Cunico rod and thus provide a simple and economic bearing system having a very low frictional resistance coupled with a long life.



[Courtesy International General Electric Co., Inc.

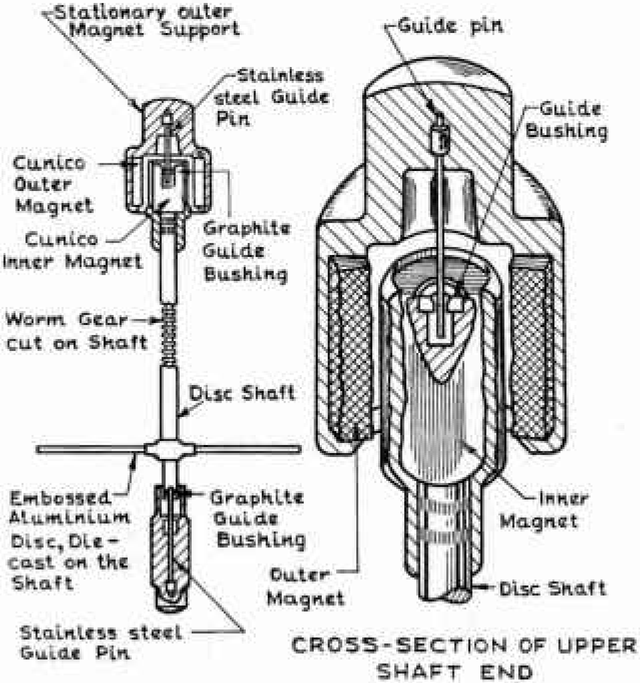
FIG. 32.—Demagnetization and external energy curves for Cunico.

Thermo-magnetic elements

Theory

Magnetism is a temperature-sensitive property and the temperature at which a metal loses its magnetism is known as the Curie point, but the rate at which magnetism changes with temperature in most magnetic alloys is small.

For sensitive instruments which depend on a constant magnetic field, this change of magnetism with temperature would give rise to unacceptable errors and one method of compensating them is to use a "magnetic shunt" of a soft material the permeability of which varies with temperature and which is so connected in the magnetic circuit that the overall effect is to give a constant magnetic field in the chosen air gap.



[*Courtesy "Product Engineering"*

FIG. 33.—Magnetic shaft bearing.

Materials

One material which is widely used for this purpose is a nickel–copper alloy with a nominal composition of 70 per cent. nickel, 30 per cent. copper. Fig. 34 shows the properties of this material as made by one manufacturer.* In (*c*) it will be observed that for a given value of magnetizing force, H, the permeability decreases with increase of temperature; hence as the temperature rises a decreasing amount of the magnetic flux is "by-passed" (or "shunted") from the main magnetic circuit by the magnetic shunt. But the main gap-flux would, if left to itself, decrease with increase

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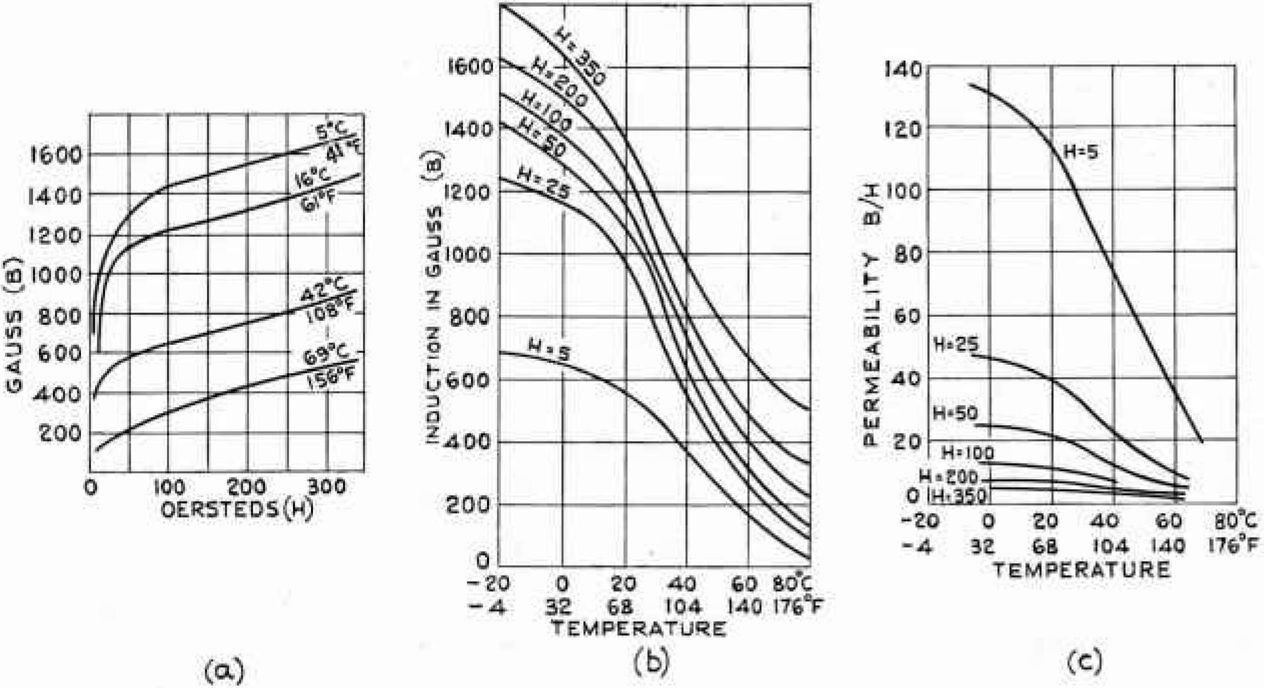
* J.A.E. metal (Henry Wiggin & Co. Ltd.)



[*Courtesy Messrs. Henry Wiggin & Co., Ltd.*

FIG. 34.—Magnetic/temperature relations for J.A.E. metal.

(*a*) B-H curves at various temperatures.
(*b*) Relation between magnetic induction and temperature at various field strengths (H in Oersteds).
(*c*) Relation between magnetic permeability and temperature at various field strengths.

of temperature; hence the shunt may be arranged in such a way that constant gap-flux at all working temperatures results.

This method of compensation can be made to allow, not only for the falling off of the main magnetic field, but also to compensate for the increase of resistance of the copper windings with temperature, which increase, in voltmeter-type instruments, would otherwise result in a decreased current and hence decreased deflecting torque, with increase in temperature.

Thermo-magnetic alloys have other uses in instruments, since they may be designed to act as temperature-sensitive contactors functioning as thermostats, while in some cases the laminations of small transformers have been made of such materials, so that the output voltage varies with temperature.

Copper/cuprous-oxide rectifiers

Theory

A rectifier is a device which possesses the property of asymmetric conduction and therefore the current flowing in it depends on the polarity of the applied voltage. Thus such a device enables a unidirectional current to be obtained from a.c. It also enables an apparatus to operate only when the applied voltage is of a predetermined polarity. Rectifiers have many applications, but for instrument purposes they are chiefly used to enable moving-coil instruments, with all their attendant advantages, to be used in alternating current circuits.

The fact that a thin film of cuprous oxide on copper has the property of asymmetric conduction was first announced by Grondahl[41] in 1926, although certain anomalies in the conductivity of copper, traceable to the oxide layer at the contacts, had, in fact, been observed many years before this; Grondahl's discovery was quickly brought from the laboratory to the commercial stage, copper oxide rectifiers having now been produced in large quantities for many years.

Almost any grade of copper can be treated so as to show asymmetric conduction at the interface, but there is a marked difference in the properties of copper/cuprous-oxide rectifiers made from different types of copper and even from the same copper when fabricated in different ways. A large amount of research, both theoretical and practical, has been carried out on the subject of asymmetric conduction and the "barrier-layer" theory appears to account for many of the observed phenomena.[42] Despite these researches, however, little knowledge of a fundamental nature can be directly applied to "metal rectifiers," but considerable empirical knowledge has been accumulated by the various rectifier manufacturers.

Cuprous oxide belongs to that class of material known as a "semi-conductor." Materials of this class differ from other classes of conductor in that minute changes in their chemical composition have a very large effect on their conductivity. In the case of cuprous oxide the necessary "impurity" to ensure semi-conduction is no more than the flaws (deficits in this case) in the crystal structure caused by diffusion of copper ions to the oxide surface. Cuprous oxide is therefore known as a "deficit" semi-conductor. In a copper/cuprous-oxide rectifier the oxide at the barrier-layer is thought to be in the pure state, the conductivity of which is only about 10^{-8} ohm^{-1} cm.$^{-1}$. Proceeding through the oxide layer, the degree of copper ion deficit increases, with consequence increase in conductivity up to about 10^{-2} ohm^{-1} cm.$^{-1}$.

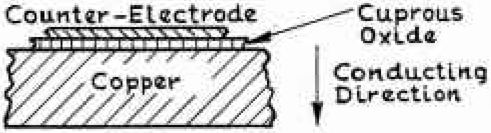


FIG. 35.—Schematic cross-section of copper oxide rectifier.

As regards the effects of impurities in the copper itself, it has been found by experiment that a grade containing at least 99·95 per cent. pure copper (with about 0·03 per cent. oxygen) is the most suitable raw material for the production of copper/cuprous-oxide rectifiers. Other impurities should be avoided, as far as possible, though some are more "poisonous" than others. The presence of silver was thought to be harmful; thus a relatively silver-free copper, such as that coming from Chile under the brand "CCC" has been widely used for rectifier manufacture. More recently it has been contended that the presence of sulphur and halogens, for example, is particularly detrimental, while even traces of phosphorus may prevent satisfactory adherence of the oxide film (see also p. 104). On the other hand, it has been claimed that the presence of some elements, such as thallium, may in some cases be beneficial.

A schematic cross-section of a rectifier unit[43] is shown in Fig. 35 and a typical rectifier characteristic is shown in Fig. 36. It should be noted that for the sake of clarity the forward scales are different from those in the reverse direction; this is almost universal practice. The direction in which the current flows more freely through a rectifier is known as the forward direction. The effects of the applied voltage are, however, complicated by a time effect known as creep. When the voltage is applied in the reverse direction the current may increase with time; this is often known as positive creep. In other cases it decreases, when it is known as negative creep. Positive creep is usually found in cuprous oxide rectifiers; the effect is very slight, but creep is very susceptible to minute changes in composition. The gas content of the copper has a considerable effect on the creep value and for this reason every effort is made to drive out any gaseous impurities during the processing of the copper for rectifiers. The physical properties of the material do

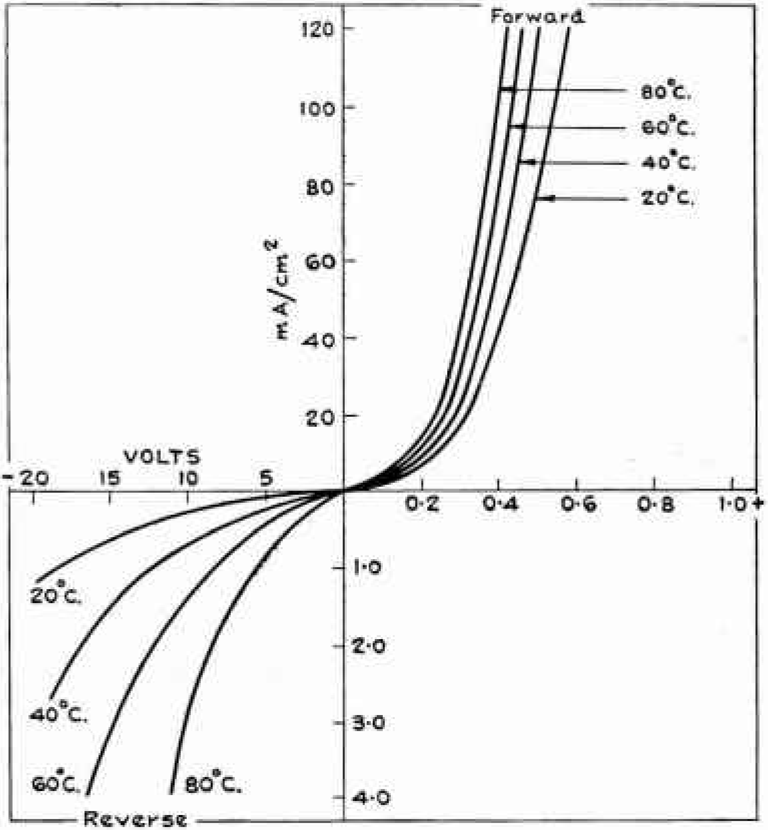


Fig. 36.—Typical current/voltage characteristic of copper oxide rectifier.

not appear to have any great effect on asymmetric conduction, and variations in hardness, tensile strength and grain size are not critical. It has been suggested, in view of the electronic nature of the rectifier action, that orientation of the copper crystals might have some effect on asymmetric conduction, but experiments have not borne out this suggestion. Rectifiers made from single crystals have the same general characteristics as rectifiers made from the same copper with a random crystal structure.

Owing to the difference in linear expansion between cuprous oxide and copper, the cuprous oxide is in a stressed condition when the unit is at room temperature. Tests have shown that the resistance in the reverse direction is reduced when the cuprous oxide is in a stressed state and the stresses may be high enough to cause fracture of the crystal boundaries. It is, therefore, necessary to reduce these stresses. (See below under *Manufacture.*)

Copper/cuprous-oxide rectifiers have a capacitance of about 0·02 μF per sq. cm., which is consistent with an insulating film between the copper and the semi-conducting cuprous oxide having an equivalent thickness of 450Å.

Manufacture

Most manufacturers have their own individual methods for the manufacture of rectifiers, but the general principles are somewhat similar and are briefly given below. Reference should be made to the work of Williams and Thompson[43] for further details. Copper discs are blanked from suitably chosen copper strip, usually about 1 mm. thick and, after degreasing, are assembled in pairs in such a manner that only one surface is oxidised. After heating in air at about 1020° C. for ten minutes, they are allowed to cool to 600° C., which temperature is held approximately constant for a further ten minutes. They are then removed and cooled either naturally or by quenching, depending on the characteristics required. The highest temperature which the discs are allowed to attain is fairly critical, as it has a direct bearing on the creep and resistance of the rectifier. Temperatures below 900° C. for the initial oxidation should not be used, as this produces a very high forward resistance. To remove the superficial film of cupric oxide which will be formed over the cuprous oxide, the discs are dipped for two to three minutes in a mixture of sulphuric and hydrochloric acid at about 70° C. and then given a final ten seconds' dip in concentrated nitric acid. Previous to this acid dip, the cuprous oxide is in a stressed condition and the preferential etching action of the acid relieves the highly stressed portions and increases the reverse resistance of the rectifier without detriment to the forward resistance.

After the acid treatment, the discs are washed and dried and a graphite compound is sprayed on the oxide surface. To make intimate contact with the cuprous oxide, the disc is pressed against a soft material such as lead, or another metal may be deposited on the surface.

As stated previously, however, most manufacturers have their own specialized techniques, some, for example, heating the copper in specially controlled atmospheres or forming thin films of other metals on the surface of the discs.

Glass-to-metal seals

Reasons for use

It is frequently necessary to make a hermetic seal between metal and glass, the two main reasons being

(*a*) to permit the observation of phenomena under controlled conditions;
(*b*) to enable an electric current to be led into or out of a vacuum or hermetically sealed chamber such as an electric lamp or electronic valve.

Types

There are two main types of seal, namely the matched and unmatched. The matched type employs a metal the coefficient of expansion of which follows closely that of the glass from its upper annealing temperature to room temperature. Most glasses have a curved thermal expansion/temperature characteristic, whereas most pure metals have a straight-line characteristic. Certain alloys are available, however, with the appropriate curved characteristic, although none of the copper-base alloys is suitable for the glasses commonly employed. The unmatched type of seal uses a metal the thermal expansion/temperature characteristic of which is different from that of the glass, but the ductility of which allows the stresses set up by the unequal expansion and contraction to deform the metal, leaving only a small safe residual stress in the glass. It is for this type of seal that copper is widely employed and is suitable for use with all the usual glasses.

Materials

A metal to form a suitable seal with glass should, in addition to the considerations discussed above, have the following characteristics:—

(1) The surface of the metal should be easily and thoroughly wetted by the glass.

(2) The adhesion between the metal and the glass, and between any oxide formed and the glass, should be good.

(3) In the case of the unmatched seal, the metal should be ductile, so that it can deform and relieve internal stress, be easily worked into the required shapes and its surface should be free from slivers, spills, laps or other defects which might cause subsequent leakage.

(4) The melting point of the metal should be above the sealing temperature of the glass.

(5) For many applications high thermal and electrical conductivity is desirable and the metal should easily be joined to copper.

It is generally considered that oxygen is essential if wetting of the metal is to occur and oxidation of the surface is generally necessary to form an adhering bond, but it is also necessary that the oxide be soluble in the glass if an air-tight seal is to be formed.

Copper and cuprous oxide admirably fulfil these requirements, either in the form of sheet or wire, or as cladding on other metals and are widely used, particularly by the electrical industry. The cuprous oxide which is formed on the surface of the copper gives this type of seal its characteristically red appearance. The thermal expansion of cuprous oxide, copper and some glasses is shown in Fig. 37.

Although an oxide film is necessary to form a good bond, in the case of thin copper sections care must be taken that the oxidation does not proceed too far or the material may become porous. To prevent this, it is usual to "borate" the copper so as to limit oxidation. This is achieved by heating the copper in air with a neutral flame until a film of cuprous oxide is formed and then immersing it in a solution of borax. The borax-coated copper is then reheated until the borax forms a continuous film over the copper.

High conductivity copper is normally used for sealing purposes, and a preference exists for an oxygen-free high conductivity copper with a phosphorus content not exceeding 0·003 per cent. For high vacuum work a specially pure grade of copper is generally required and a "certified" grade of OFHC is widely adopted for such seals. Phosphorus has the property of preventing the oxide adhering to the copper and although this is desirable for some applications, it must be rigorously avoided in copper-to-glass seals. A rough test to check that the oxide adheres is to prepare a chemically clean surface on the copper, heat the material to approximately 850° C. for half an hour in air and then plunge it into water. A suitable copper will have the oxide film still adhering to

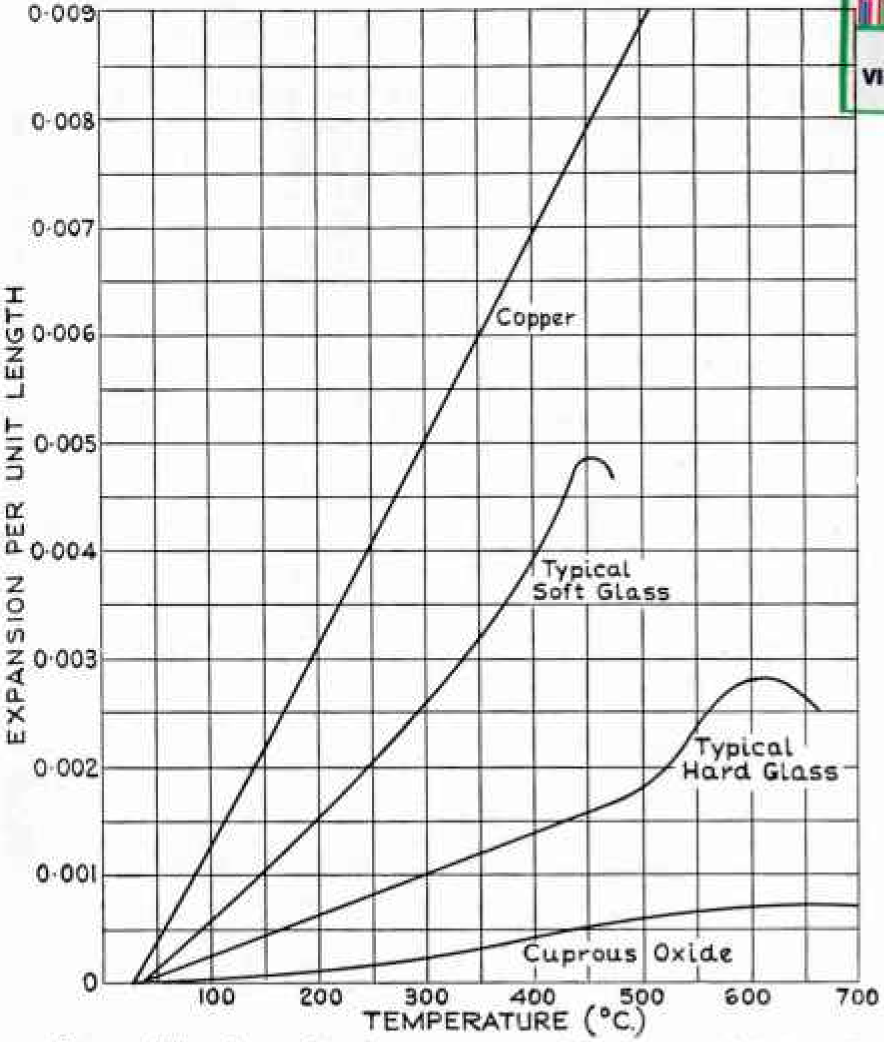


Fig. 37.—Thermal expansion of copper, cuprous oxide and some typical glasses.[44]

it after this treatment. When used in vacuum devices the copper should be free from any impurities which are volatile at the sealing temperature.

There are two main types of unmatched seal in which copper is used:—

(*a*) Copper-clad sealing wires.

(*b*) Copper-edge or tubular seals. This type is often known as the "Housekeeper" seal after the name of its inventor.[45]

Platinum wire was the original metal used for sealing into incandescent lamps, but a cheaper and equally effective alternative wire (often known as "Copperclad"), now in almost universal use, is made from a copper-sheathed nickel-iron alloy. The central core of nickel-iron (about 43 per cent. nickel) is covered with a copper sheath which varies between 20 per cent. and 30 per cent. of the total cross-sectional area. Table VII gives typical data on this material. It is not advisable to use wires larger than about 0·03 in. diameter or there is a risk of the glass cracking, as the unbalanced stress cannot be taken up by deformation. In this type of clad wire, longitudinal expansion is controlled by the nickel-iron and radial compression is taken by the copper.

TABLE VII

Properties of Copper-Sheathed Nickel-Iron Wire*

Resistivity	7·5 to 10·5 × 10^{-6} ohm-cm.
Coeff. of linear expansion (longitudinal)	7·8 × 10^{-6} (approx.) per °C.
Coeff. of linear expansion (radial)	9·0 × 10^{-6} (approx.) per °C.
Tensile strength (after borating)	32 tons per sq. in. (approx.)
Elongation (after borating)	20 to 30 per cent.

In 1923 Housekeeper[15] took out a patent covering the use of a ductile material for sealing on to glass, the physical arrangement being such that the metal deformed during thermal changes, leaving the glass relatively stress-free. As stated previously, copper is widely used for this purpose and Fig. 38 shows some typical arrangements. The edge of the copper is rolled or spun until it is about 0·001 in.–0·004 in. thick and the seal must be arranged so that the metal is free to move in at least one direction. The glass immediately adjacent to the seal will be in compression, but is stress-free a few thousandths of an inch away.

During heating, the compressive stress in the glass rapidly changes to a tensile stress which remains steady between about 100° C. and 200° C., due to the copper yielding, until the annealing temperature of the glass is reached, when the stress begins to decrease. During cooling the copper contracts more than the glass, which is placed in compression, but again the stress resulting is limited, due to the deformation of the copper.

Movements

The term "instrument movements" covers a very wide field, but here it is limited to such parts as end-plates, linkages, pinions, bearings, suspension and spring control systems.

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* Courtesy of Mullard Ltd.

Fig. 38—Some typical copper-to-glass seals, showing (a) "pinch type, utilizing copper-clad wire, as used in filament lamps; (b)—(f) Housekeeper "thin-edge" types, as used in (b) transmitting valve, showing component parts, (c) transmitting valve anode, (d) detector valve showing anode and grid discs (e) 5 kW bi-post studio lamp, (f) 5 kW lighthouse lamp.

[*Courtesy General Electric Co., Ltd.*

Construction and Materials

End-plates

Many instruments are designed so that the end-plates not only serve to locate the pinions and linkages, but also act as a bearing material for the pinion shafts. The requirements are that the material must be available in dead flat strip of consistent quality and with very fine tolerances. Punching, piercing and similar operations must be easily carried out and no burrs should be left on the parts. In addition, the material should be capable of acting as a bearing surface to avoid expensive inserts. For this purpose a brass generally known as clock brass, having a nominal composition of 60 per cent. copper, 38 per cent. zinc and about 2 per cent. lead, is widely used. For plates and pinion wheels the material is supplied in the hard condition, having a Diamond Pyramid hardness of about 150. For wheels which may require to take heavier loads a Diamond Pyramid hardness of up to 190 is sometimes specified. This material is obtainable with consistent and regular grain size, thus enabling repetitive processes to be easily carried out. The brass has a hard duplex structure in which small globules of lead are distributed; this gives an excellent bearing surface, as the lead particles bed down in the harder matrix and act as a form of lubricant. Although the initial cost of this type of brass may be greater than that of some other materials, its many advantages in production processes, and the fact that no bearing inserts are required, generally means that the final cost is less than when other materials are employed.

A typical example of fabricated clock brass is shown in Fig. 39, and Fig. 40 shows how, by careful design, economies in material can be effected so that very little scrap results. It is important that the plates be dead flat and as far as possible relieved of any internal stresses; otherwise slight distortion may occur which would cause the pinion shafts to bind in their bearings. Where this is likely to occur, a process known as "chequering" is often adopted. This consists of passing the plates between rollers which make slight indentations into the surface; it is claimed that surface stresses are thereby relieved.

Pinion wheels

Pinion wheels are often made of the same material as the end-plates mentioned above and are formed either by stamping out blanks, which are subsequently hobbed to shape or, for some purposes, the teeth may be stamped out in the original blanking process. This type of leaded brass is used because it can be supplied sufficiently hard to be wear-resisting and at

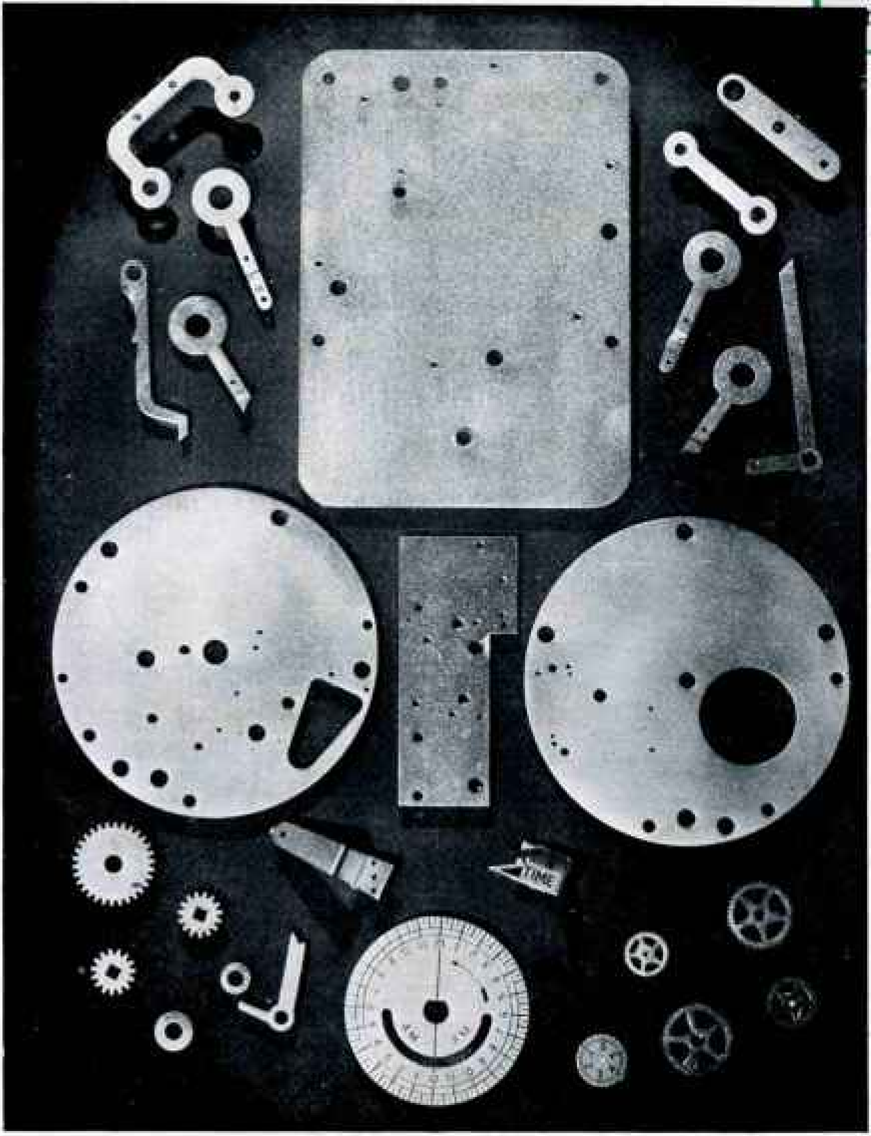


Fig. 39.—"Clock brass" components of a time-switch unit.

the same time the teeth can be accurately stamped in one process, or can be hobbed, without requiring much de-burring.

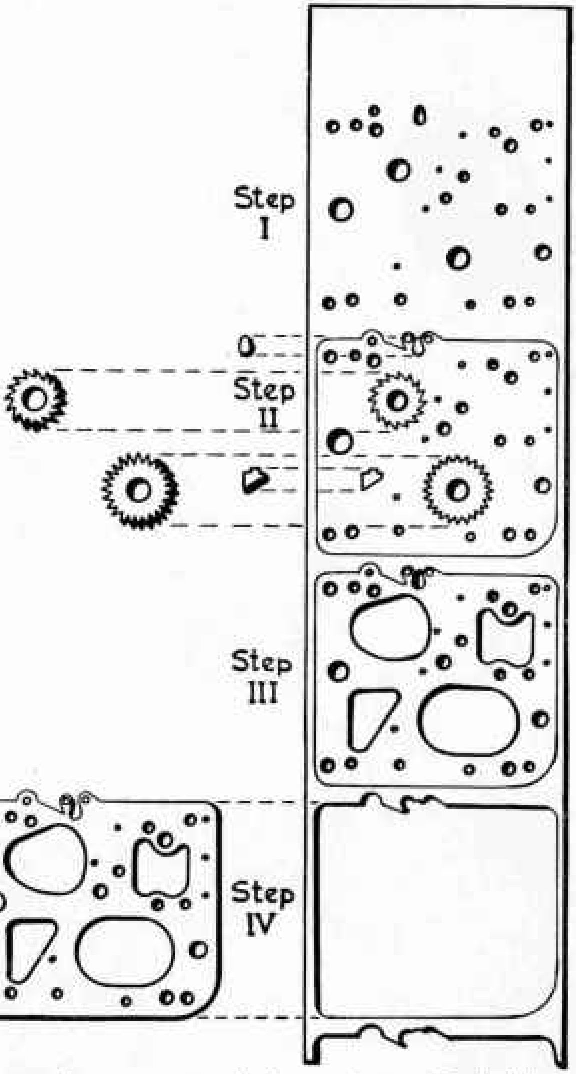


FIG. 40.—Programme steps in the manufacture of a clock frame.

For some purposes pinion wheels such as those shown in Fig. 39 are made from a special form of wire known as pinion wire. Pinion wire is extruded from a solid billet and is then drawn to size, parted into wheels of the required thickness. A typical composition for pinion wire is 64 per cent. copper, 35 per cent. zinc, 1 per cent. lead. For most instrument purposes, however, this method does not give sufficiently accurate contours to the teeth.

The appropriate British Standard for gears for clockwork mechanism, which includes gears used in clocks, watches, meters and instruments, is B.S. 978.

Sectors and linkages

Sectors and linkages are generally made from clock brass, but where appearance is of importance an 18 per cent. nickel silver is often used. Clock brass can, of course, be plated to give the same appearance, but in general this is more expensive.

Sintered bearings

In some forms of instrument construction, it is not possible to use the end-plates to act as the bearings and it is necessary to mount the shafts suitably. Sintered bronze made from metal powders is widely used for this purpose, as the sintered material can be impregnated with a lubricant so that the bearings require no attention during the normal life of the instrument.

Springs

Copper alloy springs are widely employed in all types of instruments and associated apparatus and the materials which are in general use are phosphor bronze, beryllium copper and nickel silver. These materials are described in Chapter I in connection with pressure-sensitive elements, which are themselves specialized forms of springs. The main characteristics of the various materials are detailed in Table I and in C.D.A. publication No. 39, "Copper and Copper Alloy Springs."

Copper alloy springs have the following important advantages over steel springs:—

(a) They are non-magnetic.
(b) They have much higher electrical and thermal conductivities.
(c) They have greater resistance to corrosion.
(d) They are less susceptible than steel to some conditions of combined corrosion and fatigue.
(e) They have, generally, a higher ratio of maximum safe stress to modulus, and are therefore more suitable than steel where a large deflection with a small operating force is required.

(f) They are more easily formed.

Springs in electro-magnetic instruments can be grouped under the following main headings:—

(a) Cantilever and beam springs made of strip material or wire and used to apply mechanical loads and to assist in the making and breaking of electrical circuits. For the latter purpose the strips or wires may be tipped with suitable contact materials.

(b) Spiral springs used for torque control, generally on indicating instruments.

(c) Suspension strip used for controlling the torque on moving-coil oscillographs, galvanometers, etc.

Protection

Although copper and its alloys have a high degree of resistance to corrosion, only hermetic sealing could provide protection against attack by acid fumes or ammonia. This also applies when the risk of electrolytic action is present, due to contact in a moist atmosphere with other metals; aluminium or magnesium alloys are particularly liable to galvanic corrosion in such conditions. If it is not possible to seal the entire instrument, the best solution is to coat the copper alloy with a thin covering of tin (about 0·0001 in. thick) and then cadmium-plate. This applies particularly when contact is likely to occur with aluminium; but where magnesium alloys are present, in some instances it is preferable to replace the cadmium by zinc. Nickel plating can also be used for this purpose. In certain conditions, particularly where plastic materials are also involved, cadmium tends to become coated with a fine white deposit. Although there appears to be no evidence that this corrosion is sufficiently severe to cause any appreciable loss of strength, in instances where the appearance is of importance it is preferable to omit the cadmium and rely on tin. Cadmium plating should on no account be applied to brass, nor should brass be allowed to make contact with cadmium plating on other metals.

CHAPTER III

TEMPERATURE-RESPONSIVE INSTRUMENTS

BASIC PRINCIPLES

TEMPERATURE measurements are necessary in almost every industrial process, since all chemical changes and most physical properties are materially affected by a change in temperature.

In general, it is necessary to transfer some of the heat energy to the temperature-measuring device in order that the temperature may be measured, and, in order to obtain a true indication, complete thermodynamic equilibrium must exist between the source of heat and the measuring device. The method chosen to measure temperature depends mainly on the range of temperature, the accuracy with which the measurement is required, speed of response and economic factors. The latter, apart from the first cost, also include ease of installation, maintenance, and estimated life of the measuring equipment. Many physical properties which change with temperature may be used as a measure of the latter and at some time or other almost every physical property has been used in temperature-measuring devices. In this chapter consideration is given only to the use of base-metal thermocouples and expansion and resistance thermometers.

Standards of temperature measurement

The Fahrenheit scale, which gives the freezing and boiling points of water (at a pressure of 760 mm. of mercury) as 32 and 212, was adopted between 1710 and 1742. The Réaumur scale, in which the freezing and boiling points of water are 0 and 80, was introduced in 1734. Celsius proposed the Centigrade scale, in which 100 was the freezing point and 0 the boiling point of water, but the numbers were reversed in 1742.

International agreement has since been reached on a temperature scale which is reviewed every six years, the present scale being known as "The International Temperature Scale of 1948." This scale gives numerical values to six fixed and reproducible temperatures. It specifies the measuring instruments and gives formulae for interpolating between the measurements so made. The fundamental points on the scale are the melting point of ice (0°) and the boiling point of water (100°), both under very strictly controlled conditions. It was also decided in 1948 that, in place of degrees Centigrade, the designation should be degrees Celsius and written ° C. or ° C. (Int. 1948).

The scale of temperature known as the Kelvin or Absolute scale is, however, still the fundamental thermodynamic scale to which all temperature measurements refer. On this scale the temperatures are referred to as degrees K, or degrees A, the lower limit being referred to as "absolute zero," corresponding to 273·15° C. below the melting-point of ice. This temperature scale is therefore obtained by the addition of 273·15° to the normal Celsius or Centigrade scale. Although there is a lower limit to the temperature that may be obtained, there appears to be no theoretical upper limit.

The units in which thermometers are normally calibrated are those of the Centigrade or Celsius, Fahrenheit and less familiar Réaumur scales.

CONSTRUCTION OF TEMPERATURE-RESPONSIVE INSTRUMENTS

Temperature-responsive instruments will now be discussed under three general headings: Thermo-electric elements, Expansion-type Elements and Thermometers, and Resistance Elements.

THERMO-ELECTRIC ELEMENTS

Thermo-electric principle

Seebeck[46] discovered in 1821 that when a junction of copper and bismuth (not copper and iron as is often stated) was heated, an e.m.f. was generated, the direction being such that when the circuit was completed the current flow was away from the copper through the warm junction. The copper is then said to have negative polarity with respect to the bismuth. This discovery led gradually to the development of suitable combinations of materials now known as "thermocouples," which today form the basis of one of the most widely used industrial methods of temperature measurement, since they are cheap, reliable, easy to instal, maintain and calibrate. By a suitable choice of materials it is possible to measure continuously temperatures ranging from about 1600° C. down to a few degrees above absolute zero.

Basically, a thermocouple consists of two dissimilar materials (usually metals) or two pieces of the same material in different physical states, welded or otherwise intimately joined together at one point. This junction is the temperature-sensitive element or measuring element. The junction of the other two ends is the reference junction and the e.m.f. generated is a function of the difference in temperature between these two junctions. The junctions are often known as the "hot" and "cold" junctions. The thermo-electric effect is not only used to measure and control temperatures but also for the sorting of metals, based on the e.m.f.'s which they generate when rubbed against each other, and for the measurement of electric power (thermal wattmeters) and of the pressure, velocity and composition of fluids. In general, these latter measurements depend on passing a current through the junction, the cooling effect of the gas or liquid flow producing the change in e.m.f.

It was early discovered that the e.m.f.'s of a thermocouple composed of two dissimilar materials were due to two factors which have taken their names from their discoverers. The first is the Peltier e.m.f., which is the e.m.f. that exists across the actual junction, and the second is the Thomson e.m.f., which is due to the temperature gradient along each of the wires taken separately. The Peltier effect is reversible, i.e. if a current is passed through a junction of dissimilar metals, flowing in one direction it will warm the junction and in the other will cool the junction—these effects being quite independent of the Joule loss at the junction. In fact, it was this phenomenon that Peltier in 1834 first observed. The total e.m.f. is often called "the Seebeck e.m.f.," being the algebraic resultant of the Thomson and Peltier e.m.f.'s. Platinum is the standard metal to which the e.m.f.'s of other materials are now usually referred and Fig. 41 gives the thermal e.m.f. of various metals against platinum.[47] Lead was often taken as a standard in the past as the Thomson effect in it is very small.

Materials

Elements

In order that the e.m.f. generated by a couple may be used as the basis of a suitable instrument for industrial temperature measurement or control, it should comply with the following requirements:—

(a) The e.m.f. should increase approximately linearly with the temperature over the range in which it will be used. This enables the calibration to be carried out at two points only, simplifies cold junction compensation and gives a uniform scale presentation.

(b) The thermal e.m.f. should be as large as possible to avoid unduly sensitive measuring instruments. This requires that the Thomson and Peltier e.m.f.'s should be additive.

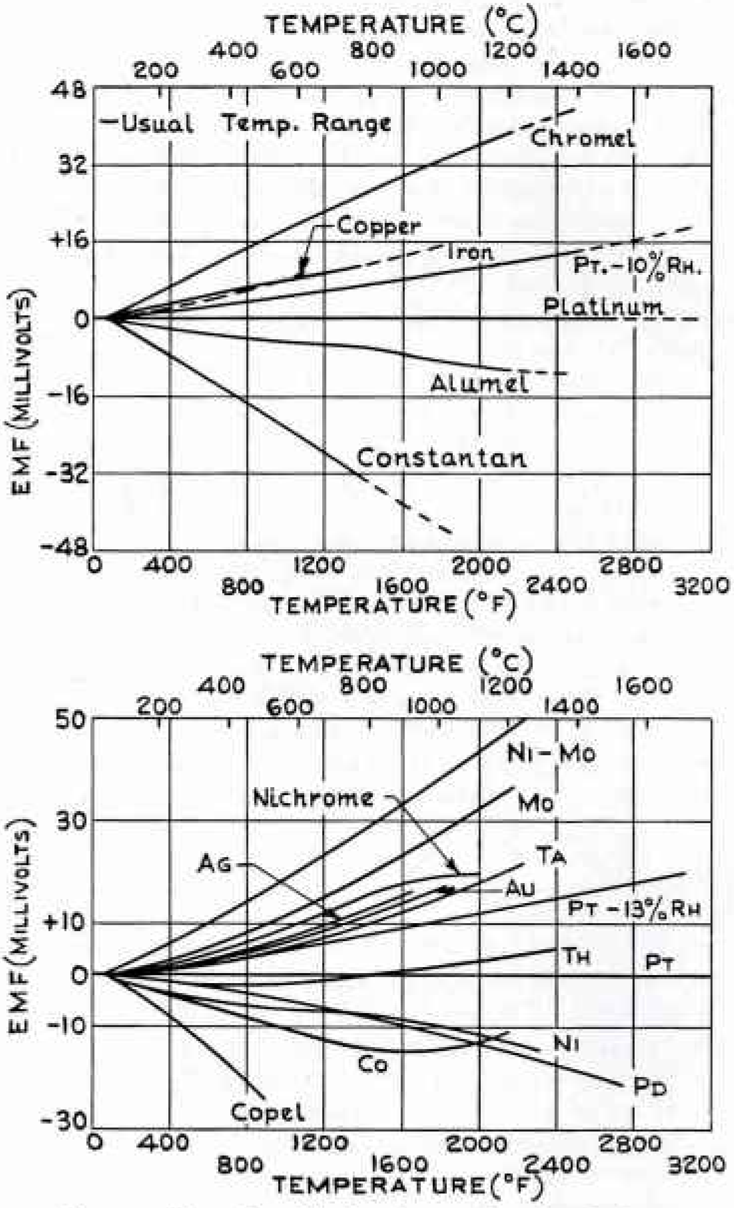


FIG. 41.—Thermal e.m.f.'s of various metals against platinum.

(c) The e.m.f. should be reproducible within narrow limits, not only when the couples are first installed and calibrated, but also in use. This is particularly valuable where large numbers of couples are used and where more than one couple is switched on to the same indicator.

(d) The materials must be easily made into wire or strip and have adequate mechanical strength. The materials should have good resistance to oxidation and corrosion over the temperature range and in atmospheres in which they will be used.

Experience has shown that there are relatively few combinations which are suitable for industrial purposes and Table VIII shows the types which have been virtually standardized and the preferred range over which they give their best performance (see p. 120).

Noble metal thermocouples are generally more accurate and have a wider range than base metal couples, but they are more expensive and generate a smaller e.m.f. Here we are mainly concerned with the copper–Constantan, iron–Constantan and Chromel-P–Constantan couples. In this connection it must be remembered that Constantan is a general name applying to a range of copper-nickel alloys, varying from 50 per cent. to 60 per cent. copper, the balance being nickel, although in some cases small percentages of manganese and iron are present. Variations of the copper-nickel content within the range specified have, however, an appreciable effect on the e.m.f. and this must be borne in mind when Constantan forms one of the thermocouple elements. Common trade names in this range of copper-nickel alloys are, Ferry, Eureka, Copel (Copnic), Advance, and Ideal, details of which will be found in C.D.A. publication No. 38.

High conductivity copper, in accordance with either B.S. 1036 or B.S. 1037, is a relatively pure form of copper and, provided the material is homogeneous and has been well annealed, the samples taken from various batches do not show any appreciable e.m.f.'s one against the other. Where high conductivity copper is used for thermocouple purposes, no special selection is therefore necessary. This, however, is not true of the other materials concerned, namely Chromel-P, iron, Constantan, etc., and it is necessary either to specify to the manufacturers the e.m.f.'s against copper required at various temperatures or to purchase to a regular specification and check each batch individually. The iron employed is usually in a very pure form containing about 99·85 per cent. iron. In all cases, it must be remembered that the physical condition of the wire, as well as the chemical composition, must be the same for each batch. Production of metals for thermocouples must be carried out with great care to avoid

TABLE VIII

Standard Thermocouple Materials

Material	Composition	Range (° C.) and Thermal e.m.f. (mV)			
		Possible		Preferred	
	%	° C.	mV	° C.	mV
Copper Constantan*	(99·9 Cu) 45 Ni, 55 Cu	— 200 to 400	— 5 to 21	— 200 to 350	— 5 to 18
Iron Constantan*	(99·85 Fe) 45 Ni, 55 Cu	— 200 to 1000	— 8 to 58	— 200 to 860	— 8 to 50
Chromel-P Constantan*	90 Ni, 10 Cr 45 Ni, 55 Cu	— 200 to 1000	— 8 to 76	0 to 660	0 to 50
Chromel Alumel	80 Ni, 20 Cr 98 Ni, 2 Al	0 to 1400	0 to 55	250 to 1230	10 to 50
Platinum Platinum-Rhodium	Pt 90 Pt, 10 Rh	0 to 1700	0 to 18	500 to 1400	4 to 14

* Or Copnic.

contamination since certain impurities, although not necessarily having an appreciable effect on the e.m.f., when the couple is new, may slowly "poison" the couple before it has finished its economic life.

Compensating leads

It was stated earlier that the e.m.f. generated by the thermocouple depended on the difference in temperature of the hot and cold junctions; it is, therefore, necessary to know the temperature of the cold junction before the e.m.f. can be translated into terms of temperature. In some installations it may be possible to connect the measuring instrument directly to the ends of the thermocouple wires themselves, but, in general, in industrial measurements this arrangement is inconvenient, partly because of the cost of running the thermocouple leads back to a suitable position. This particularly applies when rare metal thermocouples are used. It is, therefore, the general practice in such installations to use compensating leads, the result being to transfer the effective cold junction to the end of the compensating leads. The e.m.f.'s generated where the compensating leads join the actual thermocouple should be equal and opposite; and this will be so, provided both sides of the junction can be kept at the same temperature and that the compensating leads have been properly chosen.

In the case of copper–Constantan and iron–Constantan couples, the same materials are used for the leads as for the thermocouple, and are made up into what are usually known as extension leads: but in the case of platinum and platinum–rhodium thermocouples it is usual to employ a copper and copper–nickel combination to form a compensating lead, the copper being connected to the platinum–rhodium side and the copper–nickel to the platinum side; the effective cold junction is thus transferred to the end of the compensating leads, which are normally attached to the measuring instruments or indicator. In order to reduce the installation cost of Chromel–Alumel thermocouples, copper–Constantan compensating leads are often used, provided the temperature at the thermocouple terminals is below about 120° C. If the junction cannot be kept down to this temperature, then it is necessary to use extension leads of Chromel–Alumel.

The e.m.f.'s generated are very sensitive to changes in chemical composition and physical condition of the materials; therefore, it is essential that the properties of the materials must be very carefully stated and very accurate control must be used in manufacture if consistent and reliable results are to be obtained. Some of the factors affecting the thermal e.m.f.'s will now be considered in more detail, while the Bibliography may be consulted for further references to work on this subject.[48]

Effect of impurities

The thermal e.m.f. of a metal when compared with a standard such as platinum is influenced by impurities which may be present in solid solution in the metal. The effect of the type of impurity and its concentration has been studied by various investigators, for example, Crussard.[49] He found that the variation in e.m.f. depended upon the position of the alloying impurity in the Periodic Table. If the element present as an impurity was in a group in front of the parent metal the e.m.f. was increased, and if in a group after the parent metal the e.m.f. was decreased. This rule applied generally, although there were one or two exceptions. It was also confirmed that only impurities which were in solid solution had an important effect on the e.m.f. In fact, impurities which were precipitated as the result of heat treatment had virtually no effect on the e.m.f.

Effect of physical condition

Elastic strain

The thermal e.m.f. of a metal depends, among many other factors, upon the elastic deformation or strain to which it is subjected and it has been found that a linear relationship exists between the strain and the e.m.f. generated. The effect is of the order of 10^{-5} volts per °C. per unit strain. Like so many other effects which are concerned with measurements, this one was first noted and recorded by Kelvin. It applies both to tensile and to compressive strains.

Plastic strain

The effect of plastic deformation or strain is to increase further the thermal e.m.f. Brindley[50] has carried out carefully controlled experiments with copper to determine the magnitude of this effect, and Fig. 42 (taken from his work) shows the e.m.f. obtained between heavily cold-rolled copper and a fully annealed specimen. Crussard[49] has discussed the cause of this e.m.f., and considers that it is not due to the general internal stresses in the material but to localized stresses at the crystal boundaries. The e.m.f. is of the order of 10^{-8} to 10^{-7} volts per °C., depending upon the degree of cold work. The e.m.f. is such that the annealed or unstressed material is always positive with respect to the cold-worked or stressed material.

Magnetization of the wire forming the couples affects the e.m.f., but this applies only to ferromagnetic materials, such as iron, cobalt, etc.

Thermo-electric effects have been of considerable help in investigations into the effects of cold working, annealing, etc., in pure metals, but it will be seen from the facts noted above that for accurate temperature measurements it is essential that the materials should be annealed or given a stabilizing heat treatment up to the maximum temperature they are likely to reach in service. Even then there is a possibility that the material may be work hardened by stresses in the handling operations or even due to expansion and contraction caused by fluctuating temperatures.

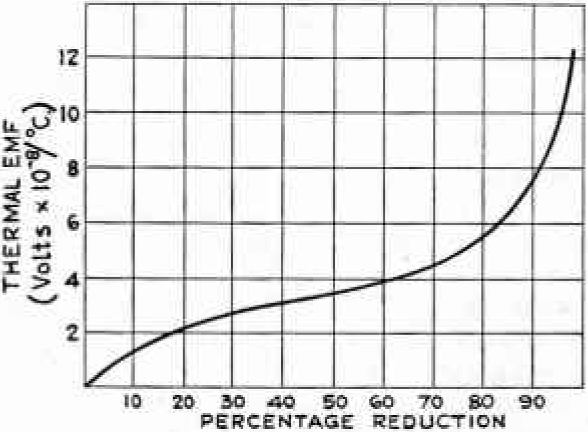


FIG. 42.—Thermal e.m.f. against percentage reduction for copper. (Hilger's H.S. purity grade.)

Construction

It is important both from a mechanical and electrical point of view that an intimate junction be made between the two materials which form the couple. The general technique is to solder or weld, but it is essential that a firm bond is made and that there is negligible contact resistance at the junction. In this connection the operating temperature must be borne in mind, since, if any solder is used in the junction, the tin and lead will diffuse into the materials and may change the generated e.m.f.; in most instances, therefore, welding is preferred. If soldering is used, then solder having the minimum "poisoning" effect on the junction has to be determined by trial at the maximum temperature and over the longest life period that is being considered. Experiments have shown that the actual form of the junction does not affect the efficiency of the thermocouple and in general the thermocouple consists of two circular wires of the appropriate materials twisted together two or three times and then welded or soldered. Another form which is sometimes used, particularly with the iron–Constantan thermocouple, is that known as the "pencil" type, in which the iron is in the form of a tube with the insulated Constantan passing down the centre and joined at the extremity.

The actual dimensions of the material used are a compromise. The thicker the material the longer the effective life, but at the same time the increased mass increases the time delay for the thermocouple to measure the temperature and also increases the rate at which heat is conducted away. The usual size of the wire for base metal thermocouples is between 10 s.w.g. and 16 s.w.g., but considerably finer wires are used in special cases.

Cold-junction compensation

It was stated earlier that the e.m.f. generated is due to the difference between the temperatures of the hot and cold junctions, but in order that an instrument may be calibrated to read in terms of temperature it is necessary that the temperature of the cold junction should be known. If the temperature of the cold junction is constant (as when an ice-box is used), then the indicator can be calibrated directly in degrees, or if it is not known an average temperature may be selected at which the calibration is carried out. It may be taken as a good average rule for base metal thermocouples that a degree temperature rise of the cold junction above its calibration temperature is equivalent to a degree temperature rise at the hot junction.

It is usual to include some form of cold-junction compensation on most forms of moving-coil indicators and this usually takes the form of a bimetallic spring, often of brass and Invar, one end of which is fixed to the indicator case and the other to one end of the phosphor bronze or beryllium copper control-spring of the moving coil. This compensation is only strictly accurate at one point of the scale, usually somewhere around mid-scale, the effect being to under-compensate at the high end and over-compensate at the low end of the scale, but for general purposes this is sufficiently accurate. To improve the compensation it has been suggested that a bimetallic spiral should be used, in conjunction with a resistance having a negative temperature coefficient at the upper end but, although this does greatly improve the overall compensation, it is not usually necessary to adopt such a refinement.

Speed of response

In many situations the high speed of response of a thermocouple makes it the most suitable means of measuring temperature. There are many factors, however, which affect the speed of response, the main ones being the thermal conductivity of the couple, thermal mass of the couple and ratio of surface area to mass of the couple. There are other factors, but these are usually associated with the fluid in which the junction is immersed and not with the thermocouple as such.

The ideal for quick response is a small mass with a low thermal capacity and large surface area per unit mass. Copper–Constantan and iron–Constantan thermocouples can be made to give very good response times, by virtue of these qualities.

In many applications it is not possible to insert the thermocouple directly into the fluid owing to the danger of corrosion and in these cases the couple has to be placed in a protecting well, pocket, sheath or bulb, sometimes known as a thermowell. The material of these wells depends on the conditions to which they are exposed and varies from glass to Monel and wrought iron, the usual materials being fireclay, graphite, silica and similar refractories. These wells increase the response time of the couple and every endeavour should be made to make good thermal contact between the couple and the walls of the well. In some cases this is obtained by using copper foil as packing material between the sides of the thermocouple and the well. The depth of insertion of the couple is most important and it should project into the fluid sufficiently far to give an accurate indication of the temperature; at the same time, the head of the couple should be insulated to prevent heat loss.

Iron–Constantan thermocouples

These couples are normally used over a range of from 150° C. to 750° C. and in this range have a good effective life, although this will vary considerably with the conditions and the size of wire chosen. The temperature of 750° C. refers to couples operating in a reducing atmosphere and if oxygen is present, then the maximum temperature should not exceed 650° C. When using a protective well, the couple can be packed in a suitable material to give a reducing atmosphere.

Copper–Constantan thermocouples

These couples are employed over a temperature range of – 180° C. to 320° C. and their e.m.f. temperature coefficient is more linear than that of the iron–Constantan thermocouple, particularly below 200° C. They have a much higher degree of resistance to corrosion than the iron–Constantan type and from about – 180° C. to about 95° C. they represent the best commercially available thermocouple.

Chromel-P–Constantan thermocouples

These are used over a temperature range of –75° C. to 650° C. and give the largest e.m.f./temperature relationship of any of the normally available materials.

Multiple thermocouples

Multiple thermocouples—also known as thermopiles—consist of a number of thermocouples connected in series, the e.m.f.'s thus being additive. They are used when it is required to measure small temperature differences or to obtain an average temperature.

Calibration

Thermocouples should be calibrated in accordance with the International Standard Scale mentioned previously. As a result of many years' careful experiment, tables have been drawn up showing to a high degree of accuracy the e.m.f. obtained by common thermocouple materials. Characteristics are obtained by averaging the results of a large number of calibrations and for checking purposes a thermocouple is calibrated at three or more fixed, or standard, points. Table VIII gives typical figures for copper–Constantan, iron–Constantan and Chromel–P–Constantan couples.

Efficiency

The efficiency of a thermocouple as a generator is very small. The highest efficiency of the commercially available types is that of the Chromel-P–Constantan, which, at approximately its maximum operating temperature, i.e. around 600° C., has an efficiency slightly under 1 per cent. As with most forms of electrical equipment, the maximum power of a thermocouple is obtained when its internal resistance is equal to the external load resistance. The thermo-electric power of a couple is expressed as the e.m.f. per degree temperature rise.

Installation

If satisfactory results from a thermocouple installation are to be achieved, it is essential that the installation be carried out with great care. A careful survey should be made to ensure that the couple is installed at a point where it will measure the required temperature—e.g. the average temperature of a furnace or the spot temperature at any selected point. Particular care should be given to the wiring of the thermocouple. It is vitally important that no spurious e.m.f.'s arise in the circuit, since the recording or indicating instrument detects e.m.f.'s and converts them into temperature equivalents. The insulation of the wiring, therefore, of the extension, compensating leads, etc., should be at least equivalent to that for ordinary 250-volt circuit wiring under similar conditions. Joints should be reduced to a minimum, all connections should be well made and care should be taken that no voltages can be induced in the thermocouple circuits from other adjacent circuits.

Where large numbers of thermocouples are installed, the use of a common return should be avoided. It is permissible, however, where several thermocouples are used, to feed one instrument through a selector switch of the type shown in Fig. 43 p. 128. This scheme has none of the disadvantages that occur with a common return.

EXPANSION-TYPE ELEMENTS AND THERMOMETERS

This class of temperature-responsive instrument includes those utilizing the linear or cubic expansion of solids, liquids or gases.

Linear expansion devices

These are limited to the solid types and usually consist of a device to use the differential expansion between two materials, one having a high coefficient of linear expansion and one with a very low coefficient. There are two main forms:—

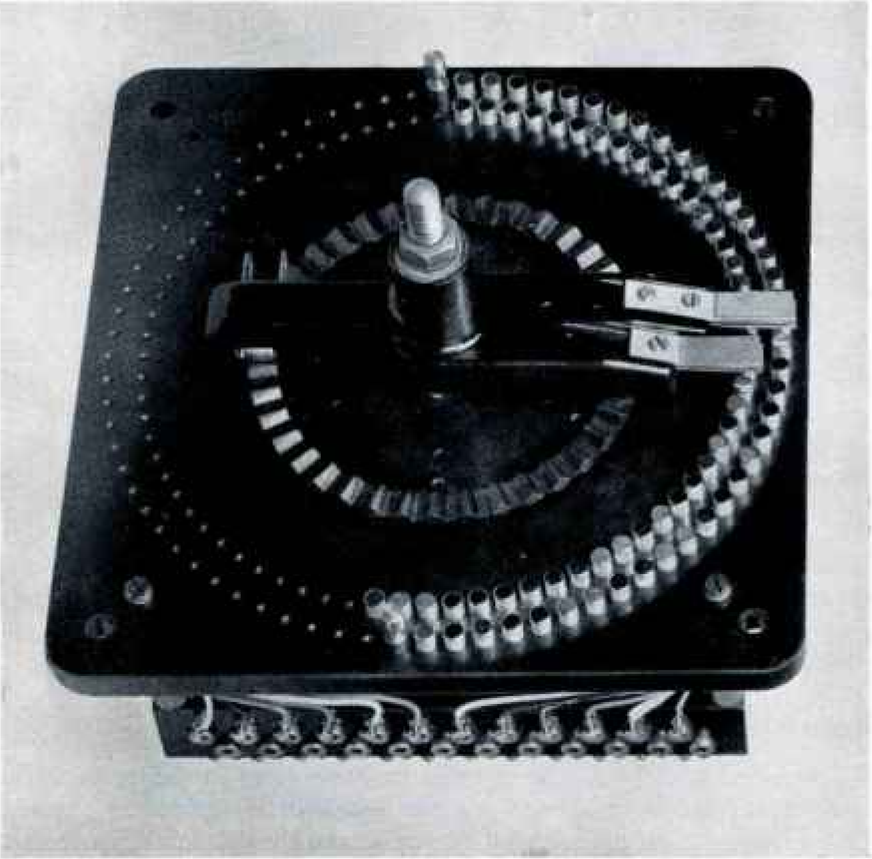
(*a*) A rod or tube of the material having a large coefficient of linear expansion is fixed with one end inside or alongside the material having a low coefficient of expansion and the differential movement is applied by a suitable mechanism.

(*b*) Two strips of metals with widely different coefficients of expansion intimately bonded or welded together to form a composite or bimetallic strip.

The first type (*a*), is generally confined to thermostatic devices, while type (*b*) is more widely used in temperature indicators, thermostats, or in temperature-compensating devices in certain other instruments. Only this latter type is dealt with in detail here.

Bimetallic elements

Bimetallic elements consist of two metals with widely differing coefficients of linear expansion joined together to form sheet or strip. They are usually made by joining two plates of the required materials together under pressure without the addition of any filler material. The edges of the two plates are sometimes tack-welded to hold them in place during subsequent operations until the joining process is complete. Great care must be taken that the inner surfaces are smooth and free from scale or oxide. The compound plate is then rolled at a suitably high temperature so that the two metals are welded together and can subsequently be treated as a



[Courtesy Metropolitan-Vickers Electrical Co., Ltd.

FIG. 43.—Thermocouple selector switch.

single solid plate which is subsequently rolled to the required thickness and cut to size. When a bimetal is subjected to a change of temperatu considerable forces act along the junction, and an intimate bond is, therefore, essential. Micrographic examination of a cross-section of a bimetallic material should show a continuous crystal structure from one side to the other. After cold working the bimetal has considerable internal stresses, which would cause erratic operation during its early life. These can, however, readily be removed by a suitable heat treatment, after which a cyclic heat treatment, ranging from above the maximum to below the minimum temperatures at which the element will operate, is given, the element being free to deflect.

Due to the different coefficients of expansion of the component metals, the element—which is usually in the form of a strip—will bend with changes of temperature, the effect being such that with an increase of temperature the side of the element composed of the material with the larger coefficient of expansion will be convex. Curvature changes will take place both along and across the strip, but as the width is usually small compared with the length, the effect of curvature across the strip may be neglected. Although generally arranged as a cantilever the strip may also be bent into the form of a helix, spiral, "hairpin," etc.

Materials

Some of the factors which affect the choice of a suitable material are:

(a) Relative magnitudes of the coefficients of linear expansion.
(b) Temperature range over which the elements will operate.
(c) Deflection required.
(d) Force to be developed.

It has been found that in general the single-phase solid-solution alloys are preferable to those in which changes in solubility occur over the operating temperature range. For low-temperature applications copper-base alloys are widely used for the high expansion side of elements, the low-expansion side usually being Invar. Brass (70 per cent. copper, 30 per cent. zinc, or 60 per cent. copper, 40 per cent. zinc), together with silicon bronze (96 per cent. copper, 3 per cent. silicon, 1 per cent. tin), are commonly employed for temperatures up to about 150° C., and give a very high degree of sensitivity. Monel is sometimes used in conjunction with Invar, when the operating range can be extended up to about 240° C., which may be increased to 310° C., if a 42 per cent. nickel-iron alloy is used on the low-expansion side.

More recently, manganese–nickel–copper alloys have been developed for use on the high-expansion side of these elements, a typical composition being 72 per cent manganese, 18 per cent nickel, 10 per cent copper.

Operation

It may be shown[51, 52] that a narrow bimetallic strip, when heated, bends to the arc of a circle, the parameters being related by the following expression:

$$\frac{1}{R}=\frac{6\alpha T(t_1+t_2)t_1t_2E_1E_2}{3(t_1+t_2)^2t_1t_2E_1E_2+(t_1E_1+t_2E_2)(t_1^3E_1+t_2^3E_2)}$$

where $R =$ radius of curvature (inches)
$T =$ temperature change (° C.)
$\alpha =$ difference in coefficient of linear expansion of materials 1 and 2 (per °C.)
$t_1 =$ thickness of material 1 (inches)
$t_2 =$ thickness of material 2 (inches)
$E_1 =$ Young's Modulus of material 1 (lb./sq. in.)
$E_2 =$ Young's Modulus of material 2 (lb./sq. in.)

The effect of the different moduli of elasticity of the two metals in most bimetallic elements is slight, and if, as is usual, the thickness of both materials is the same, then the above expression reduces to:

$$\frac{1}{R}=\frac{3\alpha T}{2t}$$

where $t =$ total thickness of element

The change in curvature of the longitudinal centre-line of a bimetallic element per unit temperature change per unit thickness has been defined by the American Society for Testing Materials (A.S.T.M.) as the "flexitivity" and is given by the formula

$$F=\frac{\left(\frac{1}{R_2}-\frac{1}{R_1}\right)t}{T}$$

where $F =$ flexitivity (per °C.)
$R_1 =$ initial curvature (inches)
$R_2 =$ final curvature (inches)
$T =$ temperature change (° C.)
$t =$ total thickness of element (inches)

(For most bimetals $F = 1{\cdot}5\alpha$)

The following formulae[53] for various types of bimetals may be found useful:—

The deflection d in inches of the free end of a straight strip of length L inches, rigidly fixed at one end, is given by the formula

$$d = \frac{KTL^2}{t}$$

where K is a constant depending on the materials used (for brass/Invar $K = 7{\cdot}5 \times 10^{-6}$).

The force P, in ounces exerted at the free end, is given by

$$P = \frac{ATwt^2}{L}$$

where $A = 525$ for brass/Invar and w = width of strip in inches.

The angular rotation, θ, in degrees for a spiral or helical coil is given by

$$\theta = \frac{CTL}{t}$$

where $C = 9{\cdot}5 \times 10^{-4}$ for brass/Invar.

The torque M in ounce-inches is given by

$$M = XTwt^2$$

where $X = 390$ for brass/Invar.

As both the coefficient of linear expansion and Young's Modulus of elasticity vary with temperature, the above formulae are only approximate and most manufacturers give their own formulae with suitable constants.

Liquid- and Gas-expansion thermometers

Construction

The liquid- and gas-expansion methods of temperature measurement can be conveniently treated under one heading, as the instruments used are similar in general mechanical construction. They are sometimes known as pressure thermometers, as they all use the principle of the conversion of heat energy to the movement of a column of liquid or gas (i.e. a pressure change) to actuate the temperature-indicator or controller.

There are three main types of temperature-indicating devices in this class, viz.,

(*a*) Liquid filled;
(*b*) Vapour pressure (tension);
(*c*) Gas filled.

Each of these three types comprises

(1) A bulb which is in contact with the substance the temperature of which is to be measured and which is filled or partially filled with the actuating medium.

(2) A pressure-sensitive element of the Bourdon tube, bellows or diaphragm (capsule) type (see p. 39).

(3) A fine-bore tube, usually known as a capillary, which is connected at one end to the bulb and at the other end to the pressure-sensitive element.

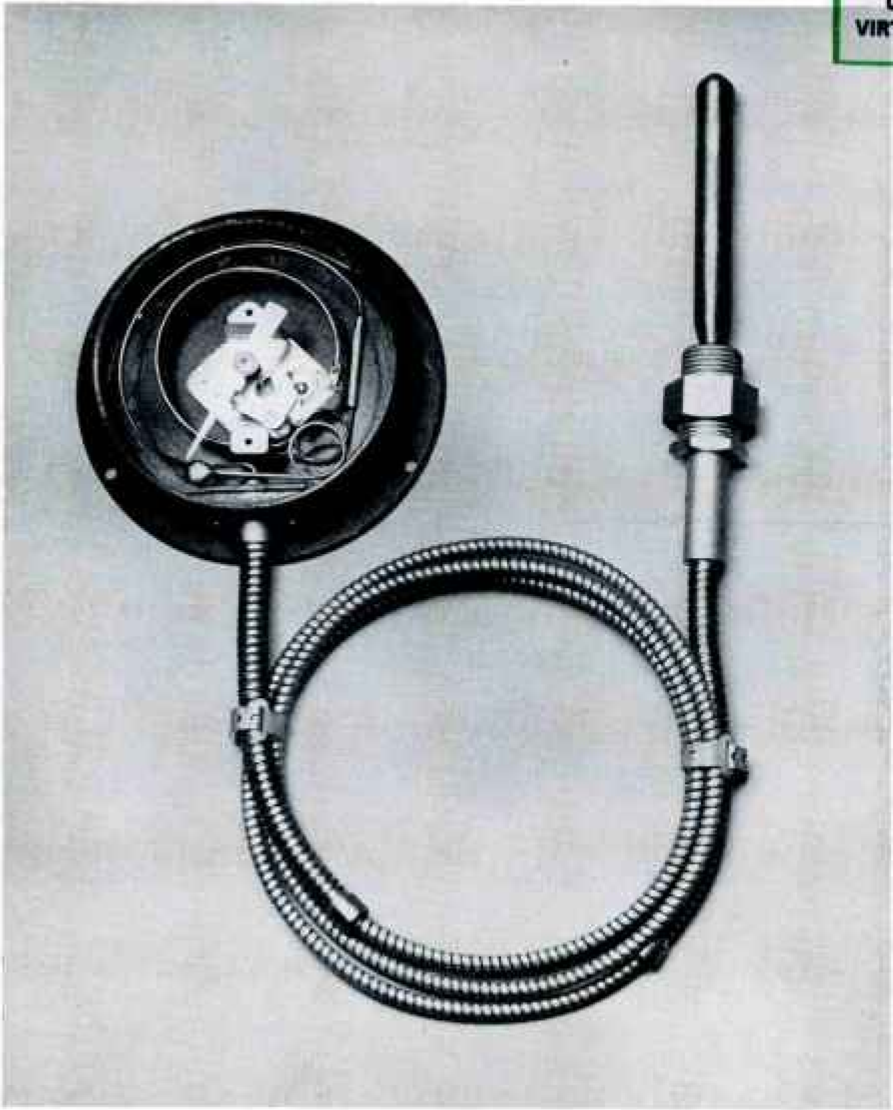
(4) A suitable linkage to indicate or record the movement of the pressure-sensitive device in terms of temperature.

Fig. 44 shows a typical vapour-pressure instrument in which the above component parts may be clearly seen.

Bulbs

The basic principle of liquid and gas expansion thermometers is to impart heat energy to the fluid in the bulb and capillary; the bulb must, therefore, be constructed in such a way and of such a material that the heat is imparted in the shortest possible time to the fluid. Therefore, the bulb should be made of a material with a high thermal conductivity, able to resist corrosion and strong enough for both internal and external pressures to be resisted by a relatively thin-walled bulb. Copper has the highest thermal conductivity of any material that can be economically used for this purpose and this, combined with its good mechanical properties and resistance to corrosion, assures its almost universal use for bulbs, except where the actuating fluid is mercury. Where the medium the temperature of which is being measured might tend to corrode the copper (see page 134) it is usual to plate the bulb with some other suitable material.

In order to obtain the maximum heat flow, the bulb should have a maximum possible surface area in relation to its volume and the mass of metal should be reduced to the minimum consistent with the stresses and the corrosion risks involved. Thermometer bulbs are, therefore, usually made long and narrow. In certain cases the bulb may consist of a length of capillary tubing coiled into the form of a spiral. Generally, however, bulbs are constructed from solid drawn copper tubing of rather larger diameter than capillary tubes with suitable end plugs silver-soldered, brazed, or welded in to seal one end. Fixed to the other end of the bulb is a suitable extension neck to receive the capillary tube, an arrangement which minimizes the risk of breakage of the capillary tube at this point; alternatively, the bulb may be applied integral with the capillary tube.



[*Courtesy Drayton Regulator & Instrument Co., Ltd.*

Fig. 44—Typical vapour-pressure dial thermometer.

Pressure-sensitive elements

These can be any of the types described in the chapter on Pressure-sensitive elements, viz. Bourdon tube, diaphragm, or bellows, but the Bourdon tube type predominates. For detailed information on the construction of these elements, reference should be made to Chapter I.

Capillary tubes

With liquid and gas expansion thermometers, the bulb is connected to the pressure-sensitive element by means of a capillary tube (of which it may be an integral extension). The tubing should have a smooth fine bore, be capable of being bent and coiled easily without damage, and be available in long lengths (up to 400 feet). Capillary tube sizes for this purpose vary from about 0·06 in. bore down to 0·008 in. bore, although the most common range is from 0·02 in. down to 0·008 inch. Dimensional tolerance is usually ± 0·001 in. on the bore and ± 0.002 in. on the outside diameter. These tubes are almost invariably made of annealed copper or annealed cupro-nickel, except where mercury is used, in which case a ferrous material is essential. Although the copper tubing is perfectly satisfactory for installations where there is a minimum of handling and little risk of damage, cupro-nickel is preferable on other types of installation, owing to its higher limit of proportionality, hardness and endurance limit. With both types of material smooth bores are easily obtained which offer the minimum friction to fluid movement and, therefore, assist in giving a high speed of response to the thermometer. Capillary tubing is frequently protected with either a metallic or non-metallic braid or armouring.

Liquid-filled thermometers

There are two main classifications into which liquid-filled thermometers naturally fall, according to the liquid employed, viz. those employing mercury, and those employing other liquids, usually hydrocarbons, such as paraffin, etc. For numerous applications the mercury-filled type is well suited; but there are many exceptions and, as mercury cannot be used with copper or copper-base alloys, it is not further considered here. The liquid-filled type of thermometer uses a pressure-sensitive element as a means of indicating volume expansion and not a change of pressure. It consists of a bulb, capillary tube and pressure-sensitive element, the whole being completely filled with liquid under a pressure of several hundred pounds per square inch. The advantages of this type of thermometer are that an approximately uniform scale can be provided, considerable power is transmitted by the pressure-sensitive device, enabling recording mechanisms to be driven directly, and a wide temperature range is possible.

The desirable features of a liquid for filling this type of system are

(*a*) High coefficient of expansion over the temperature range with which it will be used;
(*b*) Negligible vapour pressure;
(*c*) Low specific gravity;
(*d*) High specific heat and thermal conductivity.

No liquids completely fulfil all these desiderata, but pentane having a coefficient of volumetric expansion of about 0·0004 per °C. has been found suitable for copper and copper-alloy systems; xylene and toluene are also used, but are considered to be inconsistent by some manufacturers.

The indicating or recording device can be a considerable distance (up to about 250 ft.) away from the temperature-sensitive bulb, provided that a compensating device is used (see below).

Errors

There are three main sources of error in such an installation, viz.:—

(1) A head error due to difference in elevation of the bulb and pressure-sensitive device. This is usually negligibly small, since the system is sealed under high pressure.
(2) Error due to varying temperature along the length of the capillary tubing ("capillary error"). This can be serious unless very small bore tubes are used, but is easily compensated for by differential connection of two elements, one of which is connected to a sealed capillary tube of identical dimensions to the main tube.
(3) Errors due to temperature changes on the pressure-sensitive device; a bimetallic compensation arrangement is used for these.

The liquid-filled type of expansion thermometer can be used over the temperature range — 40° C. to about + 400° C., although the individual range on any instrument is generally considerably less. A factor which must be borne in mind in designing the system is that the volume will tend to increase at the higher pressures due to elastic deformation, and at the same time the liquids will tend to compress. Both these factors will tend to make the indication lower than the true reading, but this can be compensating by providing a suitable linkage in the indicating or recording device.

Vapour-pressure thermometers

All liquids exert a pressure over their free surfaces and this pressure is a function only of the temperature. The general construction of the vapour-pressure thermometer is, therefore, very similar to that of the liquid-filled type, but the filling liquid does not completely fill the system. In general, when the temperature to be measured is greater than that where the capillary and sensitive elements are located, the bulb will be filled with a mixture of liquid and vapour, while the pressure-sensitive element will be filled with liquid only. The basic problem, as in the previous case, is to impart heat to the liquid in the bulb, which should therefore be made of a material of high thermal conductivity and able to withstand corrosion. Thus, copper or copper alloys are again the materials normally used. The desirable properties of the filling liquid are:

- (*a*) The critical temperature should be above the maximum temperature to which it will be subjected.
- (*b*) The vapour pressure should be sufficiently high to develop adequate power over the temperature range being measured.
- (*c*) The vapour pressure at the low end of the temperature scale should be close to that of the atmospheric pressure in order to reduce variations due to changes in barometric pressure.
- (*d*) The liquid should be pure, so that fractional distillation does not occur, and it should not be harmful to copper or its alloys.

A large range of filling liquids is available, such as ether, ethyl bromide, ethyl chloride, ethyl alcohol, acetone, "freon," hydrocarbons of the type mentioned on p. 135, and water. The temperature limits over which this type of thermometer is used are about -45° C. to $+260^\circ$ C. Capillary tubing lengths up to about 250 feet can be used. The relationship between vapour pressure and temperature is not linear and, therefore, a non-uniform scale reading results; the scale becoming more open as the temperature increases. Provided the right temperature range is selected, this in many instances is an advantage.

Errors

As the operational pressure is comparatively low, errors can arise from the position of the bulb relative to the indicating instrument. As the error is constant in a fixed installation, it can be compensated for by setting the pointer to the correct position on the scale after installation, provided the difference in height is not too great, i.e. about 12 feet.

Since changes in temperature of the tubing and indicator cannot affect the pressure of the liquid vapour, no compensation for this effect is necessary.

Gas-filled thermometers

The gas-filled thermometer is basically similar to the liquid-filled vapour-pressure type, but is completely filled with a gas such as nitrogen. Nitrogen is usually chosen as it is normally available in a pure form, has a low specific heat combined with a high coefficient of expansion and closely obeys the gas law on which the operation of this type of thermometer is based. The gas law is usually expressed by

$$\frac{P_1}{P_2}=\frac{T_1}{T_2}$$

where P_1 and P_2 are the initial and the final pressures when the temperatures are T_1 and T_2 °K. This type of thermometer can be used over a temperature range of from 10° C. to about 500° C. with capillary lengths up to about 200 feet.

Compensation for capillary tube temperature is not normally necessary, as, with this type of thermometer, the ratio of the volume of the bulb to the volume of the capillary tubing is normally high, and should not be less than 8 to 1.

RESISTANCE THERMOMETERS

Resistance thermometers, as the name implies, are based on the principle of the change of resistance of a material with temperature. Copper and its alloys are not in general use in resistance thermometry, as other materials are available which have a greater change of resistance with temperature, and which can be used at higher temperatures. The resistance of copper in coil windings is, however, often used as a method of measuring the temperature, not only for stationary coils, but also for the rotor windings of alternators, etc. The main difficulty involved in the latter application is that the voltage drop across the windings, as opposed to the voltage drop between the brushes, must be measured with accuracy; but suitable methods have been evolved.

The average temperature of the copper winding is calculated from the formula given in B.S. 225, viz.:

$$\frac{R_2}{R_1}=\frac{T_2+234{\cdot}5}{T_1+234{\cdot}5}$$

where R_1 and R_2 are the ohmic resistances of the winding at temperatures T_1 and T_2 (°C).

The effect of temperature on the resistance of copper is dealt with in more detail in Chapter II, to which reference should be made for further information.

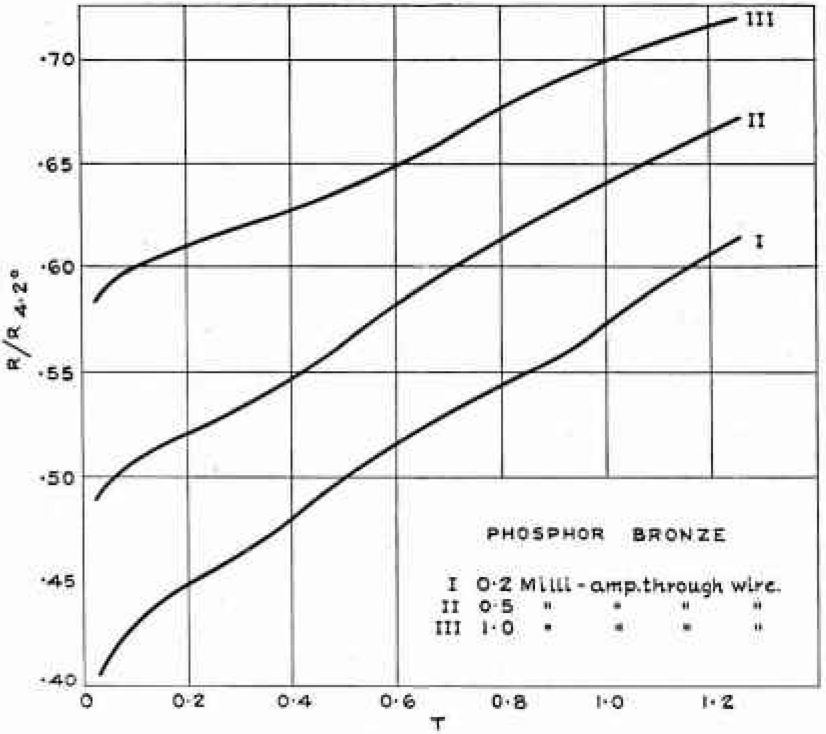


FIG. 45.—Effect of current on resistance changes at low absolute temperatures (T) in phosphor bronze resistance thermometer.

(R and $R_{4 \cdot 2}$ = resistance at temperature T and 4·2° K. respectively.)

For low-temperature measurements, in the range of liquid helium, phosphor bronze is often used. This type of thermometer is, however, very sensitive to changes in composition and physical condition of the phosphor bronze. Fig. 45, due to Allen and Shire,[54] shows the changes of resistance at different current densities. Care must be taken, also, that no external magnetic field is present, as this would have an appreciable effect upon the resistance at the lower temperatures.

SOME BRITISH STANDARDS

Title	B.S. No.	Referred to in text *Page*
Indicating ammeters, voltmeters, wattmeters, frequency and power-factor meters	89:1937	90
Metallic resistance materials for electrical purposes	115:1938	93
Dimensions and resistances of bare annealed copper wire for electrical machinery and apparatus	128:1929	86
Enamelled round copper wire (oleo-resinous enamel)	156:1951	86
Electrical performance of alternators of the steam turbine driven type	225:1925	137
Nickel-copper (cupro-nickel) sheets and strips	374:1930	22
Phosphor bronze sheets, strip and foil, excluding drawn material	407:1939	22
Motor starters and controllers, and resistors employed therewith	587:1940	89
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Enamelled round copper wire (enamel with vinyl acetal base)	1844:1952	86
Filler alloys for brazing	1845:1952	37

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