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THE DEVELOPMENT OF ELECTRICAL STRAIN GAGES

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SUMMARY

The design, construction, and properties of an electrical-resistance strain gage consisting of fine wires molded in a laminated plastic are described. The properties of such gages are discussed and also the problems of molding of wires in plastic materials, temperature compensation, and cementing and removal of the gages.

Further work to be carried out on the strain gage, together with instrumentation problems, is discussed.

INTRODUCTION TO THE STRAIN-GAGE PROBLEM

Two trends are especially observable in modern engineering progress. One is a trend toward larger structural units and higher speeds and the other is a trend toward the production of the lightest structure consistent with safety. These trends are especially noticeable in aircraft engineering. The design of large long-range military and civil aircraft requires a rigid control of weight both of the structure and of the power plant. In previous years, it was sufficient to make sure that structural elements as a whole, such as wing beams, fuselages, and so on, were capable of carrying the computed aerodynamic and inertia loads. The present rate of progress requires that the stresses be checked in the individual structural members and fittings in order to eliminate unnecessary extra strength as well as to detect sources of weakness.

In aeronautical work, it is desirable that these stresses be measured both on the ground with static loads and in flight. On the ground, the loading simulates the computed aerodynamic and inertia loads; the computed stresses can then be confirmed by placing strain gages at the desired points of the structure. In flight, the

loading assumptions can be checked. For this purpose an electrical strain gage of the resistance type is desirable, in which the strain is measured by the change in resistance of a strained conducting element. The strain-recording device is essentially a bridge with galvanometer remote from the gage. The gage itself should be compact, comparatively cheap to produce, and capable of being cemented by both hot and cold cements to steel or duralumin. It is desirable, though not essential, that the gage be removable for calibration previous or subsequent to the test. Necessary requirements of such a strain gage for static work are that the resistance of the gage be independent of temperature, and that there be no creep or hysteresis in the strain-resistance relationship of the gage.

The carbon-pile principle has been adapted, in the well-known "Ess" strip of Professor de Forest (reference 1), to a form suitable for the measurement of dynamic strains up to very high frequencies (reference 2). Unfortunately, this principle is unsuited for static work, because its resistance is very sensitive to temperature; a change in temperature of 1° C. in the gage when cemented to steel produces the same change in resistance as would a stress of approximately 1,000 pounds per square inch in the steel. Furthermore, there is a marked hysteresis in the strain-resistance relation (reference 3); in addition, the resistance is somewhat susceptible to changes in relative humidity in the atmosphere.

For accurate measurement of static strains, the Ess strip is therefore unsuitable. It was considered that the development of the Ess strip to a stage where it could be used for static work would be a long and difficult, if not an impossible, task. Accordingly, it was decided to make a fresh start, using the strain-sensitive properties of fine metallic wires.

For some months previous to the commencement of the present investigation, Professor A. C. Ruge of the Massachusetts Institute of Technology, had been investigating the sensitivity of fine metallic wires to strain and temperature. He used celluloid-acetone lacquer to attach the wires to the metallic surface, with a layer of paper (for insulating purposes) interposed. Professor Ruge contributed much preliminary data on strain-resistance relationships in fine wires, and various alloy wires were furnished through the kindness of Mr. G. E. Chatillon of John Chatillon & Sons.

The process of cementing resistance wire to paper or other insulating material is not practicable where the gage must be removed for calibration, and the good qualities of the previous Ess strip were combined with the wire gage to overcome this difficulty. The problem that presented itself was threefold.

(a) Mounting: to develop a suitable method of casting or molding the wire in a plastic material.

(b) Temperature compensation: to develop methods by which the effect of temperature on the resistance of the gage could be compensated.

(c) Attachment: to develop and test hot- and cold-cementing methods, and methods of removing cemented gages without damage.

Two simple methods of mounting the fine wires have been developed. In one, the wire is molded between layers of bakelized paper. The gages can, of course, be of any reasonable dimension, and it has been found convenient to make them about 3 inches long by 3/8 inch wide by 0.010 inch thick. In the other form, the wire is molded into a transparent thermoplastic resin, Lucite (methyl methacrylate polymer). These gages are about 4 inches long by 3/8 inch wide by 0.035 inch thick. Other forms that were developed have been discarded because of the difficulty, time, or uncertainty involved in their construction.

It would be thought that a wire such as constantan or manganin, the resistance of which is practically independent of temperature, when molded in a plastic mount and cemented to a steel or duralumin bar, would act as a temperature-compensated strain gage. This result is not forthcoming since there usually exists a difference in the thermal coefficients of expansion of the metal specimen and of the wire in the gage. When the bar is heated, this difference imposes a longitudinal strain on the wire in the gage, changing its resistance, even though the bar to which the gage is attached is unstressed. It follows that a resistance strain gage temperature-compensated when attached to steel will not be compensated when attached to duralumin, owing to the different coefficients of expansion.

Compensation has been effected by employing in the gage two types of wire. The wires lie parallel to the

length of the gage and are connected in series or parallel. One wire has a positive temperature coefficient of resistance and the other wire, a negative coefficient. The wires are so proportioned that temperature effects on the resistances of the two wires counterbalance. The materials used at present are "copel" for the negative constituent and Nichrome for the positive constituent. The gages for use on steel and those for use on duralumin are similar in design but differ in the proportions of wire used. The present gages have a resistance of about 25 ohms, yet it is possible to make, without difficulty, compensated gages having a resistance of 250 ohms and more. It is possible to adjust, by means of an external resistance, the gages that are not perfectly temperature-compensated. It is hoped shortly, however, to be able to produce gages in quantity, which are sufficiently closely temperature-compensated not to require these additional external resistances.

The bakelite gages can easily be cemented into position, using de Khotinsky cement. This method required heating of the metal to which the gage is to be attached, to 135° C. The gage can be removed, by reheating or by softening the cement in alcohol, for calibration or for use elsewhere. A compensated gage, when attached to a steel bar strained in a testing machine, shows no observable creep or hysteresis in the strain-resistance plot up to the maximum strain employed (0.0007 inch per inch). Plastic wood, as a cold cement, is hoped to behave as well. Bakelite gages cemented with plastic wood can be removed very quickly with acetone.

Lucite gages are more difficult to cement since they soften and warp on heating. They may be cemented with plastic wood; this cement dissolves in caustic-soda solution, which does not affect the gage.

THE MOUNTING OF FINE WIRES IN PLASTIC MATERIALS

In general, there are three methods of mounting wires in plastic materials: by casting in a closed mold at an elevated temperature, by molding in a closed mold under pressure and temperature, and by pressing (without a mold) resin-impregnated paper or cloth. All these methods have been tried, using different resins, with varying success. When working with synthetic resins, it is necessary to

bear in mind the essential chemical and physical processes; these are summarized below.

Thermoplastic Resins

Thermoplastic resins are usually initially in the form of fairly volatile mobile liquids, which are chemically fairly complex unsaturated organic compounds, possessing a single double bond in the molecule. In this form the molecules exist singly. Under the action of heat, light, oxidizing, and other catalytic agents the molecules combine to form long interlocking chains, with a consequent increase in viscosity of the liquid resin. The increase in viscosity is at first relatively slow, but later accelerates through a rubber-like phase to result finally in a hard, transparent mass. This polymerization process is irreversible; it is impossible to convert the solid back to the original mobile liquid. The glassy solid softens, however, at an elevated temperature. A high pressure can then be used to mold grains of the polymerized thermoplastic into any desired shape. There are thus two methods of forming a thermoplastic resin: polymerization of the liquid monomer by gentle heating (in a closed vessel to prevent evaporation) and the molding under pressure and a higher temperature, grains of the commercial polymerized resin.

Thermosetting Resins

Of the thermosetting resins, phenol formaldehyde is typical and is by far the most widely used. Heating together of phenol and formaldehyde solution results in the combination of phenol and formaldehyde molecules to form a three-dimensional network. At first, the resin molecules are small, and the resin is consequently liquid at room temperature. Liquid casting resins, such as "Marblette," are of this type. Further heating causes an increase in polymerization, so that the resin is no longer liquid at room temperature. This resin ("A stage" resin) is the basis of commercial molding powders and lacquers. Further heating results in a resin ("C stage" resin) which is solid and hard at all temperatures up to the temperature at which it chars. Molding powders are made by adding a filler (usually wood flour), accelerator, and dye to the A stage resin. Lacquers are made by dissolving the A

stage resin in alcohol. There are thus three methods of forming thermosetting resins:

(a) By casting the liquid resin around the wire under moderate temperature.

(b) By molding around the wire "A stage" resin or commercial molding powder under temperature and pressure.

(c) By impregnating paper or cloth in a lacquer of "A stage" resin and drying, and then molding fine wires under temperature and pressure between sheets of this paper or cloth.

Casting of Wires in Thermoplastic Resin

Since the casting technique did not involve the application of pressure and the danger of rupture of fine wires, this casting of wires in thermoplastic resin was developed first. Gages were successfully cast, using methyl methacrylate monomer (supplied by the E. I. du Pont de Nemours company). The polymerized methacrylate resin is known commercially as Lucite. Marblette liquid casting bakelite resin was also used. It is not possible to obtain a solid slip of resin by evaporating a solution of the resin; under these circumstances, drying would take place on the surface first, leaving the inside partly or wholly liquid. Neither is it possible to obtain a gage by casting grains of a polymerized thermoplastic resin. At the highest allowable temperature, such a resin is not really fluid, and even after prolonged heating at that temperature a great many air bubbles remain in the casting.

Of the commercially available thermoplastic resins, methyl methacrylate polymer (Lucite) has probably the best elastic properties and is the easiest to obtain in monomer form. The casting mold is shown in figure 1. The wire C, to be mounted in resin is soldered or welded to two pieces of steel shim stock A and B (fig. 2) and assembled in the mold. Before the mold is tightened up, the piece B projecting from between the side pieces is pulled taut. In this way the three parts of the wire C become tight and straight simultaneously.

The required quantity of monomer is mixed with about 1 percent of benzoyl peroxide, which acts as a catalyst,

poured into the mold, and the cover screwed down. It is necessary for the polymerization to be carried out slowly to reduce the danger of bubble formation, which is very likely to occur around the wires. The best results were obtained by raising the temperature gradually from 40° to 60° C. over a period of 3 or 4 days. A clear water-white strip of resin of dimensions about 3 inches by 1/2 inch by 1/16 inch was produced, normally free from bubbles. Figure 3 shows diagrammatically the appearance of the gage after removal from the mold and figure 4, the final appearance of the gage after removal of superfluous metal and soldering-on of connecting wires.

Since this process was long and tedious and since successful results were not always obtained, other methods were sought.

Casting of Wires in Bakelite Resin

Marblette liquid phenol-formaldehyde resin (supplied by the Marblette Corporation) was used in an attempt to cast a thermosetting resin that could be attached by de Khotinsky cement. The wire to be mounted was soldered to a copper-foil mount (fig. 5) and the assembly clamped in the casting mold. The liquid resin was poured in and the mold heated for 2 days at a temperature rising from 70° to 130° C. A hard, brown, opaque, bakelite gage was obtained that, though being thermosetting, was always full of air bubbles. This method was consequently abandoned as being unsuccessful.

The Molding of Fine Wires in Lucite

Generally speaking, it is easier to mold articles of Lucite from the commerical polymerized, granulated product than to cast the articles from the liquid resin in a lower state of polymerization. The high pressures involved in this operation (from 1,000 to 5,000 pounds per square inch) will rupture fine wires unless special precautions are adopted. Figure 6 shows the mold used for pressure molding of wire strain gages. The bolts on the lower part of the mold were adjusted so that the thickness of the finished molding was about 1/32 inch.

"Double-Decker" Process

In the double-decker process, two strips of Lucite 4 inches by 1 inch by 1/32 inch are made in the mold. A wire assembly on a gauze framework is placed between two such strips in the mold and the three components "fused" by heat and pressure.

First, a weighed quantity of commercial resin is placed in the mold and subjected to a pressure of 5,000 pounds per square inch at 160° C. for about 15 minutes. The mold is cooled under water and the molded piece removed. Two such pieces are made. One surface of each piece is moistened with the liquid monomer containing benzoyl peroxide. The wire assembly soldered to a copper gauze (or welded to a nickel gauze) framework (fig. 7(a)) is placed between the pieces, with the moistened surfaces facing each other. This sandwich is placed in the mold and heated to 160° C., then subjected to a pressure of 1,000 pounds per square inch for 15 minutes. The mold is cooled as before and the completely molded gage removed. The gage ready for use is shown in figure 7(b). The finished gage is about 0.075 inch thick. An essential part of this process is the moistening with the liquid monomer of the strips of resin before repressing. If these two strips are merely pressed together under temperature in the mold, they will fuse only at a few isolated points, where the ends of the molecular chains happen to coincide. These two pieces can easily be split apart. Wetting the surfaces with the liquid monomer produces some new chain-forming material, which cements the two pieces chemically into one coherent strip.

"Single-Decker" Process

In the single-decker process, only one strip of resin is used; thus a more flexible, thinner, more quickly produced strip is obtained. The assembly, constructed as before, is placed at the bottom of the mold, then the molded piece of Lucite, and finally a false assembly, containing no wire. The three components are pressed together under a pressure of 1,000 pounds per square inch for 15 minutes; the pressure is applied when the temperature of the mold reaches 160° C. The resin appears to flow under and around the wire; when the mold is cooled and the molding removed, both pieces of gauze and the wire appear to be thoroughly embedded in the resin. It should be mentioned that, in the absence of the upper gauze, the gage is warped on removal

from the mold, owing to the differential contraction of the copper gauze and the Lucite. Figure 7(c) shows the appearance of a single-decker gage after removal from the mold. In this process (as in the double-decker process) the wire is placed in the asembly with some slack, and very few cases of rupture or incomplete embedding of the wire are obtained. After the sides of the molding are sawed off, the ends slit down, and connections soldered on, the gage is ready for use. Figure 7(d) shows a gage which is about 0.035 inch thick constructed in this manner.

A large number of gages of the double-decker and single-decker types have been constructed since the completion of a progress report (reference 4) on this investigation. Data obtained from these gages would have enabled satisfactory gages compensated for steel and for duralumin to be constructed. Since certain cementing difficulties associated with Lucite could not be overcome, methods were developed of molding gages in Bakelite.

The Molding of Wires in Bakelite Molding Powder

Lucite was originally chosen as a casting and molding material on account of its very good elastic properties. The addition of a filler to a resin, such as wood flour, paper, or cloth, though making the resin stronger, impairs its elastic qualities, creep and hysteresis being very evident in the stress-strain properties of the filled resin (reference 5). It was felt that this strain creep and hysteresis was partly responsible for the resistance creep and hysteresis of the Ess strip and that filled resins were therefore to be avoided. This conclusion is now known to be ill-founded, since gages molded in bakelite molding powder (with wood-flour filler) and in laminated Bakelite (with paper filler) show a complete absence of creep and hysteresis in the strain-resistance relation.

It was attempted to mold single-decker and double-decker gages from bakelite resin and from molding powder. Unlike the Lucite gages, these gages could be firmly and easily attached with de Khotinsky cement. The double-decker gages were to be made by partly curing the material, so that it had sufficient strength to be removed from the mold but could still fuse and cement itself onto another similar strip. The unfilled resin when partly cured was

too weak and brittle and usually cracked on cooling. The commercial molding powder was somewhat better and, after some experiment, the correct conditions were found for the two strips of Bakelite to fuse without cleaving along the joining plane. In this process, however, the wires also became broken. It was then attempted to mold single-decker gages as with Lucite, the wire assembly being pressed into a partly cured strip of Bakelite. In only one case was the wire pressed firmly in. In all the other cases the wire could easily be pulled from the surface. This one exception, cemented to a steel bar with de Khotinsky cement, possessed a linear, strain-resistance characteristic without hysteresis. It was therefore decided to mold the gages from bakelized paper.

Paper-Reinforced Bakelite Gages

The paper-reinforced bakelite gage is of all types the simplest and quickest to make, the easiest to attach to steel and duralumin, and the thinnest and lightest.

The wires composing the gage are soldered to a framework constructed from strips of brass gauze about 1/8 inch wide. Eight strips of resin-impregnated paper 4 inches long by 3/8 inch wide are cut out. The wire assembly is tacked down to one of the strips by means of a warm soldering iron and some finely powdered A stage resin (fig. 8(a)). With a total of four strips of paper above and below the wires, the whole assembly is placed between polished sheets of chromium-plated steel and then between sheets of cardboard. Molding is carried out between platens heated to 150° C. under a pressure of 1,000 pounds per square inch for 15 minutes. The gage is then ready for soldering on contacts to the gauze strips (fig. 8(b)).

At the present moment, special soldering and molding jigs are being constructed. These jigs will enable the exact lengths of wire to be soldered on; the wires will be held taut and the pieces of paper held vertically over each other during the molding. In this way it will be possible to produce easily and rapidly temperature-compensated strain gages with reproducible characteristics.

STRAIN SENSITIVITY

Temperature-Compensated Gages

The use of fine wires to measure strains is not novel and the manner of application is fairly obvious. The resistance of metallic wires as a rule is very much more sensitive to changes in temperature than to changes in strain. For static work, therefore, it is necessary to compensate for the effect of temperature on the resistance of the wire.

It has already been mentioned that the problem of temperature compensation cannot be solved by the use of wires such as constantan and manganin. If these wires have a thermal coefficient of linear expansion different from that of steel, when cemented to a steel surface which is then heated, the wires will suffer a longitudinal extension or compression superimposed by the steel on their normal dilatation. This additional extension or compression will change the resistance of the wire and so destroy the temperature compensation. The magnitude of this effect is shown by the following example: If a wire be found that happens to be perfectly compensated when cemented to duralumin, this wire when cemented to steel will change its resistance when the temperature rises 1° C. by an amount equivalent to a compressive stress of 400 pounds per square inch in the steel. It is therefore clear that special methods of compensation will have to be sought and that gages compensated for use on duralumin will be different from gages compensated for use on steel. It is clear also that the effects of strain and temperature on the resistance of wires must be jointly considered.

Strain and Resistance

Since the electrical resistance of a metallic wire is proportional to its length and inversely proportional to its cross-sectional area, it might be assumed that the increase of resistance of a wire on straining is due to the increase in length and reduction in cross-sectional area. If the strain sensitivity S be defined as the ratio of the proportional increase in resistance $\Delta R/R$ to the tensile strain $\Delta l/l$, the strain sensitivity should be given by

$$S = \frac{\Delta R/R}{\Delta l/l} = 1 + 2\,\sigma \qquad (1)$$

where σ is Poisson's ratio. The sensitivity S should thus vary from 1.6 to 2.0. In actual practice S can vary from large positive values to large negative values, the value for most wires being about 2.4. It is clear that the specific resistivity of a wire varies when it is strained. Though this phenomenon is known (references 6 and 7), there seems to be no consistency in the scanty published data and no satisfactory explanation of the phenomenon.

Measurement of Strain Sensitivity

The strain-resistance relations of wires molded into gages were obtained by clamping or cementing the gages to steel bars 1/8 inch thick and about 7/8 inch wide and applying tension loads to the steel bars through pins. The change in resistance was measured by a Wheatstone bridge, using the deflection method. The strain was computed from the load and the cross-sectional area of the bars. For precise work, this method is likely to be far from accurate, since the bars were by no means initially straight. Since, till very recently, the gages were far from compensated, it was considered that the error due to temperature drift was larger than the error due to initial curvature of the bars. The error due to initial curvature was minimized by commencing the tests at a load of 400 pounds. Tests were usually conducted by loading the bar in steps of 400 pounds from 400 pounds to 2,000 pounds through two complete cycles. The arrangement of apparatus for a strain test is shown in figure 9.

Measurement of Resistance

Two different arrangements of Wheatstone bridge were available for measurement of resistance. In one form, a multiratio bridge, the external resistance was balanced by a decade box variable from 1 to 9,999 ohms, the ratio of the ratio arms being selected by a switch. Since these ratio arms were built into the bridge, the over-all sensitivity could not be improved by adjustment of the values of the bridge resistances. When low-resistance gages (about 25 ohms) were to be tested, the gage was placed in series with a 1-ohm resistance, across which could be connected a resistance of 24 ohms. With higher-resistance gages (of

the order of 100 ohms), a decade box containing 0.1-ohm steps was placed in series with the gage. A decade box placed in shunt with the galvanometer is open-circuited when balance is obtained. In the case of the low-resistance gages, opening or closing the calibrating switch gave the deflection corresponding to an increase or decrease in the external resistance of 0.04 ohm. The mean calibration at the beginning and end of each test was thus obtained. Individual calibration observations usually agreed to better than 1 percent. In the case of the high-resistance gages, calibration was obtained by switching into series with the gage 0.1 ohm or a higher resistance. Figure 10 gives the circuit of the bridge arranged for a test on a low-resistance gage.

The other form of bridge used was a variable-ratio bridge. The external resistance is balanced by a decade-box variable from 1 to 999 ohms: the bridge ratio is variable between narrow limits below and above unity. Calibration is effected in the same manner as with the multiratio bridge.

Figure 11 shows the over-all sensitivity calibration for the multiratio bridge for the 0.1 and the 0.01 ratios. The ordinates give the deflection in divisions of the galvanometer scale for a 1-percent change of external resistance using a 6-volt battery. It is seen that in the region of 20 to 100 ohms the sensitivity with the 0.1 ratio greatly exceeds that with the 0.01 ratio; also that maximum sensitivity is obtained with a gage resistance of the order of 20 ohms. The deflection of the galvanometer in this arrangement could be estimated to 0.01 division. Thus a resistance change of 2.5 parts per million could be detected, corresponding to a strain change of about 1 part per million. Figure 12 gives the corresponding calibration for the variable-ratio bridge used with a different galvanometer.

Results of Strain Measurements

From the tests on compensated gages constructed from laminated Bakelite cemented to steel with de Khotinsky cement, it is concluded that there is no creep nor hysteresis in the strain-resistance relations of metallic wires. Under laboratory conditions tests on noncompensated gages containing single wires gave the same result, though with such specimens variation in laboratory temperature during

a test produces a resistance drift that might be mistaken for imperfection in the strain gage. Tests on Lucite gages clamped or cemented to steel with plastic wood cement showed very little hysteresis in the strain-resistance relation. Such hysteresis as was found must be attributed to imperfect cementing or clamping.

As an example of the linearity between strain and resistance, the following table gives data obtained in a strain test on a temperature-compensated gage, designated PB 6, made in laminated Bakelite. The gage was cemented to a steel bar by de Khotinsky cement. The readings are of galvanometer deflections for two loading cycles.

TABLE I

Strain-Test Data for Gage PB 6, Temperature-Compensated, Laminated Bakelite

Gage resistance 23.0 ohms
[Galvanometer calibration 137.25 division = 1 ohm change of resistance]

Stress in steel (lb./sq.in.)	Galvanometer readings			
	First cycle		Second cycle	
	Load increasing	Load decreasing	Load increasing	Load decreasing
4,267	7.92	7.97		7.97
8,533	9.18	9.21	9.22	9.22
12,800	10.38	10.39	10.40	10.38
17,067	11.51	11.50	11.53	11.50
21,333	12.63		12.64	

The agreement between the deflections at each load station is too close to be shown on a graph. In figure 13 the mean reading at each stress level is plotted against stress. From the slope of the straight line the strain sensitivity S is obtained.

Strain-Sensitivity Data

In table III is given the measured strain sensitivity of certain wires molded into resin. The table gives the type of resin, manner of attachment, and strain sensitivity for different wires. The code used to designate the type of resin is given in table II. The source of the wires in table III is given in table IIIa.

TABLE II

Types of Resin

Type of mount	Code
Laminated Bakelite (paper filler)	PB
Molded methyl methacrylate (Lucite)	MM
Molded Bakelite (wood-flour filler)	MB
Cast methyl methacrylate	M
Cast Bakelite	B

TABLE III

Strain Sensitivity

Wire	Type of mount	Method of attachment	Strain sensitivity S
Copel	PB	de Khotinsky cement	2.38
Nichrome	PB	de Khotinsky cement	2.86
Isoelastic	PB	de Khotinsky cement	3.00
Copel	MM	Plastic wood	2.40
Ohmax (soft)	MM	Clamped	2.05
Ohmax (hard)	MM	Clamped	3.22
Advance	MM	Clamped	2.25
Isoelastic	MM	Clamped	2.94
Isoelastic	MB	de Khotinsky cement	3.47
Advance	M	Clamped	1.98
Isoelastic	M	Clamped	2.92
Monel	M	Clamped	1.92
Advance	B	de Khotinsky cement	1.94
Isoelastic	B	de Khotinsky cement	2.82
Manganin	B	de Khotinsky cement	.69
1-percent Mn-nickel	Shellac	Shellac	-1.16

It is seen that the strain sensitivity of a wire is affected only to a small degree by the type of plastic mount. The difference is probably less than appears from the table, since the data near the foot of the table represents the results of earlier, less accurate tests. With the exception of advance and monel wires, the strain sensitivities lie outside the values of 1.6 and 2.0 given by the simple theory; manganin has a small positive value and the nickel alloy a negative value.

TABLE IIIa

Wires Used in This Research

Wire	Supplied by	Remarks
Nichrome	Driver-Harris Company	Hard
Manganin	Driver-Harris Company	Hard
Advance	Driver-Harris Company	Hard and soft specimens
Ohmax	Driver-Harris Company	Hard and soft specimens
Copel	Hoskins Mfg. Company	Hard
1-percent Mn-nickel	Hoskins Mfg. Company	Hard
Monel	Alloy Metal Wire Company	-
Isoelastic	Chattilon & Sons, Ltd.	-

Wires in Series and Parallel

In temperature-compensated gages it is necessary to place different wires in series or parallel in order to obtain compensation. It is possible to compute the strain sensitivity of the combination, knowing the strain sensitivities of the individual wires in the type of mount concerned. Let one wire be of resistance R and sensitivity S, and the other wire resistance R' and sensitivity S'. Then if the wires are connected in series the over-all strain sensitivity is

$$S_{series} = \frac{RS + R'S'}{R + R'} = \frac{RR'}{R + R'}\left[\frac{S}{R'} + \frac{S'}{R}\right] \qquad (2)$$

and if the wires are in parallel, this equation becomes

$$S_{parallel} = \frac{RR'}{R + R'}\left[\frac{S}{R} + \frac{S'}{R'}\right] \qquad (3)$$

It will be shown later that, if a compensated gage is made by connecting a wire with a positive temperature coefficient of resistance with a wire with a negative coefficient, the strain sensitivity will be the same whether the wires be connected in shunt or in series.

Table IV gives the computed and measured resistances and strain sensitivities of two gages embodying a copel and a nichrome wire in parallel, embedded in paper-laminated Bakelite.

TABLE IV

Computed and Experimentally Determined Strain Sensitivities

Gage	Resistance, ohms		Strain sensitivity	
	Computed	Measured	Computed	Measured
PB 6	22.95	23.0	2.51	2.54
PB 8	24.5	24.3	2.47	2.47

TEMPERATURE COMPENSATION

Temperature-Resistance Properties

The second problem attacked in the present investigation is that of temperature compensation. To this end many temperature-resistance tests of both free wires and wires molded in to form gages were made. The following conclusions were obtained.

(a) The temperature-resistance curve of a bare wire is a straight line. No hysteresis is evident between the heating-up and cooling-down paths. It was confirmed that constantan and manganin wires have nearly zero temperature coefficients of resistance and that ohmax wire has a negative coefficient.

(b) Normally, the temperature-resistance curve of a wire molded into a plastic is a straight line without hysteresis. This result is true if the "gage" be tested either free or clamped or cemented to steel or to duralumin.

Advance and ohmax wires are exceptions to this rule; it appears that the molding or casting temperature is sufficient to cause a structural change in these wires. After these wires are cast in Lucite by heating to about 60° C. for 3 days, the temperature-resistance relationship consists of nonlinear curves forming large hysteresis loops between heating-up and cooling-down paths. These wires molded into Lucite in the shortest possible time give linear temperature-resistance curves without hysteresis. Slight increases in molding time seriously affect the value of temperature coefficient of resistance. A further slight increase produces gages which give hysteresis loops on tracing thermal cycles. Hence, advance and ohmax, which appear the most promising wires for making temperature-compensated gages, must be abandoned.

(c) Where the behavior of a molded-in wire with temperature is normal, the strain and temperature effects appear to be independent.

Methods of construction of temperature-compensated gages will be considered and, subsequently, the independence of the strain and thermal effects.

Construction of Temperature-Compensated Gages

Under the heading of temperature-compensated gages will be considered the possible methods of temperature compensation, the theory of design of each method, and the degree of success which has been obtained. The following symbols will be used:

β, temperature coefficient of resistance of a wire molded in a gage.

β_1, temperature coefficient of a wire (or combination of wires) in a gage, clamped or cemented to steel.

β_2, temperature coefficient of a wire, clamped or cemented to duralumin.

α_r, α_s, α_d, coefficient of linear expansion of resin, steel, and dural, respectively.

P_1, P_2, stress equivalent of temperature, steel, and duralumin, respectively.

Stress Equivalent of Temperature

The stress equivalent of temperature is the over-all measure of the exactness of temperature compensation of a gage. The stress equivalent of temperature in steel P_1 is defined as that stress in a steel bar to which the gage is attached necessary to cause the same increase in resistance of the gage as would 1° C. rise of temperature.

$$\text{Hence} \quad \frac{P_1 S}{E} = \beta_1 \quad \text{or} \quad P_1 = (30\ \beta_1 \times 10^6)/S$$

$$\text{and} \quad P_2 = (12\ \beta_2 \times 10^6)/S \qquad (4)$$

A strain gage of the Tuckerman or Huggenberger type (made in steel) is not temperature-compensated when attached to duralumin; the value of P_2 for these gages is $(25 - 11) \times 12 = 168$ pounds per square inch. In this work a value of ±100 pounds per square inch for P_1 or P_2 has been regarded as the outside permissible value, though it has been possible to obtain without difficulty values about ±10 pounds per square inch per °C.

The following are the possible methods of construction:

(a) By embedding a single wire in the plastic material.

(b) By embedding two parallel wires, connected in series or in parallel, one with a positive and one with a negative temperature coefficient of resistance.

(c) Using one kind of wire, part lying along the length of the gage and part disposed at right angles.

(d) By embedding a wire with negative strain sensitivity together with wires with positive strain sensitivity.

Method (b) has been successfully worked out. Method (c) is now a possible solution. Method (a) might give

success after a prolonged investigation of suitable materials. Method (d) is virtually unworkable. The experimental results supporting these conclusions are now given.

Single Wire in Plastic Material

It was hoped that advance wire (constantan type) when embedded in resin and cemented to steel would have a very low temperature coefficient of resistance and would therefore act as a temperature-compensated gage. As previously mentioned, it was found that the temperature coefficient of resistance of such a gage was very variable, depending critically on the molding conditions. Hysteresis looping in the temperature-resistance characteristic arose on molding for a slightly longer time or on casting.

Of all the many wires tested, the only one found to be anywhere nearly compensated was copel wire. This wire was found to have a negative temperature coefficient of resistance. The following data were obtained with gages consisting of copel wires embedded in Lucite and in paper-laminated Bakelite, cemented to duralumin.

TABLE V

Copel Gages: Dural

Gage	Resin	Temperature coefficient cemented to dural β_2	Strain sensitivity S	Stress equivalent of temperature P_2 (lb./sq. in.)
MM 17	Lucite	-37.4	2.40	-187
PB 4	Bakelite	-55.2	2.38	-278

The simple copel gage is therefore not sufficiently closely compensated to be of any use.

This method might be made to work by baking a suitable wire, such as isoelastic, nichrome, copel, etc., and heat-treating this wire. It might be possible to adjust

the temperature coefficient of resistance by suitable baking to values that are nearly zero when the wire is molded into a plastic mount and cemented to steel or duralumin.

Wires with Positive and Negative Temperature Coefficients

Another method requires two types of wire, one of which must have a small negative temperature coefficient of resistance and the other a small positive coefficient. The stipulation of small values of coefficient is made so that slight errors in the construction of the gage will not cause serious errors in temperature compensation.

Ohmax was first used for the negative component. It was found that slight prolongation of molding time produced temperature-resistance hysteresis. Ohmax has to be welded, and the spot-welding of exact lengths of fine ohmax wire to nickel gauze is a rather difficult operation. Subsequently, copel was found to have a negative temperature coefficient of resistance, smaller than that of ohmax, and the wire could be easily soldered. Copel was therefore chosen for the negative component. Table VI gives the necessary data for copel molded in Bakelite and in Lucite for steel and for duralumin.

TABLE VI

Resin	Temperature coefficient of resistance		Stress equivalent of temperature (lb./sq. in.)	
	On steel β_1	On dural β_2	On steel P_1	On dural P_2
Bakelite (laminated)	-76.3	-55.2	-962	-278
Lucite	-62.2	-37.4	-777	-187

For the wire with positive coefficient, Nichrome was chosen, since it had the lowest coefficient. Advance was ruled out owing to its erratic behavior and manganin, owing to its low strain sensitivity. The following table shows how Nichrome compares with other wires.

TABLE VII

Characteristics of Wires with Positive Temperature Coefficients

Wire	Resin	Gage cemented to steel		Gage cemented to dural	
		Temperature coefficient β_1	Stress equivalent P_1	Temperature coefficient β_2	Stress equivalent P_2
Nichrome	Bakelite (laminated)	182	1,910	222	932
Isoelastic	Lucite	523	5,340	-	-
Monel	Lucite	502	7,840	-	-
C-steel (piano wire)	Lucite	2,890	34,600	-	-

Design of Nichrome-Copel Compensated Gages

Enough data are now available to design temperature-compensated gages. Let the resistances of the required lengths of copel and nichrome wire be R and R', respectively, the temperature coefficients, cemented to steel, be β_1 and β_1', respectively, and the strain sensitivities S and S'.

Wires in parallel.- If the temperature rises t° C. the resistance of the gage, with wires in parallel, rises from

$$\frac{RR'}{R + R'} \quad \text{to} \quad \frac{RR'(1 + \beta_1 t)(1 + \beta_1' t)}{R + R' + t(R\,\beta_1 + R'\,\beta_1')}$$

The condition for temperature compensation is that this increase be zero, hence

$$R\,\beta_1' + R'\,\beta_1 = 0$$

or

$$\frac{R}{R'} = \frac{-\beta_1}{\beta_1'} \tag{5}$$

This is the condition for temperature compensation on steel, when the wires are placed in parallel. For compensation on duralumin, the condition becomes

$$\frac{R}{R'} = \frac{-\beta_2}{B_2'} \tag{6}$$

Under these conditions, the over-all strain sensitivity of the gage (equation (3)) becomes

$$S_{parallel} = \frac{\beta_1 S' - \beta_1' S}{\beta_1 - \beta_1'} \quad \text{for steel} \tag{7}$$

$$S_{parallel} = \frac{\beta_2 S' - \beta_2' S}{\beta_2 - \beta_2'} \quad \text{for dural} \tag{8}$$

Thus the strain sensitivity of the compensated gage lies between the strain sensitivities of the component wires. The sensitivity of the steel gage is slightly different from that of the dural gage.

Wires in series.- The condition for temperature compensation on steel with wires in series becomes

$$\frac{R}{R'} = \frac{-\beta_1'}{\beta_1} \tag{9}$$

The strain sensitivity is the same as for parallel connection. The choice of series or parallel connection is determined by the relative lengths of wire required.

Nichrome-Copel Gage for Steel

The specimens used had the following resistances per foot:

Wire	Diameter (in.)	Resistance (ohms per ft.)
Nichrome	0.001	680
Copel	.0015	136

The ratio of the length of Nichrome to copel wire can now be computed. For series connection, compensation on steel, this ratio is 8.4 percent. For parallel connection, compensation on steel, the computed ratio is 47.7 percent. For compensation on dural it is 80.6 percent. Hence, for the wires available, the parallel arrangement was chosen as being the more suitable.

When the wires are about the same length, the characteristics of a gage change only slowly with slight changes in ratio, assuming that the temperature coefficients of resistance of the wires do not vary from gage to gage. The first few gages, made before correct data had been obtained, possessed length ratios of Nichrome to copel of 53 percent (for steel) and of 73 percent (for dural). Table VIII gives the characteristics, computed from later data, for some of these early gages.

TABLE VIII

Comparison of Computed and Measured Properties of Nichrome-Copel Gages

Gage No.	Compensated for	Nichrome-copel length ratio (percent)	Temperature coefficient of resistance, cemented		Stress equivalent measured (lb./sq. in.)
			Computed	Measured	
PB 5	Steel	57	-7.30	-10.0	-122
PB 10	Steel	56	-8.23	-10.2	-125
PB 8	Dural	73	+4.52	+2.94	+14.3

The computed data will be observed to agree well with the measured data and, in spite of the wide difference between the correct length ratios for compensation and the ratios given, the degree of compensation is quite good, especially in the case of specimen PB 8. The length ratio does not therefore appear to be critical. Gages are now being made with the length ratios given in table VIII. Difficulties are, however, being experienced in assessing the stress equivalent with the present equipment.

It is suspected, however, that there may be some variability in the characteristics of the wires after molding in. The molding temperature (140° C. for 15 minutes) might

have some effect on the complex alloys used, so that slightly different molding times might produce appreciably different temperature coefficients. The coefficient of expansion of laminated Bakelite is about 30×10^{-6} per °C., i.e., slightly greater than that of duralumin. Hence, in the cooling down of the gage after completing the molding, a linear compressive strain in the wire of about 0.002 inch per inch is to be expected. It might be possible that the compressive strain suffered by the wire on cooling be of a hydrostatic nature and therefore has no large effect on the properties of the wire.

Other Aspects of Two-Wire Gages

A gage of two-wire type may be temperature-compensated as closely as is desired by means of external resistances. In the series type, the predominating resistance is shunted by a resistance external to the gage; this resistance might be a small coil of constantan wire lightly cemented to the surface of the gage. In the parallel wire type, the resistance is placed in series with one of the wires.

In this way it could be possible to make a gage designed, say, to be compensated on dural to be compensated also on steel. Such a gage, when cemented directly to steel, would have a temperature coefficient of the order of -35×10^{-6} per °C., corresponding to $P_1 = -450$ pounds per square inch per degree. This value can be made zero by placing a resistance in series with the copel wire.

Compensation in this manner is very difficult, since the required resistance is very critical and has to be determined by trial. Figure 14 shows the results of tests on a copel-advance gage molded in Lucite, containing a copel wire of 29.9 ohms resistance (the negative component) in series with an advance wire of 23.0 ohms resistance. This gage, when clamped to duralumin, was found to be very nearly perfectly compensated for temperature. When clamped to steel it had a temperature coefficient of resistance of $\beta_1 = -27.6 \times 10^{-6}$, corresponding to a stress equivalent of $P_1 = -340$ pounds per square inch in steel. Tests were made using different values of external resistance in shunt with the copel wire. Figure 14 shows the observed values of β_1, the computed values of S and the values of P_1 for different values of the external resistance. It is observed that P_1 varies rapidly in the region near where $P_1 = 0$.

It is possible, however, to arrange a gage compensated for both steel and duralumin, for example, by having a tap in the nichrome wire in the nichrome-copel design. If part of the nichrome wire is shortened so that its effective length is reduced from 81 percent to 48 percent of that of the copel wire, a "dural" gage is then compensated for steel.

Self-Compensating Gage

If a gage be constructed of a length of wire of resistance R_1 lying along the length of the gage, and of a length of the same wire of resistance R_2 arranged at right angles to the length of the gage, then this gage should measure the difference in strains along and at right angles to the axis of the gage. These resistances form adjacent arms of a Wheatstone bridge (fig. 15). If, for example, the gage be cemented to a bar subjected to a simple tension strain e, then the resistances will change to

$$R_1(1 + Se) \quad \text{and} \quad R_2(1 - S\sigma e)$$

Hence the ratio changes from

$$\frac{R_1}{R_2} \quad \text{to} \quad \frac{R_2}{R_2}\left[1 + S(1 + \sigma)e\right]$$

The deflection is therefore linear with strain. Such a gage should be self-compensated, for, if the resistances in the gage be heated, these will increase in the same proportion and hence the ratio of the arms will not be changed; temperature effects will thus cause no deflection of the galvanometer.

Much effort was expended in the earlier stages of the research to make compensated gages in this manner, using cast Bakelite and cast and molded Lucite for the mount. It was not found possible to cement these early, comparatively thick, gages effectively in the lateral direction. This method of construction might be successful, using the present 0.010 inch thick bakelite gages.

Gage with Negatively Strain-Sensitive Wire

The negatively strain-sensitive wire type of gage would contain three types of wire, joined in series. One wire would be the wire of negative strain sensitivity forming one arm of the bridge. The other two wires would be in an adjacent arm and would be arranged to have the same over-all temperature coefficient of resistance as the negatively strain-sensitive wire. In this way, the strain effects of the wires would reinforce each other, and the thermal effects would counterbalance. The wires of negative strain sensitivity appear to have extremely high temperature coefficients of resistance (e.g., for 1-percent Mn nickel $\beta = 2440 \times 10^{-6}$ per °C.) rendering this method impossible.

Measurement of Temperature Coefficient of Resistance

Changes of resistance with temperature were obtained by heating the specimen slowly (6° C. per hour) in a well-stirred oil bath, the temperatures being read on a thermometer graduated in tenths of degrees Centigrade. Figure 16 shows the apparatus arranged for a thermal test. On the electrical side, the arrangement was the same as for the strain tests. It has been mentioned that, with the commercial bridges used in most of the tests, a change in resistance in a gage of 25 ohms of about three parts per million can be detected. Though this sensitivity is ample for strain measurements, it is too low to assess accurately the degree of compensation of the recent gages. Better apparatus is being consequently designed for this purpose.

Independence of Strain and Temperature Effects

The theory of temperature compensation of wire strain gages presupposes that the effects of temperature and of strain on resistance are independent, in other words, that gages compensated at zero strain are compensated for temperature also when under load. This fact could be checked by cementing a temperature-compensated gage to a bar, placing the bar in bending, and making a thermal test on the gage. This method has not yet been tried. If a gage be cemented (or clamped) first to steel, then to dural, and finally left free, and if a thermal test be made on the gage in each state, the temperature coefficients obtained in each case should be related by a simple law. This law has been checked on a few occasions and has been

found to be reasonably true. The theory and data are given in the following paragraphs.

Consider a fine wire embedded in synthetic resin, in the form of an experimental gage. When such a gage is heated, it expands linearly at a rate given by the coefficient of expansion of the resin, since compared to that of the resin the cross-sectional area of the wire is negligible. The coefficient of expansion of resins is much greater than that of metallic wires. Some values are given in table IX.

TABLE IX

Resin	Coefficient of linear expansion per °C. $\alpha_r \times 10^6$
Bakelite (laminated paper)	30
Bakelite (cast)	60
Lucite	70

Hence on heating the gage, the wire is stretched elastically by the resin. It would thus be expected that the temperature coefficient of resistance of the wire when embedded in resin would be greater than that of the free wire. Furthermore, if the gage be firmly cemented to a metal bar, and so constrained to expand thermally at the same rate as the bar, the temperature coefficient of resistance of the cemented gage would be expected to be dependent on the coefficient of expansion of the bar.

Assume that the <u>lateral</u> strain of the gage has no effect on the resistance of the wire. Consider two identical gages, one firmly cemented to a steel bar and the other free. Let both be heated through 1° C. Let the steel bar be now stretched so that the total increase in length of its gage, due to temperature and strain, is the same as the increase in length of the free specimen. If the lateral restraint of the cemented gage can be neglected, the gages are under identical conditions, hence the increases in resistance must be the same. The increase in resistance of the cemented gage is then $R\ \beta_1$

(where R is the gage resistance) owing to temperature rise of 1° C. and is $RS(\alpha_r - \alpha_s)$ owing to the subsequent strain, where the symbols are as previously defined. The increase in resistance of the free gage is $R\beta$, hence

$$\beta_1 + S(\alpha_r - \alpha_s) = \beta \tag{10}$$

If the cemented gage be attached to dural,

$$\beta_2 + S(\alpha_r - \alpha_d) = \beta$$

therefore,

$$\beta_2 - \beta_1 = (\alpha_d - \alpha_s)S \tag{11}$$

Taking $\alpha_d = 24 \times 10^{-6}$, $\alpha_s = 10 \times 10^{-6}$,

$$(\beta_2 - \beta_1)\ 10^6 = 14\ S \tag{12}$$

The following table gives some data collected during the course of the research on five gages, of which one is molded from laminated Bakelite, three molded in Lucite, and one cast in Bakelite.

The results of two of the five sets suggest that the temperature and the strain effects are independent and that lateral effects are negligible. The other three results might contain some incorrect data, yet they suggest that these conclusions are not true. For final confirmation, it is necessary therefore, as previously mentioned, to make a thermal test on a compensated gage under strain.

TABLE X

Thermal and Strain Data

Wire	Copel	Copel	Advance-copel	Ohmax	Isoelastic
Resin	Bakelite (laminated)	Lucite	Lucite	Lucite	Bakelite (cast)
Designation	PB 4	MM 17	MM 10	MM 4	B 4
$\beta \times 10^6$	-	-	-	51.4	603
$\beta_1 \times 10^6$	-76.3	-66.2	-27.6	-88.7	471
$\beta_2 \times 10^6$	-55.2	-37.4	-1.4	-57.6	515
S	2.38	2.40	2.44	2.22	2.82
$(\alpha_d - \alpha_s) \times 10^6$ (computed)	8.87	10.3	10.7	14.0	15.6
$\alpha_r \times 10^6$ (computed)	-	-	-	74	57
Method of attachment	de Khotinsky	Plastic wood	Clamped	Clamped	de Khotinsky

CEMENTING OF GAGES

A strain gage is essentially an instrument which can measure with sufficient accuracy the strain over any suitable gage length and which can readily be calibrated. It is therefore highly desirable for the resistance strain gage to be able to be firmly cemented to a metallic surface and also to be capable of removal for previous or subsequent calibration when necessary. This removability, and the property of individual calibration, differentiates the type under development from a nonremovable assembly of wires capable of measuring strain. This latter method has been shown by Professor Ruge of the Massachusetts Institute of Technology to work very successfully. By the use of a cement, such as celluloid dissolved in acetone, the mounting problem, and the effect of molding temperature and molding strains mentioned previously, do not exist. Nevertheless, it is felt that a gage which can, if necessary, be individually calibrated for strain sensitivity, temperature compensation, and maximum allowable strain and which can be shipped through the mail and attached by unskilled labor, is very desirable. The problem of cementing is therefore not the least important of the problems associated with the construction of electrical resistance strain gages.

Hot Cementing

De Khotinsky cement (hard grade) is a very satisfactory hot cement for laminated bakelite gages. The metal surface is heated to 135° C. and the cement spread on. The gage is then gently placed in position and the metal allowed to cool. The gage can be removed either by reheating the metal or by dissolving in alcohol.

Lucite gages cannot be attached by de Khotinsky cement, since at the required temperature they soften and warp, owing to the release of internal molding stresses. Likewise, de Khotinsky cement is difficult to use when the gage has to be attached to a large mass of duralumin such as a propeller blade. The great heat conductivity of duralumin and heat-treated aluminum alloys makes it difficult to obtain the proper local temperature without danger of overheating the metal and changing its strength characteristics. A cement that will set without elevated temperature, even though more time is required, is highly desirable.

De Khotinsky cement appears to be completely effective up to strains of 0.07 of 1 percent, which is the maximum strain used at present in the tests. In the strain tests on compensated gages (and under steady temperature conditions on uncompensated gages) readings at a given strain are almost identically reproducible when de Khotinsky cement is used; no creep is observable. (See table I and fig. 13.) To strain a bakelite gage 3/8 inch wide by 0.010 inch thick by an amount of 0.0007 inch per inch requires a pull of about 2.6 pounds. If the only area effective in cementing the gage is assumed to be a tab of about 0.14 square inch area beyond the terminal points of the wires, then the mean shear stress in the cement becomes about 20 pounds per square inch. There seems to be no reason why the laminated bakelite gage should not go up to strains of 0.2 of 1 percent, corresponding to a shear stress in the cement of about 60 pounds per square inch.

There is reason to suspect, however, that the successive heating and cooling of the gage involved in cementing and removal might affect its characteristics. This point is at present being investigated. Prolonged baking of the gage before calibration or use might overcome any such trouble.

Cold Cementing

The cold cements which have been studied are plastic wood, Duco, and casein cement. All these cements have been tried using various Lucite specimens. Their use with the laminated bakelite gages is now being studied. Plastic wood seems to be the best, having good adhesion to steel, duralumin, and Lucite. Table XI gives data obtained in a strain test on a Lucite gage with copel wire cemented to a steel bar with plastic wood. These results are plotted in figure 17.

TABLE XI

Strain Test on Gage MM 17: Copel Wire Molded in Lucite

Cemented with Plastic Wood to Steel

Gage resistance 69.4 ohms
[Galvanometer calibration 49.1 divisions = 1 ohm change in resistance]

Stress in steel (lb./sq. in.)	Galvanometer readings			
	First cycle		Second cycle	
	Load increasing	Load decreasing	Load increasing	Load decreasing
4,267	5.60	5.60		5.65
8,533	6.75	6.80	6.75	6.85
12,800	7.90	7.95	7.90	7.95
17,067	9.03	9.05	9.05	9.06
21,333	10.20		10.23	

A slight hysteresis is observed in the readings; even so, the average width of the hysteresis loop corresponds to about 200 pounds per square inch or roughly 1 percent of the total stress range.

Bakelite gages attached with plastic wood may be quickly removed by soaking for a few minutes in acetone. Lucite gages cemented to steel may be removed by soaking for several hours in strong (20 percent) caustic soda. This method, of course, cannot be used for Lucite gages cemented to duralumin.

Casein cement seems to lack adhesion to steel and to attack duralumin, being alkaline. This difficulty can be overcome by interposing a layer of unsized paper cemented with Duco cement. Nevertheless, the adhesion to Bakelite and Lucite is poor, fairly wide hysteresis loops are produced, and creep is observable on loading. It seems possible that the cementing properties of the bakelite gage might be improved by using a sheet of plain instead of impregnated paper for the lowest sheet when the gages are

molded. Casein cement can be removed readily with caustic soda; though this cement does not attack Lucite or steel, it attacks dural and also the cellulosic filling of the bakelite gages.

One attempt using Duco with a Lucite gage was unsuccessful. This cement, together with cements of the urea-formaldehyde type (which are quick-setting) will be tried on the bakelite gages.

CONCLUDING REMARKS

1. A method of making electrical strain gages of the resistance type has been developed. Fine wires are molded into laminated Bakelite (paper filler). These gages are about 3 inches long by 3/8 inch wide by 0.010 inch thick. Temperature compensation is effected by having in series or parallel wires with positive and negative temperature coefficients of resistance. The proportions of the wires are different, in gages temperature-compensated for steel, from those in gages compensated for duralumin. These gages can be cemented to steel or duralumin with de Khotinsky cement.

2. It has been found that, in any given design, the properties of a gage are not always reproducible, and sometimes erratic results are obtained. These results might be due to overheating of the wires, overstraining of the wires on cooling the gage, imperfect cementing either of the wires in the gage or of the gage itself. The conditions under which gages with reproducible properties can be made are now being investigated. Cold-cementing methods, obviating repeated heating and cooling of the gage, are also being tried.

When the correct conditions have been established, it is proposed to make jigs for the production of temperature-compensated gages of about 250 ohms resistance. The applicability of these gages up to strains of 0.2 percent will be studied. It is proposed to use these gages on impact work. Short gage-length gages for work on stress concentrations are also being considered.

3. Temperature compensation requirements are such that the change in resistance due to temperature change is of a

smaller order than the change in resistance due to strain. This necessitates a much more sensitive apparatus for measuring resistance changes than is required for normal strain measurements. This necessity will require the design of a special bridge to give the maximum sensitivity with the given gage; also a more sensitive galvanometer will be required, and this galvanometer must be chosen with the desired characteristics.

For work in the field, low-resistance gages and deflection methods of measuring resistance changes are undesirable. In the first case, the resistance of long leads might be of the order of 0.5 ohm; a gage resistance of 250 ohms or more is therefore required. A copel-nichrome gage embodying four lengths of wire in a gage 1/2 inch wide and 3 inches long would have this resistance. The deflection method requires a long-scale, sensitive galvanometer, free from vibration, and also a constant voltage on the bridge.

A null method may be used by placing a high resistance in series with a decade box across the balancing arm of the bridge. Figure 18 shows an arrangement suitable for use with the multiratio bridge. In this example, the gage resistance is 25 ohms. The balancing resistance consists of the resistance R in the bridge and a shunting resistance r, the value of r consisting of a resistance of 5,000 ohms in series with a decade box variable in steps of 0.1 ohm. When the decade box reads zero and the resistance R is set to 263 ohms, the balancing resistance will then be about 250 ohms, which is the correct value for balance when the ratio of the ratio arms is 0.1. If now, the gage resistance be altered by say 1 part in a million, then to restore the galvanometer deflection to zero the balancing resistance must be altered by 1 part in a million by putting a resistance dr in the box in series with the 5,000-ohm resistance.

Hence,

$$\left(\frac{Rr}{R + r}\right)\frac{dr}{r^2} = 10^{-6}$$

or

$$dr = 0.1 \text{ ohm}$$

Hence, 0.1-ohm steps in the external-resistance box correspond to increases in gage resistance of 1 part in a million.

A null deflection method has two further advantages. The measured resistance is independent of voltage variations, and hence high-voltage "B" batteries can be used for supplying current. The only limitation is the permissible current and power dissipation in the gage and bridge circuit. The null deflection method also leads to the possibility of using an a.c. voltage on the bridge, an amplifier and oscillograph taking the place of the galvanometer; when no signal is recorded on the oscillograph, the bridge is balanced.

To summarize, the program of future work consists in standardizing and producing in quantity wire-type resistance strain gages as well as developing cold-cementing methods and methods of instrumentation suitable for use in the field.

Massachusetts Institute of Technology,
Cambridge, Mass., July 1939.

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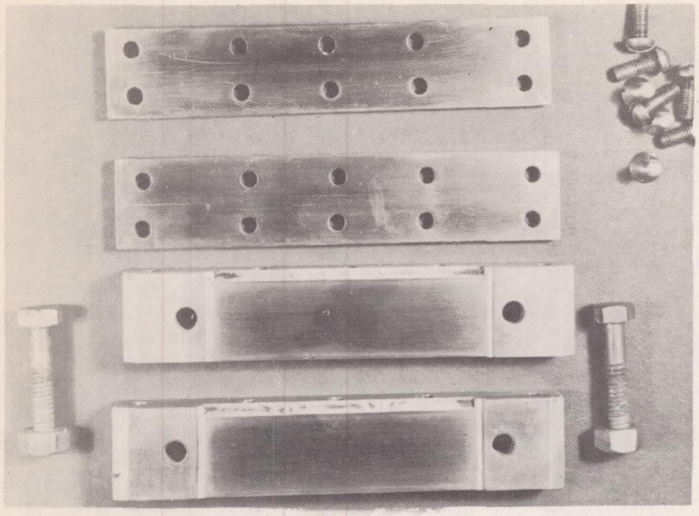
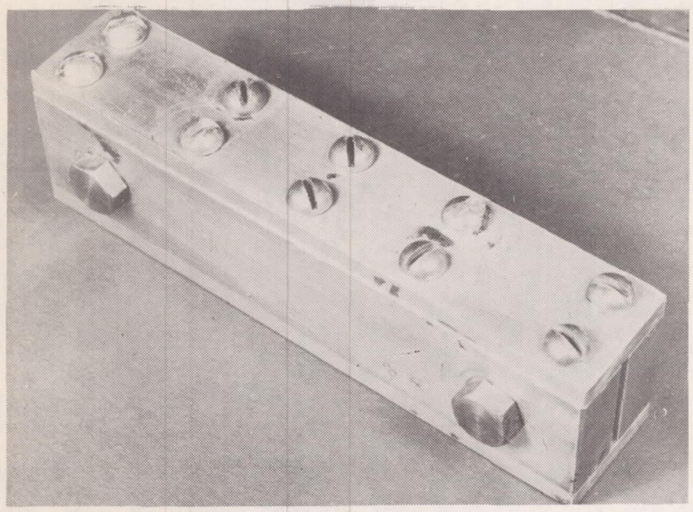


(a) Component parts



(b) Mold assembled.

Figure 1.- Casting mold for Lucite.

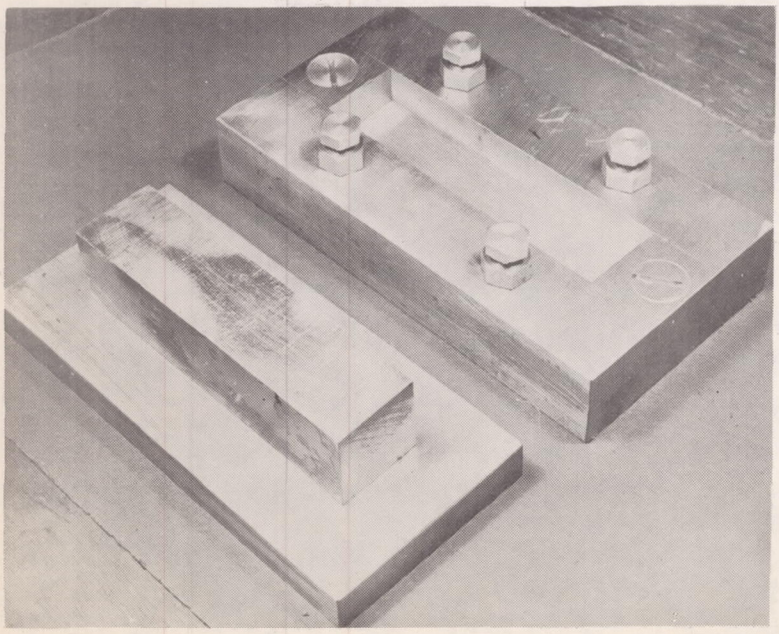


Figure 6.- Pressure mold for Lucite.

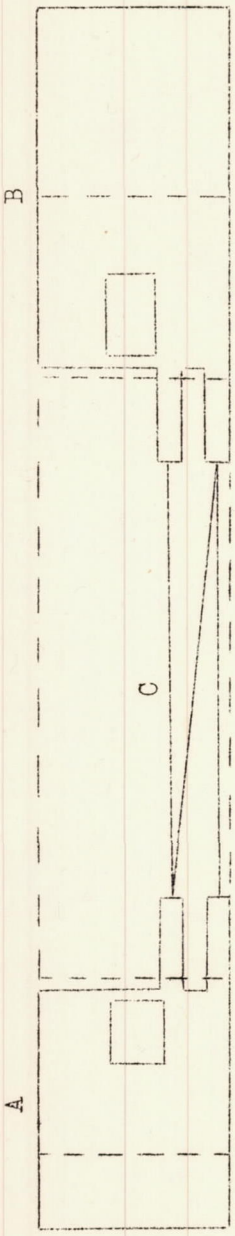


Figure 2

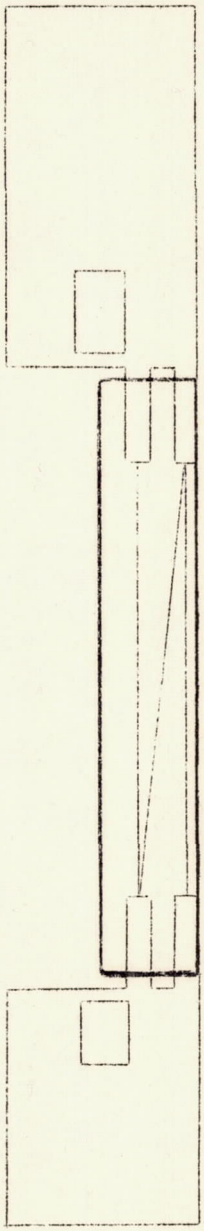


Figure 3

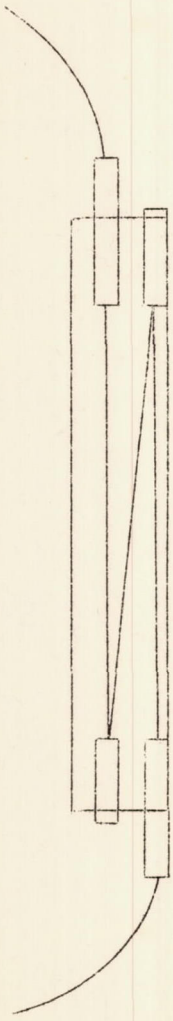


Figure 4

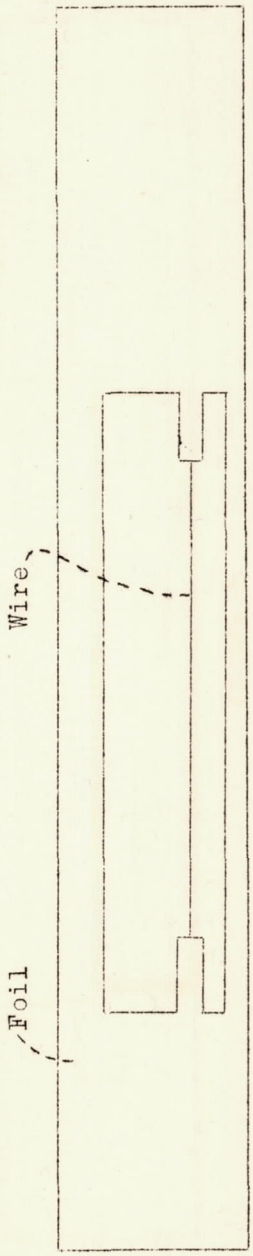
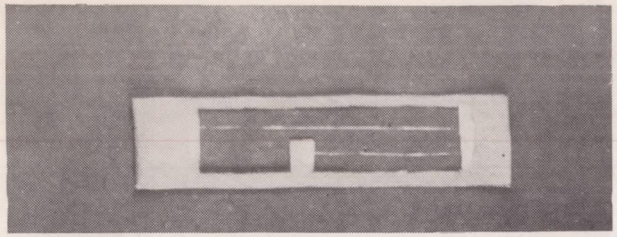
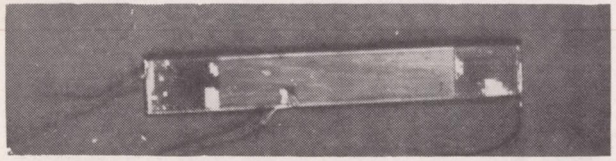


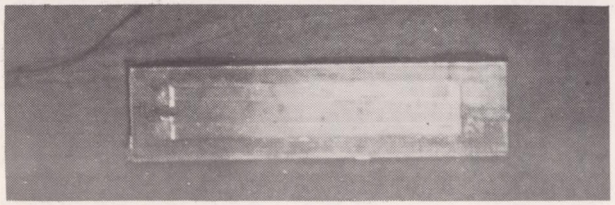
Figure 5



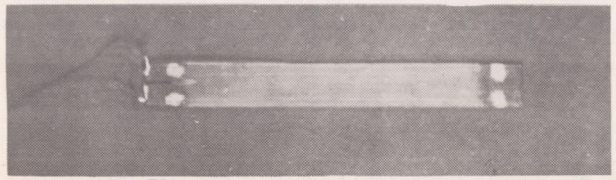
(a) Assembly for double-decker Lucite gage.



(b) Double-decker gage ready for use.

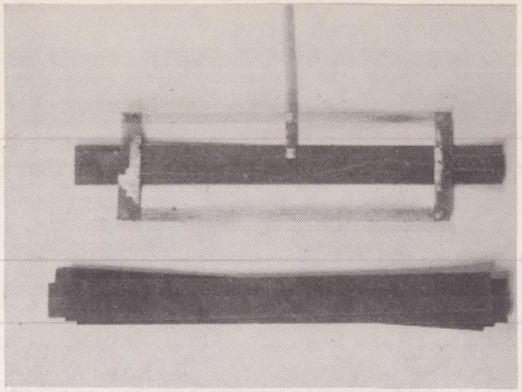


(c) Single-decker gage after removal from mold.

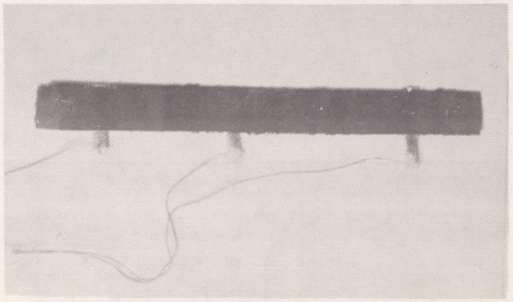


(d) Single-decker gage ready for use.

Figure 7.- Lucite Gages



(a) Assembly for laminated bakelite gage.



(b) Gage ready for use.

Figure 8.- Bakelite gages.

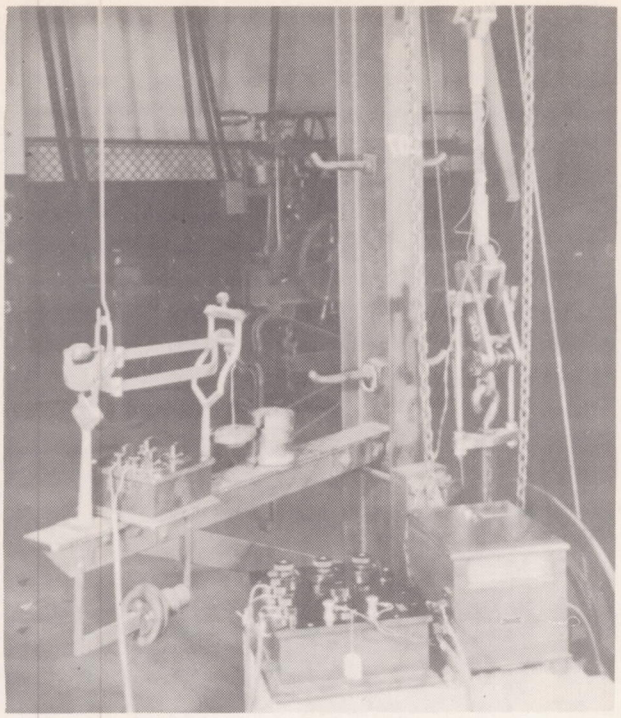


Figure 9.- Arrangement of apparatus for strain-resistance test.

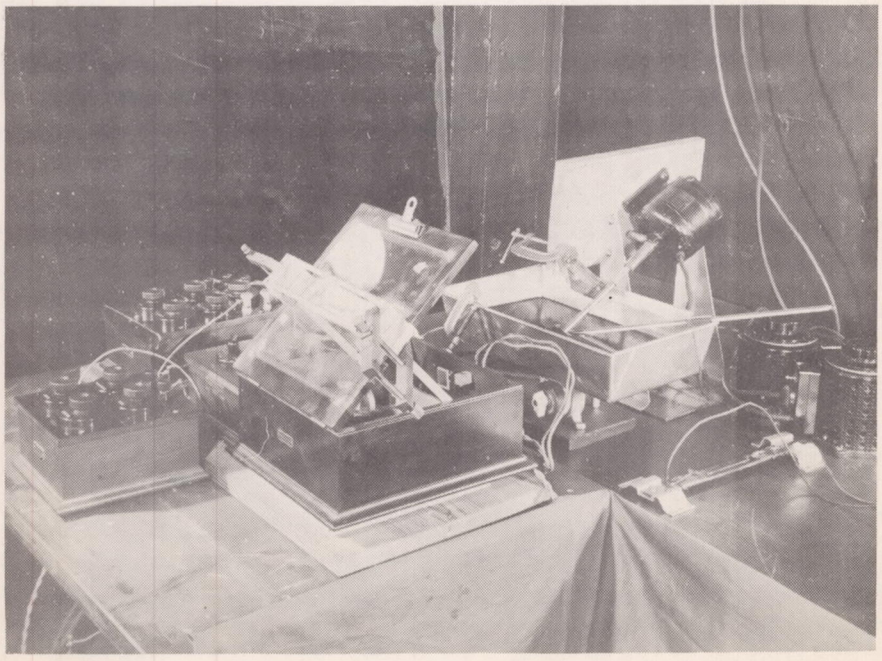


Figure 16.- Arrangement of apparatus for temperature-resistance test.

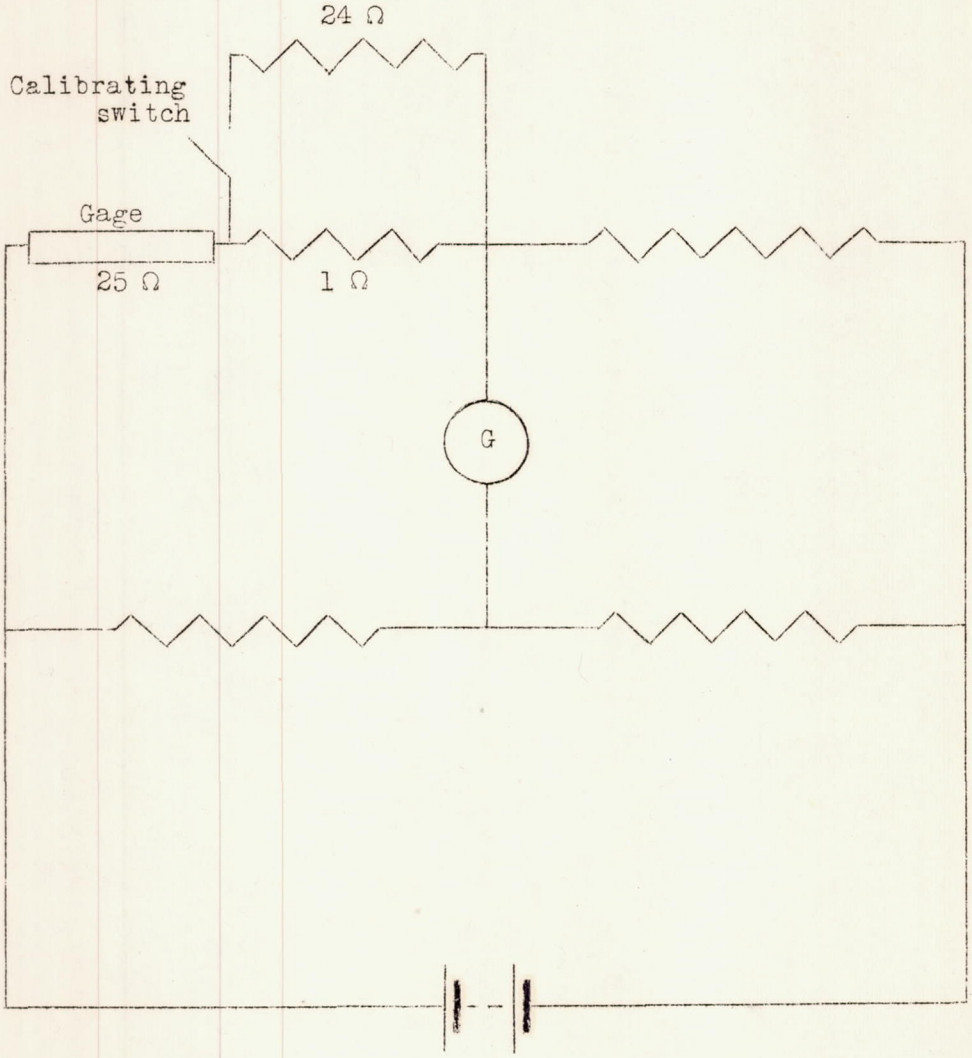


Figure 10.- Bridge for test on low resistance gage.

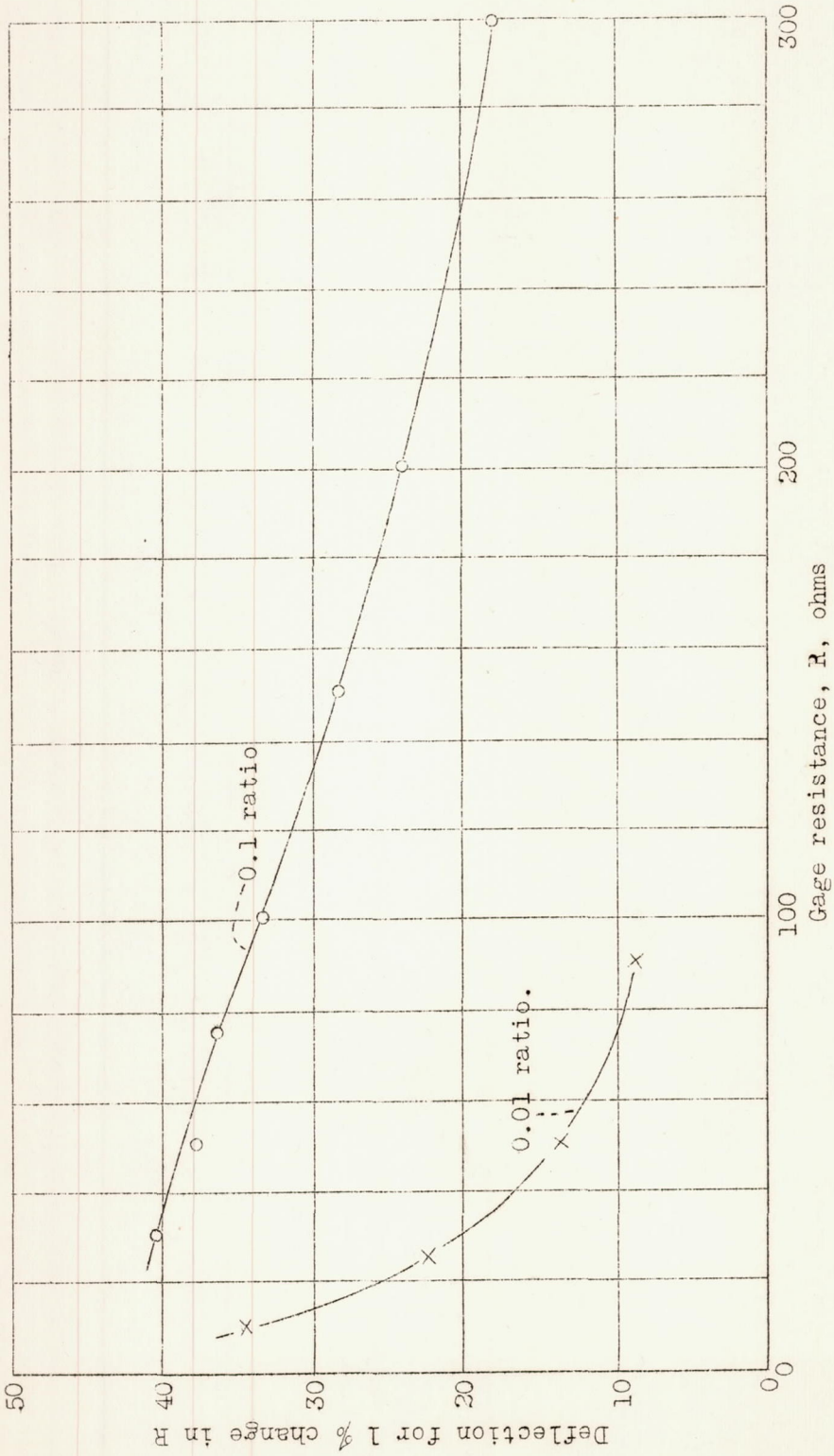


Figure 11.- Calibration for multiratio bridge.

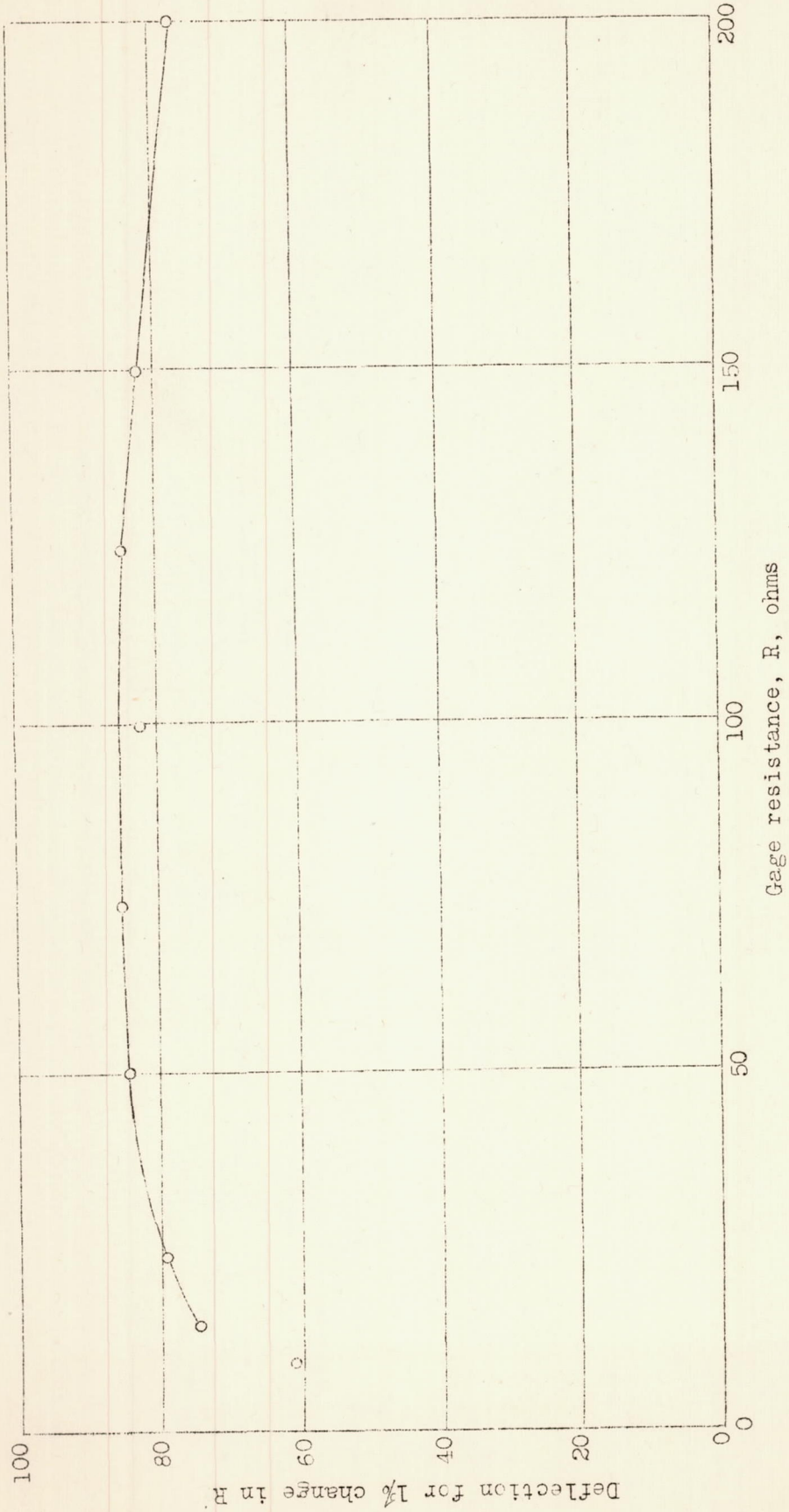


Figure 12.- Calibration of a variable-ratio bridge.

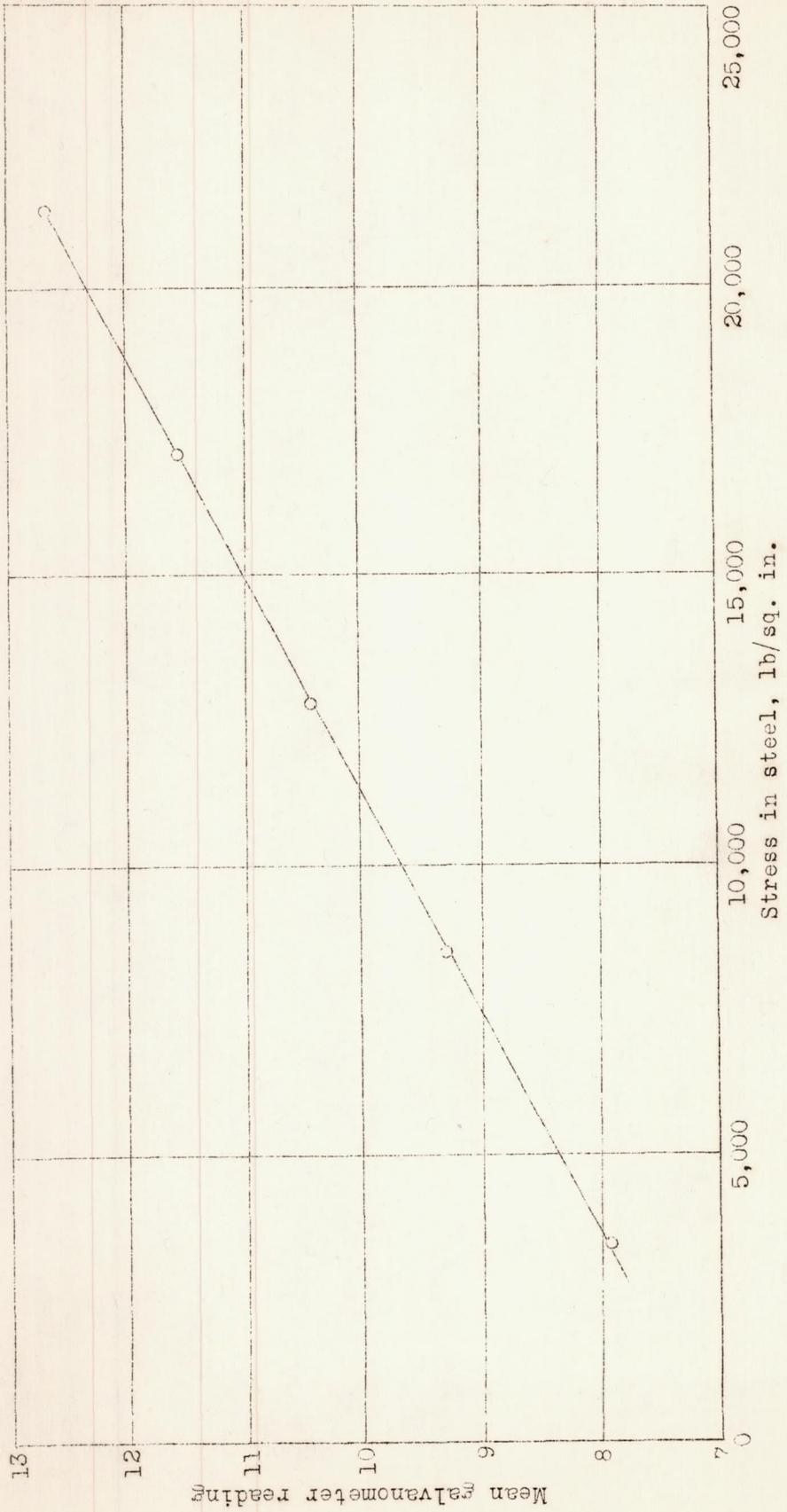


Figure 13.- Bakelite gage, de Khotinsky cement.

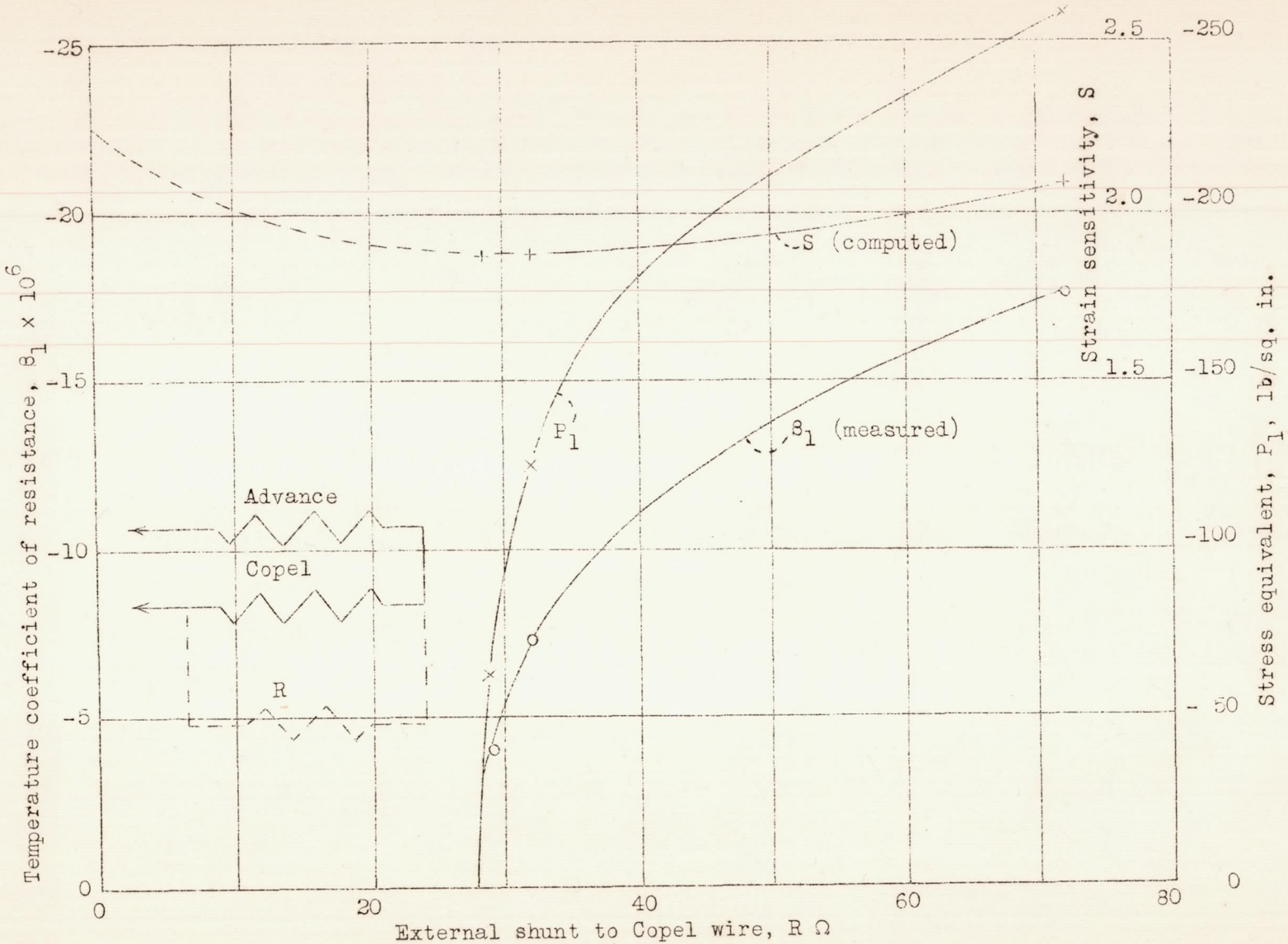


Figure 14.- Temperature compensation for Copel-advance gage.

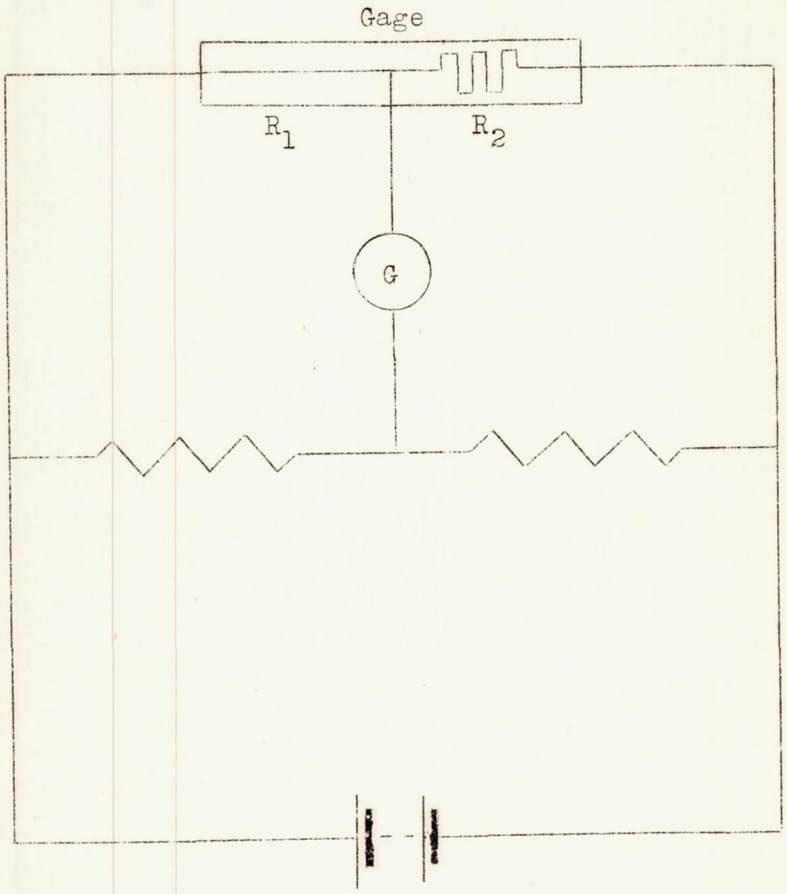


Figure 15.- Wheatstone bridge for self-compensating gage.

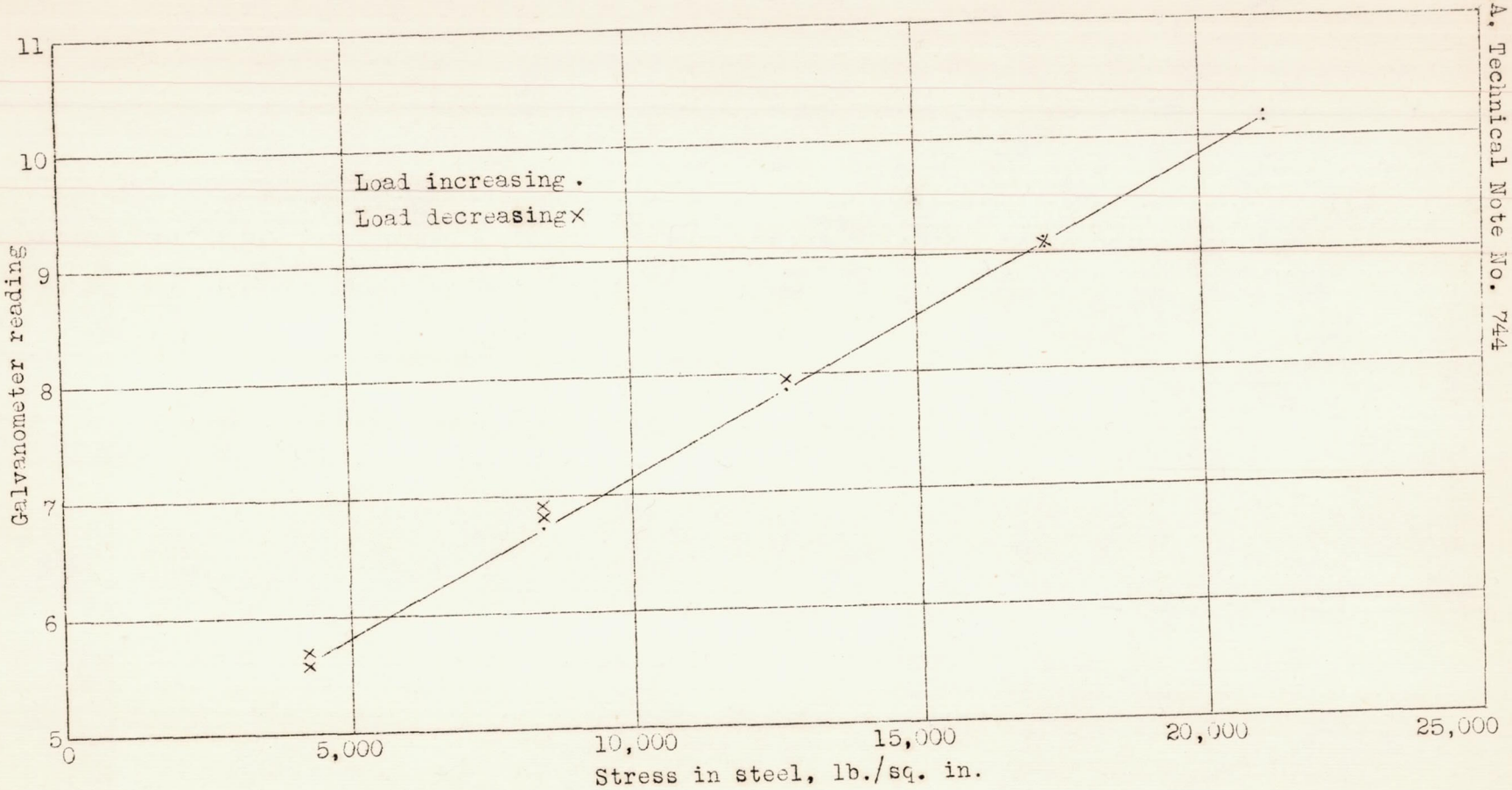


Figure 17.- Lucite gage, plastic wood cement.

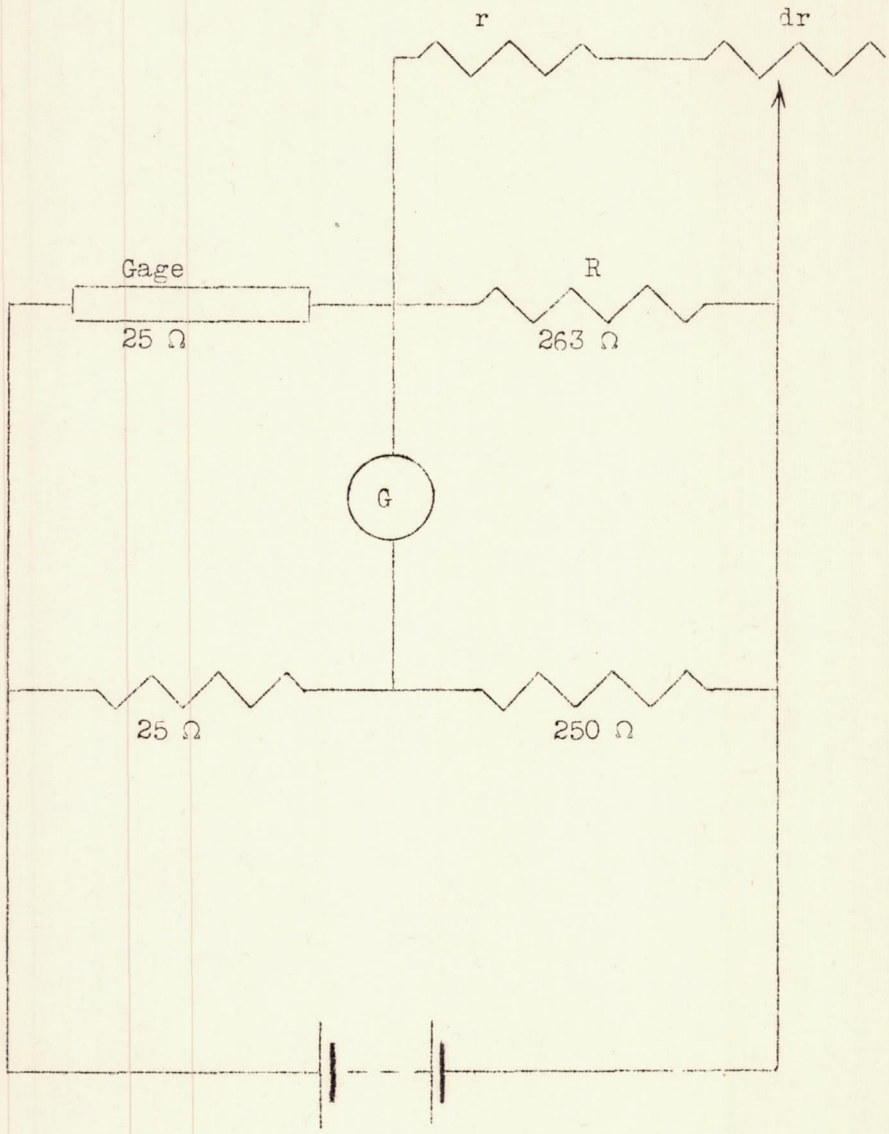


Figure 18.- An arrangement for a multiratio bridge.