I

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HIGH TEMPERATURE STRAIN GAGE RESEARCH

Summary Report

By
Francis G. Tatnall

January 25, 1955

Baldwin-Lima-Hamilton Corporation
Philadelphia, Pennsylvania

Technical Information Service, Oak Ridge, Tennessee

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Subject Category, INSTRUMENTATION.

This is a joint report submitted in fulfillment of the following contracts: Contract NONR-845(00), Office of Naval Research, Navy Department, Washington 25, D. C. and Sub-Contract No. 513 (Under W-7405-eng-26), Carbide and Carbon Chemicals Company, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Francis G. Tatnall, Manager of Testing Research

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HIGH TEMPERATURE STRAIN GAGE RESEARCH

Summary Report

By Francis G. Tatnall

SPECIFICATION OF WORK

The Contractor (Baldwin-Lima-Hamilton Corporation) shall furnish the necessary personnel and facilities for and, in accordance with any instructions issued by the Scientific Officer or his authorized representative, shall *conduct research* in respect to the *development* of a *static strain measurement gage* which can be successfully *used at elevated temperatures*, such work to include, but not necessarily be limited to, a study of metals and bonding materials, their use and combination.

SCOPE OF WORK

The Subcontractor (Baldwin-Lima-Hamilton Corporation) shall supply the necessary services and facilities and will use its best efforts to *develop a bonded wire strain gage* for use at 1600°F. that will be stable for at least a thousand hours.

The Subcontractor (Baldwin-Lima-Hamilton Corporation) shall furnish five (5) copies of a quarterly progress report and five (5) copies of a final report containing its detailed findings and recommendations at the end of the period of performance.

The treatment of such other related problems as may be mutually agreed upon.

ACKNOWLEDGEMENT

For much technical assistance and aid in preparing this report, acknowledgment is accorded to Fred N. Singdale.

Mr. Singdale was not listed as a co-author of this report as a result of his complicated status which changed in mid-

stream from that of an independent sub-contractor on High Temperature Strain Gage Research to that of Senior Project Engineer for Baldwin-Lima-Hamilton Corporation in the same field.

INTRODUCTION

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HIGH TEMPERATURE STRAIN GAGE RESEARCH

I. HISTORICAL

The earliest information on high temperature strain gages came to the attention of the author of this report from OSRD Report No. 1871 (Heat-Resisting Metals for Gas Turbine Parts), dated October 1, 1943.

Mr. Howard Cross of Battelle Memorial Institute, who carried on this work, states that he became familiar with similar previous research by General Electric Company in which bonded strain gages of platinum wire and Sauereisen cement were used on a tuning fork to determine the damping capacity of heat-resisting material. This research at General Electric Company was carried on up to a temperature of 1200°F.

At Battelle, the tuning fork studies were carried up to 1500°F, at which temperature the bonded strain gages behaved inconsistently and were replaced by an optical method.

Mr. Cross believes that the General Electric explorations in the field can be traced back as far as late 1942.

The next information which came to the author's attention was a paper by Schabtach and Fehr, General Electric Company, Schenectady, N. Y., entitled, "Measurement Of The Damping Of Engineering Materials During Flexural Vibration At Elevated Temperatures". It was presented at the annual meeting of the A.S.M.E. in New York in 1943 and, later, appeared in the Journal of Applied Mechanics in June, 1944. From this date, the use of such gages for dynamic use spread slowly among those concerned with the manufacture of gas turbines.

The urgent and increasing need for gages to be used in static measurements at high temperatures spurred the research and investigations covered in this report.

II. PLAN OF REPORT

These investigations were carried on with funds provided by two contracts, namely:

Office of Naval Research, Contract No. NONR-845(00)
Carbide & Carbon Chemicals Co., Sub-Contract No. 513
under W-7405-Eng.-26.

Some of the investigations were financed by the Office of Naval Research while others were paid for, from the Carbide and Carbon Chemicals Co. subcontract. Of the total funds available, approximately two-thirds came from ONR and one-third from Carbide and Carbon Chemicals contract.

By combining the funds available from both contracts, there was sufficient support to finance eleven diversified investigations so as to approach the problem of high temperature strain gages from several directions.

In addition to the ten sponsored investigations which were maintained on a pay-as-you-go basis, there were also twenty-three individuals and organizations who contributed without cost to the project. These contributions of thoughtfully-proposed ideas, information, data, experience records or formal reports served, in great measure, to impart to the undertaking a comprehensive variety and completeness for which the director of the project is ex-

tremely grateful. A 24th contributor was the Baldwin-Lima-Hamilton Corporation, who administered and directed the project without fee for the two years of its duration.

At the end of this report is a list of the sponsored investigations and the names of all contributors. All reports contained in this book have been edited and condensed where possible. In some cases, the material for these reports has been compiled and written by the author from information supplied by the principals to whom the reports are attributed. The original reports and all pertinent notes have been retained in their original form and have been placed in a central reference file. This reference file may be opened to those who obtain approval from the sponsors. Included in this reference file, besides all written material, are the actual strain gages, gaged test bars and exhibits of materials and methods applicable to this work, as well as early gage forms which were superseded by later development.

III. PLAN OF THE INVESTIGATION

A deployed attack was decided upon which would seek out those who were known to be skilled in the strain gage art, to inspire those who accepted the challenge in a manner which would encourage enthusiastic and original thinking along any line which might yield a strain gage idea, a high temperature material, a process or technique, or data or experience of any kind whatever which could advance the project.

The goal itself was simply stated: "A strain measuring device of any kind which could be applied in the field and which would be stable under static load at 1600°F for 100 hours while exposed to a destructive environment, including radioactivity."

A secondary goal defined a static gage for service in the range of 600°F to 800°F as a desirable development because of the number of applications appearing in this range.

Many declined the invitation. Some later changed their minds after thinking it over. Still others, starting with one idea ended up with several.

Because of the limited duration of the contracts, and because the available funds had to be spread so thinly over so many investigations, all ideas appearing, at first, either workable or unworkable were accepted for study. The practical as well as the far-fetched ideas were rounded up and boiled down into a groundwork of good raw material for future refinement, as there was neither time nor money here to complete such refinement.

This was in contrast to the more conventional method of concentrating upon a few of the more practical and obvious approaches. Through such pre-occupation in a narrower field, there is too much danger of overlooking the more obscure but brilliant products of original thinking. An excess of material leaves something to discard as refinement progresses. Was not the bonded wire resistance strain gage itself the product of "attic inventing" and an ingenious expedient branded at first by many as "interest-

ing, if true"? The best in creative imagination has to be sought out and encouraged and progress must take place in an atmosphere of sustained interest and enthusiasm.

The areas covered by the search included United States, Canada and Great Britain, but old and new literature of all countries was studied by the contributors.

IV. ORGANIZATION OF THE REPORT

All reports and contributions are placed in five categories:

- Class A. Gages which may become available to government agencies.
- Class B. Gages which seem practical and are advanced to the point of evaluation and criticism.
- Class C. Gages which require a reasonable amount of additional development.
- Class D. Ideas providing material for possible future study.

Class E. Background data: Notes, references, materials, methods, techniques and pertinent information.

Reports which describe more than one type of gage are carried intact in the classification where the most advanced gage belongs. The editor hesitates to dismember a report simply to maintain the integrity of any classification.

V. FUTURE WORK

It is not claimed that gages, materials and methods described in this report have attained the ultimate project requirements or that some gages are ready for immediate application to structures in the field by those skilled in the art, or that they will serve under the combination of severe conditions toward which the study is directed.

What is reported here is exploration and groundwork, as a starting point for intense development when time and money are in greater supply.

FRANCIS G. TATNALL
Manager of Testing Research
Baldwin-Lima-Hamilton Corp.

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DEVELOPMENT OF HIGH TEMPERATURE STRAIN GAGES

SUBMITTED BY
FRED N. SINGDALE
2335 Sesmas Street
Duarte, California

AECU-3003

FOREWORD . . .

The following is a formal report of manufacturing procedures, instructions for application, and test data of four various types of high temperature strain gages which utilize ceramics in their manufacture.

This work is part of an effort initiated and coordinated by Mr. Francis G. Tatnall, Manager of Testing Research, Baldwin-Lima-Hamilton Corporation, as a means of eventually making available to industry a strain gage which will operate at temperatures of approximately 2000°F.

The period covered in this report extends from January, 1954, through May, 1954. The work was pursued in accordance with P.O. No. S-526085, Baldwin-Lima-Hamilton Corporation, Eddystone Division, Philadelphia 42, Penna., sub-contractor to Carbide and Carbon Chemicals Company, on Sub-Contract No. 513.

Due recognition and appreciation is extended to the following:

Mr. Hyman Leggett, 9302 Horley Ave., Downey, California, for his untiring efforts in behalf of the program.

California Metal Enameling Company, 6904 E. Slau-son Ave., Los Angeles, California, for making their laboratory facilities available for this work.

Mr. A. M. Bounds, Superior Tube Company, Norristown, Penna., for his part in making available samples of small diameter tubing for use in this work.

Mr. Robert Krueger, Unitek Corporation, 427 No. Halsted Avenue, Pasadena 8, California, for making available a Unimatic Model 1015 Weldmaster for use in this work.

INTRODUCTION

As a result of certain research and development work covered in a report entitled "Development Of High Temperature Strain Gages", by Fred N. Singdale, dated February 1, 1954, an order was issued calling for the furnishing of four various types of strain gages. These four types of gages are described as follows:

- a) Nichrome wire mounted on ceramic coated metal foil, capable of resisting oxidation and intergranular corrosion at elevated temperatures (1900°F). This gage is now known as the "Foil Backed Gage".
- b) Impregnated resistance material mounted on ceramic coated metal foil, capable of resisting oxidation and intergranular corrosion at elevated temperatures (1900°F). This gage is now known as the "Grid Type".

- c) Karma Alloy encased in "Singdale's Thermo-coat".

- d) Karma Alloy mounted on coated metal screen, capable of resisting oxidation and intergranular corrosion at elevated temperatures (1900°F).

As a result of information obtained after the original order was received, it became necessary to substitute nichrome wire for the Karma Alloy.

The methods for attachment of gages to the test component involves ceramics, Singdale's Thermocoat, and a spot welding technique.

PRELIMINARY EXPERIMENTAL WORK

Ceramic Coatings Made Into The Form Of Decals:

The initial approach for the experimental manufacturing of ceramic strain gages involved the use of ceramic decals.

A ceramic decal is made by applying a fire lacquer to simplex paper, and allowing it to dry, then screening a ceramic material suspended in fire lacquer onto the simplex paper. Fire lacquers are similar to lacquers used in painting. The fire lacquers are designed with a low flash point especially suited for use with ceramics since they will "burn-off" at approximately 600°F. These fire lacquers serve a purpose similar to the mucilage on the backs of postage stamps, in that they cause the decal to adhere to the surface to which it is applied prior to firing. Simplex paper is an ordinary stiff type paper characterized by a quality of extreme absorbency. When moistened with water, it carries the water to all parts of the opposite side at the same time. Simplex paper can be likened to an ordinary ink blotter. In this case, it is merely a backing for the fire lacquer and ceramic material.

The finished decal is used by wetting it with water, sliding the simplex paper away from the ceramic material, which then is caused to adhere to the surface desired by the action of the fire lacquer drying out, much like a wetted postage stamp. Since the ceramic material is suspended in fire lacquer, it is not affected by this brief immersion in water.

Three coatings were made into decals. These coatings are essentially lead borosilicates designed to mature at temperatures between 950°F and 1100°F, thus affording a broad firing range. The thermal coefficient of cubical expansion for all three coatings is approximately 400×10^{-7} cm/cm/°C. The coating adheres by virtue of its ability to absorb and react chemically with the oxide formed at maturing temperatures. The coating is designed to be applied in extremely thin layers and is not affected

by strains set up as a result of the difference in the coefficients of expansion between the ceramic coating and the metal.

Nichrome Wire Used In Combination With Decals To Form A "Decal Type Strain Gage":

The first attempt to manufacture a strain gage from this type of decal consisted of the application of a thin coat of fire lacquer on the surface of the decal. The fire lacquer coating was allowed to become tacky, at which time a strip of clean, uncoated .001" nichrome wire was placed on the tacky surface. After the fire lacquer dried, the under side of another decal of the same composition was placed over the first, by wetting the decal with water and sliding it off the simplex paper, thus forming a "super-decal". This decal then consisted of two layers of fire lacquer, two layers of coating suspended in fire lacquer, and nichrome wire. These components had one layer of simplex paper on the bottom to protect the adhesive side of the "super-decal". The decal was allowed to dry thoroughly so that a positive bond was made between the segments of the "super-decal".

The decal was soaked in water until the simplex paper was wetted enough to slide off. The decal was then placed on 18 gauge 321 stainless steel. All water was removed by gently applying pressure with a rubber roller, and ample time was allowed for thorough drying. Next, the decal was charred at 500°F for 3 minutes, after which the entire assembly was fired at 1100°F for 8 minutes.

The fired "super-decal" matured well but it was later found coatings LTA-0009B* and LTA-0002B matured with the best surface. Further experimentation showed these coatings had greater resistance to the common acids such as sulphuric, nitric, and hydrochloric. The nichrome wire adhered well to the ceramic coating, although the entire assembly was fragile as is true with all ceramic bonded material. The wire was checked at 6 volts for current leakage and none was found between the base metal and the wire.

Recognizing that this type of mounting was not practical in the firing stage, the next attempt involved the firing of the decals using localized heating. Two semi-circular nichrome-wound heating cores were wired in parallel for 110 volts. Refrasil insulation (woven spun silica) was wound around the outside to keep heat loss at a minimum. The assembled heating cores were placed over a mounted decal and the temperature rise was noted with a potentiometer. The mounted decal was fired at 1300°F (which is 200°F above the maturing temperature), to allow for the difference in temperature between the center of the core and that of the metal. After 12 minutes of firing, the decal did not mature because heat loss through the metal was excessive. Firing of the mounted decal using localized heating is an excellent approach, but techniques to prevent heat loss and more exact control of actual metal temperatures is essential.

Probably one of the main prerequisites for a ceramic coating used in a decal is its ability to heal itself through a lower viscosity at maturing temperatures. With this thought in mind, a new composition has been made and designated as LTA-0009C. This coating has additives as mill additions consisting of high lead oxide and boron oxide to form a lower maturing eutectic compound which also imparts a lower viscosity at maturing temperatures. Since coating LTA-0009C has been found to have excellent

workability and shows the best surface when fired, it will be used in place of LTA-0002B and LTA-0009B in future work.

"Decal Type Strain Gage", Used in Combination With Ceramic Coated Metal Foil To Form A "Foil-Backed Gage".

The use of .001" 302 stainless steel foil as a mounting base for a "super-decal" was tried. A coating of ceramic number XS-3* was applied to both faces of a foil and fired at 1850°F for 8½ minutes. Thickness of coating on each face was .0006". This particular coating possesses a dielectric strength of 150 volts per mil, thus making it useful as a strain gage component. The coefficient of thermal expansion of the coating is much less than that of 302 stainless steel, but it has the ability to bend and distort with the base metal without cracking because of its thin application. Decals of XS-3 ceramic coating were made and used to form a "super-decal". This method consisted of applying fire lacquer to one face of the coated stainless steel foil and applying the uncoated nichrome wire to the tacky surface. The fire lacquer was allowed to dry thoroughly, after which a decal of XS-3 was applied to the assembly. The entire assembly was allowed to dry thoroughly and then fired at 1850°F for 6 minutes.

This type of mount was not successful as the sudden exposure of the fire lacquer to 1850°F caused a violent flame which disturbed the bisque ceramic and the wire. Charring of the decal before firing was not successful as the thin ceramic coating was disturbed in charring.

The use of decals of XBH-18* mounted with nichrome wire on coated stainless steel foil, has since proven successful when heat was applied at the rate of 800°F per hour to a maximum temperature of 1850°F. Charring of the decal proved unnecessary and no disturbance of the encased wire was noted. Techniques were varied and improved until a more realistic approach was evolved. This approach, which appears to be the most plausible, consists of applying a lower-maturing ceramic coating, designated XBH-20, to properly prepared .003" 321 stainless steel foil. While preparing the foil, a ¼" border is left uncoated. The coating is applied at a thickness of .001" to .002" and fired at 1730°F for 9 minutes.

The use of decals on 2-S aluminum foil was explored. Aluminum foil was coated with LTA-0009C and fired at 980°F for four minutes. A "super-decal" of LTA-0009C was applied to the coated aluminum foil, charred and fired at 980°F for 3½ minutes. The same method was used on clean uncoated aluminum foil. Neither method was successful as charring disturbed the thin ceramic coating.

Aluminum foil, approximately 2" x 2", was folded in such a way that a surface ¼" by 2", was exposed with the longitudinal edge made into a Dutch edge to prevent current leakage. The assembly was coated with LTA-0009C and fired at 980°F for 6 minutes. Nichrome wire was wrapped around the fired assembly, sprayed with LTA-0009C so that the wire was coated, and the entire assembly

*LTA — Ceramics that mature at low temperatures; coded by California Metal Enameling Company, Los Angeles, California.

*XS — Ceramics that mature at high temperatures. Modified Solaramic, Solar Aircraft Company, San Diego, California.

*XBH — A modification of National Bureau of Standard high temperature coating A-418.

refired. The wire was checked for current leakage. It was found that no current leaked into the aluminum foil.

The use of screening pastes as a means of attaching nichrome wire to aluminum foil was investigated. Coating LTA-0009C was made into a screening paste using commercial low carbon squeegee oils. A block 2" x 2" was screened through silk and the wire deposited on the wet paste. Unfortunately this coating was too thin for the nichrome wire to adhere.

It was thought at this time that a change in firing technique would be advantageous. A "super-decal" was made utilizing LTA-0009C, then applied to 18 gauge 321 stainless steel. After thorough drying, the part was placed in the furnace at room temperature. The temperature of the furnace was increased at the rate of 200°F per hour until a temperature of 1000°F was reached. The assembly was allowed to cool slowly until room temperature was reached. This assembly shows the best surface and the wire is adhering firmly.

Foil Backed Gage

This gage is manufactured by preparing stainless steel foil (.001" thick), so that it might accommodate a special high temperature ceramic material, designated as XBH-18. This ceramic coating is used as an insulating bed for a strain gage grid formed from .001" nichrome wire. This gage is illustrated in Figs. 1 and 2.

Figure 1 — FOIL BACKED GAGE — Foil backed gage made with Decal of XBH-18. .001" nichrome wire encased as strain gage grid.

Steps followed in the manufacture of the Foil Backed Gage are:

Prepare stainless steel foil for coating by treating with various acids and wetting agents. This will create a micro-etch which is necessary for the proper adherence of the ceramic coating.

To further improve the adherence of the ceramic coating to the foil, an oxide is built up on the clean micro-etched surface by an additional acid dip and annealing.

Mask off both sides of the foil so that a border of uncoated foil will surround a coated area approximately $\frac{3}{4}$ " x $\frac{1}{2}$ ".

Coat foil on both sides by spraying with a ceramic designated as XBH-18. The foil should have a finished thickness (after firing) of between .0005" and .0007".

Dry coating at 190°F for approximately 10 minutes.

Strip masking from the foil.

Fire at 1840°F for approximately 9 minutes. A properly matured coating should possess a dielectric strength of 200 to 240 volts per mil of finished thickness.

Prepare a $2\frac{3}{4}$ " section of .001" nichrome wire attached to heavier leads by use of a Unimatic Stored Energy Spot Welding Unit*. This assembly is formed into a strain gage grid and sandwiched between decals of XBH-18. From

Figure 2 — FOIL BACKED GAGE — Foil back gage coated with XBH-18. .001" nichrome wire encased as a strain gage grid.

Fig. 3 it will be observed that $2\frac{3}{4}$ " of .001" nichrome wire will yield a resistance of approximately 140 ohms.

The prepared strain gage grid is attached to the strain gage bed by wetting the decal in plain cold water and sliding it off the simplex paper onto the coated foil. A drying period of from 8 to 24 hours is allowed prior to firing.

NOTE:- This step may be altered by laying the strain gage grid down directly on the coated bed. The wire is then coated with XBH-18 either by spraying or brushing. This approach appears to give more satisfactory results than the decal method but is more difficult to master.

Figure 3.

Fire the assembled strain gage at 1840°F by a graduated firing technique starting from ambient temperature.

*Unimatic Stored Energy Spot Welder, Manufactured by:— Unitek Corporation, Pasadena, California.

The Unimatic Weldmaster has been designed for the metal joining applications found in electronics, precision instruments, and related manufacturing fields. This unit incorporates the latest developments in stored energy welding equipment. The equipment is simple to operate and does not require trained personnel. It is anticipated that a light-weight portable unit, will eventually result from the strain gage work now in progress and be designed specifically for attachment of metal foil strain gages.

Graduated firing assures a slight charring of the volatile material in the decal and the continuous firing to maturity assures an undisturbed strain gage grid. (When following the alternate described in the note above, it is not necessary to follow the graduated firing technique. The gage may be immediately put into the furnace at a temperature of 1840°F and held at this temperature for approximately 9 minutes.)

Prepare gage for assembly to test component by removing excess oxidation from the stainless foil border.

Methods of attaching Foil Backed Gages to the test component may be varied. This problem has been approached during this work by only three methods. It is highly probable that other materials or methods are available with which the author is not at this time familiar. The three methods used during this work are:

1. Preparing the surface of the test specimen by sandblasting and removing all surface grease, oil, and scale. To this surface a suitable ceramic material is applied which will both mate with the ceramic coated foil and the metal of the test specimen. The gage is laid over this coated area, pressed down, and dried in. The assembly is then fired until the ceramic coating matures.

This method has definite possibilities but is difficult to master. Another disadvantage is the undesirable feature of heating the test assembly to extreme temperatures such as 1500°F to 1800°F. Future refinements of this method could prove it more attractive than at present.

2. The second method of attachment, which has many attractive aspects, involves the use of an air hardening material, designated "Singdale's Thermocoat". The surface of the test specimen is prepared as in Method I and Thermocoat is spotted in the center on the back of the strain gage. The gage is then laid down wherever desired on the test specimen. The edges of the strain gage are held up so that a free circulation of air will surround the Thermocoat, meanwhile a slight pressure is applied on the center of the gage with the finger. Warm air blowing across the gage will hasten the drying period to approximately 3 to 5 minutes. After drying, and when there is evidence that the gage is held fast, Thermocoat is applied to the edges of the gage and a similar procedure followed. It is desirable to coat all around the edges of the gage as an added precaution. Place the gage in a drying oven at 150°F for approximately 15 minutes. From present test data it appears that Thermocoat will retain its bond in excess of 8 hours at 1800°F.

3. In the third method of attachment investigated a Unimatic Stored Energy Spot Welder was used, (See Fig. 4). At this writing, the foil-backed gage has been attached to metal test specimens by spot welding along the uncoated border of the strain gage. It has been necessary to remove the oxidation which was formed by the firing of the gage during manufacture in order to assure a good strong weld. Removal of oxidation is achieved either by sanding or acid dip. It is anticipated that in the future attachment of the gage a fine border of uncoated foil will be left directly beside the wire grid along its entire length. This will allow spot welds to be placed adjacent to the wire grid and along its length, which will result in a minimizing of

the small error factor caused by differences in the expansion characteristics of the various materials. The use of welding as a means of attachment is both rapid and positive. Initial tests will indicate a good or bad gage immediately and once the effectiveness of the gage is established there are very few ways in which it can be destroyed.

NOTE: This latest development in the manufacture of the foil backed gages is included in an effort to make this report as complete as possible:-

Through work completed after this report was written, a new type decal has been developed which utilizes a new type of carrier instead of the fire lacquer. This carrier is activated by an external adhesive, so that drying time is accelerated and assemblies can be fired within 1/2 hour

Figure 4 — Unimatic Stored Energy Spot Welder. Used in lead attachment of metal backed strain gages.

after winding. In addition, by virtue of the action of the activator, the nichrome element can be wound directly onto the ceramic backing.

Grid Type Gage

This gage consists primarily of a core of stainless steel foil coated with a thin ceramic coating. Proper mixture of palladium and silver are applied over the ceramic coating in the form of a grid with suitable leads attached, so that a continuous circuit is achieved between leads and the grid. This gage is illustrated in Fig. 5.

The strain gage bed consists of an 18-8 type stainless steel foil prepared as in the Foil Backed Gage, with the exception of steps which are concerned with laying the wire grid on the bed. Nichrome wire .005" diameter is used for lead wires and is attached to the strain gage element and by using a low temperature maturing coating which has a slight fluxing action on the original coating. This method consists of applying a thin coating of powdered silver in the form of a dot at the points chosen for the junction of the nichrome wire and the silver-palladium grid. The dot of silver is matured by a gas-air torch. A thin coating of the lower fusing ceramic coating is placed over the matured silver coating and is matured with a gas-air torch. Another coating of silver is placed over the ceramic coating and the nichrome wire is fused to the terminal point.

Figure 5 — SCREENED GRID GAGE — Printed circuit drawn with a silver-palladium mixture on an XBH-18 coated foil bed.

The silver-palladium mixture is prepared by accurately weighing 42.30% silver and 57.70% palladium. This mixture, when applied in a band .025" wide, .001" thick, and 3" long, will give a total resistance of 140 ohms. Illustrated in Fig. 6 is the resistance vs. silver-palladium mixture as applied to a strain gage bed. The silver-palladium mixture is applied to the foil and the entire assembly is fired to maturity at 1600°F. Connections between the terminal points and the beginning of the silver-palladium mixture are made with silver. It can be observed from Fig. 6 that variations in the total resistance can be achieved by varying the amount of palladium-silver deposited. Variation in the stroke of the grid shows that an optimum stroke or width is .025". Rate of deposition is critical when using an ordinary ruling pen and is difficult to control. It becomes necessary, therefore, to apply the silver-palladium mixture through a silk screen or as a decal.

Methods for attaching the strain gage to a test component are the same as listed for the Foil Backed Gage.

Standard Strain Gages Using "Singdale's Thermocoat"

A coating was compounded and designated as Singdale's Thermocoat. This coating consists of a refractory cement, a metallic oxide, and a binder. Three standard A-7 strain gages were dipped into this coating so that the gages were completely covered, including soldered joints of the lead wires. The coating was allowed to dry for 1 hour at a temperature of 150°F.

It was decided that test work would be performed on standard size test bars $\frac{1}{4}$ " x 1" x 12". These test bars were loaded as a beam in bending, on a cam type deflecting device (stress coat loader) to a deflection which would produce 60,000 psi on the tension side at room temperature.

Local areas, on a mild steel and aluminum test bar, were prepared by light sanding and cleaning with a solvent. The coating was brushed onto the local areas to a thickness of approximately .003". Type A-7 paper strain gages were immediately applied to the bars by submerging in the Thermocoat thereon and the assemblies were allowed to dry four hours at a temperature of 150°F. These applications are illustrated in Figs. 7 and 8.

Temperature tests were conducted to evaluate heat insulating characteristics of the Thermocoat, which was used as a protective coating for the strain gages. The A-7 strain gages, which were applied to the test bars, were

Figure 6.

tested by deflecting the bars at room temperature and indicating the strain with the SR-4 type MB Portable Strain Indicator. The steel test bar was heated to a temperature of 1400°F for two hours; the aluminum bar was heated to a temperature of 1100°F for two hours. Again the bars were loaded in bending to produce the same deflection and the gages returned to zero within 15%. An acetylene torch was used to induce a flame temperature of approximately 5000°F directly over the coated gages for a period of one second, and with the same loading conditions as before, the gages again returned to zero within 15%. The coatings were chipped from the gages and it was found the strain gage paper was not scorched.

The coating material, Thermocoat, was formed into a disc 1" thick. An acetylene torch was used to induce a flame temperature of approximately 5000°F directly onto the disc for a period of approximately 10 minutes. It was discovered that the naked hand could be placed on the opposite side immediately upon removing the torch. Examination of the disc after exposure to the flame evidenced a cavity burned $\frac{3}{4}$ " into the disc.

When the coating material was tested as a protective coating for $\frac{1}{8}$ " aluminum sheet, it was proved a coating .005" thick would prevent an acetylene flame from burning through for 15 seconds as compared to a burn-through time of 2 seconds for uncoated $\frac{1}{8}$ " aluminum sheet. A .010" thick coating extended the burn-through time to 32 seconds.

It was determined that the coating material, when properly cured, would resist abrasion from a knife blade and could resist a 30 degree bend without flaking off.

Other tests on the heat resistance of Thermocoat were performed by coating $\frac{1}{32}$ " thick, 24ST aluminum test plates with varying thicknesses of Thermocoat. The graph in Fig. 9 illustrates the results obtained. In this instance, the time for an acetylene torch to burn completely through the test plate was plotted against the thickness of the coating. All other factors remained constant.

Thermocoat was used as a matrix material and bonding agent for three special high temperature strain gage grids. These grids were supplied by Baldwin-Lima-Hamilton Corp. The grids were imbedded in Thermocoat applied to steel tensile test coupons. The specimens were prepared as follows:-

The steel was cleaned with sandpaper, followed by

Figure 7 — **STANDARD STRAIN GAGES** — Standard A-7 strain gages coated with Thermocoat. Mild Steel Bar.

washing with carbon tetrachloride.

A thin precoat of Thermocoat was applied to the test coupons, then immediately wiped off. The residue coating was allowed to dry.

The gage grid was bonded to the precoated test coupons by another coat of Thermocoat approximately .020" thick.

The samples were allowed to dry out thoroughly (at least 48 hours).

Resistance between the gage and tensile coupon leveled off at 50,000 ohms. The gage was baked at 250°F for several hours and resulted in a change of resistance to 1 megohm for two out of three samples; the third sample proved to be shorted to the bar and was abandoned.

This evaluation was conducted by a major west coast air craft company and their comments on the above were:

"This cement might prove useful for bonding a gage which did not depend for electrical insulation on the bonding agent. It will be necessary, however, to modify the bonding material or technique for its use so that heating will not cause the Thermocoat to 'froth' and become porous."

Further work with Thermocoat has proved that this "frothing" occurs when the coating is allowed to dry too rapidly. Rapid drying causes the surface to cure while leaving the under-layers in a more or less fluid state. Slower and more positive drying can be accomplished by the use of thinner coats.

Additional laboratory work on Thermocoat has proven that the strain gage wires should be coated with XBH-18 prior to use. At the present time, the extra insulation appears essential.

Figure 8 — **STANDARD STRAIN GAGES** — Standard A-7 strain gages coated with Thermocoat. Aluminum Bar.

Coated Wire Encased in Singdale's Thermocoat

As mentioned in the introduction to this report, nichrome wire has been substituted for Karma Alloy. This

substitution is a result of a letter received from Dr. J. C. Wilson, Oak Ridge National Laboratory, Oak Ridge, Tenn. Dr. Wilson stated that according to his data, the resistance characteristics of Karma Alloy were erratic at elevated temperatures. Rather than delay this present work by a long evaluation program, nichrome was substituted for the Karma so that all evaluation resulting from this work would be consistent as to the wire used. If the methods recorded here for manufacturing a strain gage give any evidence of success it will be an easy matter to substitute various other wires until the ideal wire is discovered.

The principles underlying this method of manufacturing a strain gage are simple. It was thought that if a strain gage could be made by attaching the wire grid directly to the test component, there would be less chance of errors introduced by the use of additional materials necessary to carry the wire grid. Theorizing further, it appeared that if some protective methods could be devised that would

Figure 9.

eliminate the possibility of oxidation of the small diameter strain gage wire, still less chance of error would be introduced. Then, again, a means of insulating the wires from the base metal of the test component had to be devised. All this resulted in coating the wires with XBH-18 after the leads were attached, then forming the grid and attaching it to the test component.

Preparation of the wires for forming into a grid is again accomplished by cutting .001" nichrome wire so as to arrive at a finished length of 2 3/4". Leads are attached by use of the Unimatic Spot Welder. The wires are then coated by spraying them with XBH-18, drying, then firing at 1800°F. This is illustrated in Fig. 10.

The coated wires are formed into a grid; the base metal of the test component is prepared by the same methods described earlier in this report; a thin coating of Thermocoat is deposited on the base metal; the strain gage grid is placed into the Thermocoat; and the assembly is then heated to 150°F for a period of 15 minutes. At this point, the strain gage is ready to operate. Longer leads are attached, the gage checked out, and recording begun. It is possible to use any adhesive for this method. Thermocoat is utilized primarily because it can be matured at room temperature, or at low heat, and is capable of withstanding extreme temperatures. One method of forming a grid is shown in Fig. 11. Other adhesives or cements which may

be utilized for this method are: Allen P-1, Quigley Blue, and G.E. LP-28 — LP-29.

Screen Type Gage

As in the preceding section, nichrome wire was substituted for Karma Alloy. This gage consists primarily of type 302 stainless steel bolting cloth, coated to form a strain gage bed, with a strain gage grid of .001" nichrome wire threaded through the screen openings. This type of gage does have an advantage over the foil type, in that it will conform to a specific configuration very readily. It should be possible to mount this type of gage over any irregular shape and treat it much like the wire alone. Although type 302 stainless steel was used in this work, the purpose would be better served by the use of Columbian and Titanium type stainless steel such as types 321 and 347. These stainless steels are more adaptable to ceramic coating procedures. This gage is illustrated in Fig. 12.

The screen is prepared for coating as with the stainless foil. The strain gage wire and the screening are both coated with XBH-18 and fired at 1840° to 1870°F until the coating is matured.

Attachment of this gage is made as described for the other types. It will be found that when using the Thermo-coat, the screen openings will enhance the bond and make initial attachment more positive. The Unimatic Spot Welder works efficiently with the screening.

DISCUSSION

In the manufacture of strain gages by the methods described in this report, it was discovered that existing methods of lead attachment were out-dated and useless. It became necessary to search for a method that would give a positive bond over extended periods of time, possess high sensitivity, and yet be sturdy enough so that ordinary handling would not break the leads. Various methods of attachment were investigated until all but two were eliminated. One of these methods involves the use of a small diameter tubing (either stainless steel or nickel), which is manufactured and supplied by the Superior Tube Company, Norristown, Penna.

The initial method of assembling the .001" wire to the small diameter tubing consisted of inserting the wire into the tubing then crimping the tube over the wire. This method has since been improved by using a spot welding unit to make the bond secure. This latter method seems, by far, to be the best and most positive method of lead attachment.

Another method of lead attachment which has won favor at this writing is the use of a "Unimatic Stored Energy Spot Welding Unit".

Although the use of spot welding has been mentioned

Figure 10 — COATED WIRE — .001" nichrome wire welded to .005" nichrome wire, coated with XBH-18.

Figure 11 — Nichrome Wire threaded through Stainless Screen. Strain Gage Grid attached to bar using Thermo-coat.

previously, there are several approaches to lead connection with the assistance of this unit. One method consists of welding directly .001" wire to .005" wire. Another method consists of welding the two wires of different diameters together by use of a tab of either stainless steel or nichrome. This is accomplished by folding over a small piece of the stainless foil, inserting both wires into the fold, then spotting it with the welder. This latter method of joining is, by far, the best and most positive of the two mentioned. Other methods attempted were discarded as not being practical.

The Unimatic Spot Welder was utilized extensively in strain gage attachment. It was discovered that a positive and rapid bond could be formed. This method of gage attachment will only be useful where the strain gage grid is mounted on a metal. By setting the heat control of the welder at 150V, it was found that the thickness of the base test component made little difference in the type of weld. This is one of the advantages of using this type of welder. The heat control can be set for the thickness of metal in the strain gage and remain fairly constant.

During some preliminary test work, that of attaching a strain gage to a stainless steel bar and submitting the assembly to 1800°F for 12 hours, it was found that the bond remained firm, but that the gage raised in the center, where there was no weld. To eliminate this condition in the future, it has been decided to pursue the problem by leaving a border of uncoated foil around the wire. This will allow the spot welding to follow alongside the wire. It has been found that the gage assembly may be welded flatter to the test component if more care is taken during the welding operation.

That the attaching of strain gages by use of Thermo-coat is effective is evidenced by tests performed to date. Several

Figure 12 — SCREEN TYPE GAGE — .001" nichrome wire threaded through stainless steel screen and coated with XBH-18.

gages have been attached to test bars with Thermo-coat as the bonding agent. These bars have been tested at 1800°F for various periods of time. The longest test in-

volved 16 hours at 1800°F. In this particular test, the test bar was mild steel. Originally, the test was not intended to run at as high a temperature or for as long a period of time. However, the results were encouraging. The steel bar was oxidized to an extent where large areas of

Figure 13 — FOIL BACKED GAGE — Subjected to 1850°F for 2 hours. Purpose: To check effectiveness of Thermocoat as a bending agent. It can be noted that Thermocoat held true. Mild Steel Bar.

oxidized metal could be picked off. The area over which the strain gage was placed, was not oxidized and the strain gage was still held securely. This bar is now on exhibition at Baldwin-Lima-Hamilton Corporation, and to the author's knowledge the strain gage is still held securely. An illustration of this particular application may be seen in Fig. 13.

The use of Thermocoat is a critical operation at this time. As a result of its critical drying characteristics, it

Figure 14.

Figure 15.

becomes necessary to dry slowly, without rupturing, until a good bond is in evidence. Elsewhere in this report the procedures used to attach gages with Thermocoat are explained. Additional research is being completed at this writing in an attempt to change the drying characteristics of Thermocoat. Difficulty is experienced because the coating requires a free movement of air in order to dry thoroughly. It is also a requirement that all water be evaporated slowly to assure a positive bond.

At this point it might be advisable to discuss the reasons which dictated the employment of ceramic coatings in this

Figure 16 — Left, Uncoated stainless; Right; Coated stainless; after subjecting to 1900° F.

project and also give some pertinent data covering the performance of the high temperature ceramics employed here. Coatings of a ceramic nature for metals are not new, as witness porcelain enamels on home appliances, signs, etc. Unlike their counterpart, porcelain enamels, which are designed primarily for decorative purposes, ceramic coatings are used to prevent oxidation of metals at elevated temperatures. In addition, ceramic coatings prevent embrittlement of the leaner alloys caused by carbon absorption resulting in loss of ductility and corrosion resistance. As indicated in Fig. 14, the oxidation rate at 1700°F of ceramic coated stainless steel is less than that of uncoated Inconel. In addition, as mentioned before,

ceramic coating prevents intergranular corrosion and loss of ductility at elevated temperatures. It is imperative that this property exist in a metal type high temperature strain gage because loss of ductility after an extended period of time will lead to erroneous results. Fig. 14 also shows the rate of oxidation for uncoated stainless steel at the same temperatures.

At a temperature of 1900°F the rate of oxidation of coated stainless steel is 1 to 20. This fact is shown in Fig. 15 and Fig. 16.

Ceramic coatings, in addition to preventing oxide formations, are also dielectrics, having dielectric strengths exceeding 200 V per mil of fired thickness.

10

HIGH TEMPERATURE STRAIN GAGES

SUBMITTED BY
D. J. DeMICHELE
GENERAL ELECTRIC COMPANY
General Engineering Laboratory
Schenectady, N. Y.

This report covers the progress of investigations into the development of high temperature strain gages of three types, resistance, inductance and capacitance. These gages are to be used in the static measurement of strain in the temperature range not covered by commercially available gages. They are designed for field installation so that no permanent disfiguring of the component will be necessary.

THE RESISTANCE GAGE

The techniques for the fabrication and mounting of resistance type ceramic strain gages have been developed so that they will soon be commercially available. Such gages will be suitable for both static and dynamic measurements; static gages up to 1000°F and dynamic gages above this figure. Tests on various wires may be summarized as follows:

1. Nichrome wire, although it will reproduce its performance after subjecting it to temperature cycling, has a relaxation point at approximately 1000°F, (see Fig. 1).

Figure 1.

2. Alloy wire, having approximately 75% Ni. and 20% Cr. maintains its gage factor within ten percent up to 1000°F after temperature cycling, (see Fig. 2). All wires appear to have a hump in the temperature-resistance curve as a result of relaxation at 1000°F during the first cycle. This curve flattens out on the second and consecutive temperature cycles. This relaxation point within the 1000°F range was minimized during the second cycle of operation.
3. Although Platinum-Iridium wire has a high gage

Figure 2.

factor and is resistant to corrosion attack its large resistance change with temperature makes it unsuitable for use in a strain gage for static measurements, (see Fig. 3). However, it may be used for dynamic work.

Figure 3.

4. Manganin wire was selected for test because of its negative characteristics, (see Fig. 4). It was thought desirable to use Manganin wire in conjunction with Karma for the purpose of temperature compensation. This idea was abandoned when certain test work proved the Manganin wire possessed a low strength above 600°F, (see Fig. 5).
5. Iron-Palladium and Platinum-Cobalt exhibited large resistance changes with temperature changes,

approximating .05 ohms/degree for Iron Palladium and .4 ohms/degree for Platinum-Cobalt.

- Tests showed negligible effect of the cement on the characteristics of the wire at elevated temperature, (see Fig. 6).

Figure 4.

The life of Nichrome and Karma gages, made by the technique of wires pressed flat between plates, was approximately 100 hours at 1000°F. When the temperature was held constant and the load varied, the return to zero was faithfully repeated. Fig. 7 shows that the variation in calculated strain plotted against measured strain is approximately 7% at 1000°F.

Figure 5.

The gage factor of Nichrome and Karma wire varies less than 10% between 70°F and 1000°F.

CONCLUSIONS:

- Alloy wire having approximately 75% Ni. and 20% Cr. is more suitable for static measurements.
- All gages should be temperature cycled before making test runs. Cycling cures the cement and

relieves residual strain in the wire and in the material under test.

- Ceramic cements, such as G.E. LP-28 and LP-29 developed by the General Electric Co., and P-1 Allen Cement (Robert G. Allen Co., Mechanicsville, N.Y.) have coefficient of expansion characteristics closest to that of steels. Coefficient of expansion of LP-28 is above that of steel and LP-29 is below.
- It is necessary that all lead wires be secured up to the point of junction with the gage to prevent motion resulting from vibration.
- The preferred cement is a 50-50 mixture of G.E. LP-28 and LP-29 for application on steels.

ADDITIONAL TESTS:

The following tests are to be made:

- Tests of a temperature-compensated alloy wire gage having 75% Ni. and 20% Cr. which consists of two gages so constructed in one unit that one gage lies at 90° to the other, (see Fig. 8). This is made possible by the flat wire technique.
- Seek new materials for gage wire. Wires must have characteristics so that when used in conjunc-

Figure 6.

Figure 7.

tion with certain other wires, temperature compensation will be achieved.

FABRICATION OF THE GAGES:

The procedure for making the gage is described below:

The wire is wound on a jig to form a grid, (see D. J. DeMichele patent No. 2,548,592 — April 10, 1951. Application has been made for additional patents on this method.) A mat of wax paper is placed under the grid while in the jig and Duco cement is brushed on the wire. After the cement is air dried, the mat holding the wire is removed from the jig and the wax paper is peeled from the wire-cement film. This leaves the wire suspended in grid form in this Duco cement wafer. The wire is placed between two hardened steel, highly polished flat plates.

Figure 8.

Pressure is applied so that the wire is flattened to approximately one-third its original diameter. The plates are then separated, the wafer removed, and the Duco cement washed off the flattened wire grid with acetone. The wire grid is next laid on Teflon and held in place with scotch tape until ready for use.

MOUNTING OF THE GAGE

Prior to mounting the gage, the surface of the part to receive it was sandblasted, followed by a thorough cleaning with alcohol. An undercoat .001" thick (preferably less) of Allen P-1 cement or G.E. LP-28-29 mixture was brushed on the surface and air dried for 30 minutes, then placed in an oven to cure for two hours at 300°F to 500°F. The grid was next applied to this cured undercoat and additional cement similar to that used in the undercoat was brushed over the grid. The same curing procedure as with the undercoat was then followed. In every case the lead wires were secured in place with G.E. LP-28 cement because of its superior physical strength.

In all cases, temperature cycling 5 to 10 times in the expected operating temperature range prior to test produced more stability and less drift.

The following points seemed very evident in observing behavior of this gage under test:

1. Fresh cement material, regardless of manufacture, gives the best results, less expansion, and a

smoother and repeatable expansion curve.

2. Temperature cycling the cements in the range in which they are going to be used makes for better stability.
3. A very thin coat of cement gives a better bond than a thicker coat (preferably less than 3 mils).

TESTING METHODS FOR RESISTANCE TYPE GAGES:

Two gages, one over the other, were mounted at 90° in the same cement bed in the center of a stainless steel test strip 10" x 1" x .125".

Figure 9 — Furnace for testing high temperature strain gages.

The gaged test strip was placed in a furnace and the heat applied. The resistance change was measured during the first three or four heat cycles using a resistance bridge. After the gages stabilized, an SR-4 Strain Indicator was used to replace the resistance bridge and the apparent strain was measured. Thermocouples on both sides of the gages measured the temperature continuously, and assured accurate readings.

Figure 10.

An especially built furnace, Fig. 9, was employed in which the test strip was subjected to prescribed loads at elevated temperatures.

The furnace-enclosed loading fixture suspended the gaged strip as a free-free beam with two point loading.

The deflection of the beam was measured by micrometers making electric contact with pins on the beam. From these micrometer readings the strain was calculated. The SR-4 Strain Indicator measured gage output. Fig. 10 shows a test curve of crossed gages.

Gages were quenched from 1500°F into cold water to study the effect of thermal shock. Fatigue tests on a vibrating beam were run on sample gages. Resistance tests to ground at temperature were run on all gages.

To obtain the linear coefficient of thermal expansion of the cements, a rod 2" long by $\frac{1}{8}$ " diameter was formed by dropping cement into an absorbent sleeve in such a manner as to eliminate any possibility of layering effect. This rod of cement was then measured in a homemade dilatometer at various temperatures.

HIGH TEMPERATURE RELUCTANCE GAGE:

The variable air gap gages are those in which the reluctance of the magnetic circuit is varied by changing the air gap. The miniature air gap gage, Fig. 11 (a), consists of two laminations with a core carrying a coil on one or two legs. The laminated armature moves relative to the core to form the variable air gap.

SINGLE GAP GAGE

Figure 11.

A single gap gage is not linear in response except over small portions of its range or when used with very special circuits. In order to improve linearity, double sensitivity, and provide temperature compensation, a double gap gage can be used, (see Fig. 11 (b)).

DOUBLE GAP GAGE

The feasibility of developing such a gage was explored by devising and testing several types of construction, especially to obtain best cancellation of temperature ef-

fects. The types built and tested were the double window type, (see Fig. 12 and photograph Fig. 13), the compensating coil type (Fig. 14 and photograph Fig. 15) and the closed type (see Fig. 16).

Figure 12.

Figure 13 — Double Window Type reluctance strain gage.

Figure 14.

Figure 15 — Compensating coil type reluctance gage.

CONSTRUCTION OF RELUCTANCE GAGE:

The gage consisted of a strip of laminated 416 stainless steel, one inch long, 10 mils thick and one-half inch wide. This strip was machined to form the various configurations, as shown in the Figs. 12, 14 and 16.

Figure 16 — Closed type reluctance gage.

The coils were wound with .004" diameter copper wire, nickel plated for protection against oxidation. The wire was insulated prior to winding on the lamination with Allen P-1 ceramic coating which was applied after preparing the wire by proper cleaning procedure. The ceramic was allowed to air dry for several days and then fired at 500°F for two hours. Two coils were wound on each gage and matched accurately for inductance and resistance. The coils, as wound, produced an inductance of approximately 85 microhenry and d.c. resistance of 12 ohms.

Figure 17.

MOUNTING OF RELUCTANCE GAGE:

Standard test strips similar to those used for the wire resistance gage were used to test the reluctance gages.

The test strip was prepared as described for the resistance gage. The gage was placed in the center of the strip. A 2 mil air gap was used for all tests. With the gage located in a central position on the strip, Sauereisen cement was used as the bonding material. It was found that Sauereisen 31 had superior characteristics as a mechanical bond for this application.

The output of the gages was recorded on a BL-320 Brush Strain Analyzer modified to achieve balance of the circuit.

Figure 18.

RESULTS OF TESTS:

Investigation shows that higher sensitivity can be obtained with reluctance gages than with resistance gages.

Fig. 17 shows the effect of temperature on the double window type; Fig. 18 shows the effect of temperature on the compensating coil type; while tests are still in progress on the closed type.

Figure 19 — High Temperature Capacitance Gage. This consists of two ceramic plates on which silver electrodes are plated separated by mica. The ceramic plates are cemented to a steel plate which is designed so that the gap between the capacitor plates is maintained. The steel plate is bonded to a test structure by Sauereisen ceramic cement.

CONCLUSION:

These gages show promise for high temperature service. However, it is suggested that further work be done along the lines of investigating materials to obtain still better cancellation of temperature effects.

The various possible ways of bonding the gage to the test piece also bear further study.

THE CAPACITANCE GAGE:

The high temperature capacitance gage consists of two ceramic plates with a silver electrode plated on the inner edge of each, separated by a mica strip, (see Figs. 19 and 20). The ceramic plates are, in turn, cemented to a steel plate which is so designed that the gap between the ca-

capacitor plates is maintained. The steel plate is mounted to the test piece by means of Sauereisen 31.

The main advantage in the capacitor gage is the opportunity offered for mechanical design.

The influence of the mica is to make the equivalent air gap smaller which increases the sensitivity and permits a reduced range of movement thereby improving linearity.

The relation between capacitance and the separation between plates is as follows:

$$C = \frac{aK}{3.6 \pi t}$$

C = capacitance in micro-microfarads

a = area of plate in square centimeters

t = separation between plates in centimeters

K = dielectric constant

TEST RESULTS:

Fig. 21 shows the apparent strain as a function of temperature.

The sensitivity of the gage to strain change with the .002" gap compares favorably with the wire resistance gage. No calibration curves were obtained as yet because the primary object at the moment was to investigate performance at elevated temperatures.

RECOMMENDATION:

This gage shows promise, so further tests should be made to evaluate its performance. The tests should include both materials and circuits.

Plans are under way to carry out such work.

Figure 20 — Photo of High Temperature Capacitance Gage shown in the drawing in Figure 19.

Figure 21.

THE WELDABLE WIRE STRAIN GAGE

CONTRIBUTED BY
JOHN D. RUSSELL
CHIEF ENGINEER
MICRO-TEST, INC.
Los Angeles 36, California

The Weldable Wire Strain Gage discussed in this report is a new type strain gage which features a resistance wire in a very small, flanged tubular metal shell. See Fig. 1 (a) and Fig. 1 (b).

Figure 1a — Micro test gage showing leads coming straight out. Comparative size is indicated by the paper clip in photo.

Figure 1b — Micro test gage showing crimping method of holding leads.

This gage may be installed by spot welding the flanges to a flat or curved surface and is usable to at least 1800°F.

Important advantages are:-

1. Rapid, permanent installation.
2. Usable immediately after installation.
3. Will operate at high temperatures.

4. Resists corrosion and abrasion.
5. Electrical shielding.
6. Improved temperature compensation.

Basically, the gage consists of a fine resistance wire located within and insulated from a very small, flanged tubular metal shell.

A circumferential stress in the shell exerts a clamping force on the insulation which, in turn, exerts a radial clamping force on the entire surface of the fine wire (and part of each lead wire). The resulting friction prevents relative motion between wire and tube. Thus, a change in dimensions in a structure is transmitted through the flanges to the shell and then through the insulation to the fine wire.

Fig. 2 shows two weldable gages installed on a bar and tested to 1650° F. Fig 3 shows earlier models.

The tubular shell of this particular gage is made of very thin flat sheet (.020" O.D. x .002" wall).

The top or "hat" section is formed in a die to the dimensions shown.

The lower section is essentially flat.

After installation of wires and insulation within the hat section the insulation is compacted and the bottom or flat section of the gage is spot welded on by a method which produces a circumferential tension in the shell.

The following dimensions and materials are being used in some of the first commercial forms of the gage:

Lead wire — .006" "Evanohm" (Nickel-Chromium)

Resistance Wire — .001" "Evanohm"

Note:- There is no welded joint between lead wire and filament.

Two methods are used to avoid the joint:

1. The end section of filament wire is built up by electro-plating.
2. The center section of the larger lead wire is reduced to filament size.

Figure 2 — Weldable Wire Strain Gage shown installed on a bar and tested to 1650°F. This gage was invented by J. D. Russell and constructed for Mr. Russell by R. R. Bauman at Micro-Test, Inc.

Figure 3 — Weldable Wire Strain Gage shown installed on a 1" x 16" x 14" steel bar after being subjected to a temperature of 1650°F. This gage was invented by J. D. Russell.

Shell — .002" Haynes #25 Steel

Insulation — Powdered Magnesium Silicate

The gage resistance is 75 ohms and the gage factor is approximately 2.0. Higher resistance gages are under development.

Figure 4 — Sketch showing top view of weldable wire strain gage with filament and leads. Dimensions are exaggerated.

Many other versions of the weldable gage are possible. Some significant variations are:

1. *Weldable gages* using both a bond and mechanical pressure.
2. *Weldable gages* using as a bond, air-drying cements such as Duco for ambient temperatures.
3. *Weldable gages* which include multiple elements in one shell. For example, a four-arm bridge circuit with two active and two dummy gages.
4. *Weldable gages* with open-faced construction—i.e., a wire bonded to a flat piece of metal or flanged partial tube—that is, tube with upper portion left out (could be called flanged metal trough).
5. *Weldable gages* utilizing flanged tubular shells manufactured in one piece before assembly.
6. *Weldable gages* which are hermetically sealed and evacuated or filled with inert gas.

TEST PROCEDURES

Single gages have been calibrated under stabilized temperature conditions.

Complete bridge circuits of four single gages and special gages containing all four elements in one shell will be tested for static stability.

For the test described herein a weldable gage was mounted on a 1.00" x .375" x 24" stainless steel bar.

The bar was mounted as a cantilever beam through a Marshal Electric Furnace.

The free end of the bar was loaded with known weights.

Figure 5 — Sketch showing side view of same weldable wire strain gage shown in Figure 4.

A cable and pulley system provided means for applying upward loads, as shown in Figs. 6 and 7.

A thermocouple spot-welded to the bar adjacent to the gage was used to measure temperatures.

The weldable wire strain gage was connected to form one arm of a bridge circuit with the other three arms consisting of resistors.

All connections within the furnace were spot-welded. The wires extending from the gage to the exterior of the furnace were insulated with mica.

A Brown Electronic Indicating Potentiometer was used to measure resistance changes.

Calibration was accomplished through the momentary connection of a precision resistor in parallel with the gage (taking note of gage resistance at each temperature), a procedure similar to measurements involving bonded SR-4 strain gages.

Fig. 8, illustrates the basic circuit.

The gage resistance to ground was measured at various temperatures.

Each individual gage can be calibrated before use by clamping gage at its flanges to a test bar, and unclamping after test.

The resistance of the gage can be adjusted within limits by subjecting it to a tension or compression stress in the shell during installation. This is done by spot-welding one end and holding the other end in tension while welding it in place. This can be a final trim to a bridge balance.

If all gage resistance were made slightly under prescribed value, then desired final value could be attained by placing a permanent extension in the shell by rolling the flanges or pulling the gage in tension.

TEST RESULTS

Figs. 9 and 10 provide a summary of gage performance.

As shown by the graph of strain versus $\Delta R/R$, Fig. 9, the room temperature gage factor is approximately 2.0. The graph also shows (1) linearity and hysteresis errors of less than 2%; and, (2) tension and compression sensitivities which are in close agreement.

For elevated temperatures, stress versus $\Delta R/R$ (rather than strain versus $\Delta R/R$) curves were plotted because the modulus was not accurately known. For a comparison, the room temperature data was also plotted in stress versus $\Delta R/R$ form.

It should be noted that the gage performance was satisfactory to as high as 1775°F for the limited conditions involved (high loads could not be applied because of the low modulus of 302 stainless at the high temperatures involved).

DISCUSSION

In general, the results to date are promising and no serious disadvantages are apparent.

Questions pointing out possible disadvantages are frequently asked. Some of the more important questions are answered as follows:-

1. Q. Doesn't welding alter the material and structure significantly and therefore change the test conditions?

Figure 6 — Test set-up for weldable wire strain gage.

Figure 7 — Weldable Wire Strain Gage Test Set-up.

- A. The minute spot weld beads probably alter the structure less than the installation procedures for a regular cemented gage — an insignificant factor for all but very special cases. This conclusion results from the fact that a surface must be sanded or otherwise scratched or roughened prior to installation of a cement type gage. In contrast, the weldable gage can be installed on a polished surface. Furthermore, it is probable that (1) the spot welding beads do not penetrate much deeper, (probably less than .002" deep), than the scratches required for a cemented gage; and, (2) these very small shallow beads of metal, even if altered by the heat, are better than no metal

Figure 8 — Circuit diagram of the equipment used in the test set-up.

(as in the case of scratches). This shell-enclosed gage can, of course, be installed by other methods such as cementing (no insulation required), riveting, clamping, embedding, etc.

2. Q. Doesn't the metal tube offer excessive restraint — i.e., doesn't the gage add significant strength to the structure and thereby change test conditions?
 - A. Obviously restraint is no problem on (1) large structures; and, (2) on calibrated devices such as force rings, etc. Furthermore, the dimensions of the tube can be (and are being) made so small that its restraining effect is probably no more than that of some regular cemented SR-4 types — insignificant in most cases.
3. Q. Can thin metals such as used for construction of the weldable gage be welded to a thick,

Figure 9.

Figure 10.

large mass of metal without burning or damaging the thin metal?

- A. Laboratory experiments prove conclusively that this is no problem where spot welding and especially where DC or condenser discharge types of welders are used.

Welders supplied by the Unitek Corporation of Pasadena, California, are quite satisfactory.

The installation of a gage by welding and the use of a clamping principle to eliminate or supplement bonding types of insulation has resulted in an improved high temperature gage which has been proven to be practical for some dynamic conditions.

The weldable gage also offers possible improvements for measuring *static* strains at elevated temperatures.

The accurate measurement of *static* and/or dynamic strains under varying elevated temperature conditions requires that all four bridge arms react identically to temperature changes. Other supplementary methods such as the use of wires of different materials spliced in proper proportions to reduce thermal effects in a given bridge arm may, of course, be used. However, since thermal effects are generally non-linear, the latter approach cannot alone provide ideal compensation over a wide range of temperatures. The primary consideration should be the attainment of equal temperature and equal reaction to temperature in all four bridge elements. This equality should persist through wide variations in overall temperatures.

Some of the requirements are as follows:

1. Identical materials.
2. Identical heat transfer.

3. Location of all elements as near as possible to the same point.
4. Equal spacing of wires from ground and from each other.

The tubular gage offers one of the best possible configurations for satisfying the above conditions because all four elements can be placed in one shell.

In this connection it should be noted that Poisson's ratio effects would tend to provide circumferential strains which are opposite in sign to the axial strains. Thus two coiled elements and two straight elements would provide a complete bridge circuit with an output approximately proportional to axial strain. Furthermore, if the shell material and test material are matched, then thermal expansion errors will be cancelled to some extent.

The possible effects of transverse strains on the dummy coils and/or active elements can be substantially reduced by making the cross sectional width of the material joining the tube and flange very narrow.

Fig. 11 illustrates one form of a four element gage. Note that the four elements could be of one continuous loop of wire (by joining a straight length at one point). Thus no lead wire connections and no thermocouple action would exist within the bridge circuit.

Some temperature compensation may be attained with four single element gages.

Where strains of opposite sign exist as in bending measurements, all four gages could be installed by welding over the entire gage length.

Where no strains of opposite sign are usable (or strains of widely different magnitudes), then two of the gages would be welded only along that portion of the shell which is occupied by the leads. These two gages would thus react only to temperature changes but not to strains induced by changes in stress.

The use of two or four single element gages would provide adequate compensation for ambient conditions and for some elevated temperature conditions.

At present single element gages could be used alone on a structure (with the other three bridge arms consisting of remotely located resistors) only for checking dynamic conditions — and even in this usage the dynamic effects of temperature changes would have to be considered.

All methods previously described herein for cancellation of undesirable temperature effects can only provide compensation for free thermal expansion of a metal. The cancellation or separation of thermally induced stresses as distinguished from stresses due to other variables has not been considered in detail. A possible method for separation of stresses would involve simultaneous recordings of temperature and strains. The resulting records could, with the aid of static calibrations, afford a possible means of separating thermally induced stresses from those induced by other sources.

The weldable wire gage can be used in conjunction with other devices such as rings, links, beams and tubes to provide means for measuring and/or controlling other variables such as force, acceleration, pressure, etc. at normal or elevated temperatures.

The improvements involved to date in SR-4 types of gages such as dual leads, spliced or coated filaments, improved cements, etc. could be adapted to the weldable gage.

Figure 11 — One form of a four-element gage.

Every effort is being made to place the present gage in production and to continue research for better materials, methods and configurations.

The primary object at present is to produce a satisfactory gage for measuring static and dynamic strains to 2000°F. Note:-

This new approach, disclosed to Mr. F. G. Tatnall at a strain gage conference in November of 1952, was described in the writer's report of July 12, 1953 (Mechanical Pressure Type Resistance Wire Strain Gage).

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GILMORE REPORT

SUBMITTED BY
R. J. CARLETON, Jr.
GILMORE TECHNICAL ASSOCIATES
Cleveland 3, Ohio

SUMMARY OF RESULTS

Karma wire bonded with modified Quigley ceramic cements were selected as the basis for this study. This report covers about one year's study including some 20,000 gage hours of testing.

STATIC TESTING

(1) Gages were developed and tested to 600°F with characteristics which are comparable to the commercial Baldwin SR-4 type "A" gages. These gages can then be said to extend the usable temperature range to 600°F.

(2) The temperature strain sensitivity of the Gilmore High Temperature Strain Gages is equal to the SR-4 type "A" gages. To reduce the temperature strain, the usual methods can be used: Dummy gages; hold temperature stable; zero at test temperature.

(3) Gages tested up to 600°F were found to have a recurrent "zero drift versus temperature" or "apparent strain reading versus temperature", characteristic. This makes possible the zero balance or initial reading of the gage at 70°F or room temperature and, knowing the temperatures to which the gage is subjected, a reading of the time-load strain from a single strain gage is adequate.

(4) Over the 70°F to 600°F range, the tests show that the sensitivity or gage factor is stable with temperature up to 600°F.

(5) The sensitivity or gage factor up to 600°F is stable with time as shown by tests over periods of 1500 hours of continuous heating.

(6) Cements were used which permitted the installation of the gage without high temperature curing. Thus, gages can be used on aluminum and in instances where material cannot be preheated to high temperatures because of size or location.

(7) Gages were also tested up to 1000°F. It was found that the apparent strain due to temperature was not sufficiently stable above 700°F for use as a static gage. However, for dynamic work and short time high temperature testing to 1000°F, the gages are practical as a result of stability not being required in the first case, and the zero strain being measurable over a limited time-temperature variation in the latter case, gage factor remaining stable.

INTRODUCTION

All known current practices for the manufacture or production of high temperature strain gages were reviewed. The major references are listed at the end of this report.

Our evaluation indicated that a gage using Karma wire bonded with modified Quigley ceramic cements offered

the best possibility for a practical gage. The Karma wire was known to have some temperature limits for use as a static gage over 900°F. Since the object was to produce a practical gage for 600°F, this combination was selected as a first step with later work either pushing this limit over the 600°F mark or taking other approaches for the 1000°F operations.

Porcelains, silicones, enamels, and other miscellaneous cements were briefly investigated, though little development or testing was scheduled because the known performance would not match up with the ceramic type cement.

TEST PROCEDURE

Three basic types of tests were conducted in this study:

First, to test the sensitivity of the gages with temperature, gages were mounted on $\frac{3}{4}$ " and 1" wide x $\frac{1}{16}$ " thick Inconel strips and heated in an electric furnace. Weights were applied at the end of the beam with a 12" moment arm at various temperatures to record strain up to 25,500 psi. Gages were tested in both tension and compression and at various temperatures and over long periods of time to obtain both temperature versus sensitivity and sensitivity versus long time heating.

Second, to determine the apparent strain produced in the gage versus temperature at unloaded beam conditions, strain readings were recorded under "no load" from 70°F up to 1000°F at temperature equilibrium.

From this was plotted the zero drift or apparent strain sensitivity of the gages, on Inconel, versus temperature.

Third, to determine the shift of the apparent strain reading when held at a constant temperature and load versus time. For static testing over long periods of time without return to zero, the zero stability must be within strict tolerances so a plot of the apparent strain versus time is required. Tests were also run under constant load to determine drift and creep.

TEST APPARATUS

All of the gages were constructed on Inconel strips and tested in bending, under varying temperatures in the furnace shown in Fig. 1. This furnace had a vertical holding plate with slots to mount 12 beams for simultaneous testing and long-time soaking. The slot in the front allowed the connection of a small wire to the ends of the beams for load application. The electric furnace is rated 1800°F with temperatures controlled and recorded by a potentiometer strip chart recorder.

Strain measuring equipment was a 12 channel DC and AC bridge type potentiometer strip chart recorder and also a Baldwin Type L strain indicator.

Figure 1.

CONSTRUCTION OF STRAIN GAGES

Gages were hand made with simple metal jigs and fixtures. Most of the gages were approximately $\frac{1}{4}$ " wide by $\frac{7}{16}$ " long in the range of 250 to 300 ohms. Lead wires of .010" diameter were mechanically swaged around the .001" Karma gage wires with the .010" lead wires projecting up at 90° from the finished gage. To prevent strain and external forces from acting on the gages, .01" wire loops were then welded from the primary leads in a loop to heavier leads of solid Advance (cupro-nickel) wire. Advance wire leads of 20 gage x 3 ft. long were used to couple the strain gage in the furnace to the recording instruments outside. The Advance wire was used to prevent or to minimize temperature effects on the lead wires since it has a low temperature coefficient of resistivity.

All gages were mounted on the Inconel beams using various ceramic cements. The Inconel beams were sanded and cleaned. A pre-coat of cement approximately .003" thick was applied to the beam and air dried at 150°F. When dry, the gage was then attached to the beam with a second coat of similar cement and air dried in an oven at 150°F until resistivity of the gages to ground was very high. Some trouble was experienced with DC voltages which developed in the material between gage wire and the metal. For long-time use with stable zero, this voltage must be eliminated or precautions taken to prevent corrosion of the gage wire which will appear as a zero drift.

RESULTS

A. Static Gages

For use in static testing, it is essential to know the zero drift and the "no load" characteristics of the strain gages. In present use, static testing refers to test conducted over a period of time under essentially constant temperature conditions counting on the zero point of the strain gages to hold true. Baldwin SR-4 Type A gages are most com-

monly used for this work because of their low temperature sensitivity, yet, many precautions must be taken to get a successful static test. These precautions include holding of temperature as nearly constant as possible by shielding; testing in enclosures or buildings; the use of similar gages in self-compensating circuits as the "dummy" compensating gage; and testing as rapidly as possible with frequent rechecks of the zero point whenever possible.

It is known that the temperature sensitivity even on type "A" gages can be observed. In Fig. 2 are plotted a number of temperature drift curves for "A" gages as determined by several sources. Lines, A, B, C, H and J, are the apparent strain produced by temperature changes on Baldwin Type "A" gages. These are the standard commercial paper base gages used for most static work. Line K shows a typical Baldwin Type "C" gage with high output, but also high temperature sensitivity. For comparison, several of the high temperature strain gages are shown on lines, D, E, F and G. These are typical Karma wire gages with slightly different techniques in construction and cement which accounts for the difference between gages. While there is a noticeable difference between their tem-

Figure 2.

perature sensitivities, note the difference between the lines C and J, both of which are the Baldwin Type "A" gages.

Gages E and F were made at the same time and were intended to be identical but with hand construction there were differences as shown on the curves. The line shown as D represents two high temperature strain gages back to back on a single beam to test the self-compensating possibilities of two like gages. These gages were more

nearly matched since they show only a little over 200 micro-inches at 500°F while gages E and F have a difference of 600 or 700 micro inches. Also, it might be possible that there were differences in the two separate Inconel beams used for E and F which would increase the strain sensitivity recorded.

The time lapse between 70°F and the 500°F or 600°F readings of gages D, E, F, and G represents two to four hours' time required for the furnace to come to equilibrium at each of the successive test points.

Gages H and J were Baldwin Type "A-5" gages of the same gage factor and lot number, mounted back to back on a single aluminum bar. They show differences comparable to E and F, the High Temperature gages.

The apparent strain caused by temperature change of a Gilmore high temperature strain gage is shown in Fig. 3. This gage has a higher strain sensitivity to temperature

Figure 3.

caused by the fact that this gage has been previously tested up to 1200°F and had, in the process, lost its flat strain versus temperature characteristics. It is shown here because it was subjected to a number of tests over a long period of time. The strain caused by change in temperature alone is plotted for three periods: first, as a relatively new gage, but after some 1200°F testing; second, a repeat test is plotted after 840 hours of soaking at 500°F to 600°F; third, a plot is shown of a test after 1340 hours of 500°F to 600°F soaking. The results show that this apparent strain versus temperature characteristic holds over long periods of time providing the gage is not heated over 600°F.

With a gage of this type, even with high temperature sensitivity, a zero strain reading can be made at room temperature and if the temperature of the gage is measured, compensation can be added to read actual metal or gage strain above that caused by temperature change alone.

The third factor of interest for both static and dynamic work is the stability of gage factor with temperature. In Fig. 4 is plotted a typical gage showing a gage factor test from 70°F to 600°F over a period of 1220 hours. This gage, while it has a peculiar S-shaped curve, will follow this curve over the range up to 600°F and also holds it over a long period of time. This gage was kept at elevated temperatures during the entire 1220 hour period. Fig. 5

Figure 4.

Figure 5.

shows the gage factor versus time indicating a relatively stable gage as far as sensitivity is concerned.

Fig. 6 (b) shows a plot of a typical high temperature strain gage mounted on an Inconel beam, pictured in Fig. 6 (a), loaded in compression and tension. This shows

Figure 6a — High Temperature Strain Gage mounted on an Inconel beam.

that a well mounted high temperature strain gage does have a linear output from 600 micro-inches per inch tension to 600 micro-inches per inch compression.

A number of tests were run to determine what creep there might be in the gages under constant load at elevated temperatures. In summary, the creep was so small that it

Figure 6b.

could not be detected or separated from minor temperature changes and slow drift of the gages with time.

Fig. 7 shows the drift that occurred on most of these gages with time and elevated temperature. The drift is an equivalent tension strain which means an increase in resistance. This can be explained by either a metallurgical

Figure 7.

change in the wire to increase the specific resistance, or a corrosion of the wire to decrease its diameter. No attempt was made here to eliminate corrosion through DC

voltages between gage and beam. This is an undesirable characteristic, but brought out here since it would not allow use of these gages for long time creep measurements in which a single stable zero point is required to determine that the material is creeping and not the gage. This will require future tests to separate metallurgical changes in the wire, producing a resistance change, from the corrosion factor which will also produce a resistance change. A preliminary test of the wire alone at 200°F over 1000 hours showed only a very slight change in resistance. Further tests with the wire while in a resistance spool form with welded connections should be made at the 600°F temperature.

B. Short Time Testing and Dynamic Testing

In this field, the important items are the stability of gage factor with time and a constant gage factor with temperature. Fig. 8 shows a plot of gage factor versus tem-

Figure 8.

Figure 9.

perature from 70°F to 1000°F. This gage has a mean gage factor of 1.82 with a variation of plus or minus 7% from 1.72 to 2.0. For dynamic work, results could be read directly within the 7% limit over any temperature from 0 to 1000°F. These gages can be used for short time static testing if the temperature is held relatively constant. This also requires a zero load reading at the test temperature.

Fig. 9 shows some of the apparent temperature strain

occurring over 700°F. The strain readings produced by temperature change alone between 800°F and 1000°F are quite large and not as predictable as they are below 600°F, where the relation holds, such as shown on the 1000 hour period in Fig. 4.

In computing the gage factors for these tests, a Modulus of Elasticity of Inconel was selected to suit the temperature from handbook data, and not actual tests of the Inconel material used.

CONCLUSIONS

1. A high temperature strain gage described herein has the characteristics equal to the commercial Baldwin Type "A" gage for use on short time static tests in the order of 4 to 8 hours. For tests of longer duration, the corrosion problem must

be solved to match the long time stability of the low temperature type A gages.

2. For dynamic testing, these gages are suitable up to 1000°F. They are also usable for a short time static testing up to 1000°F if the temperature is held constant and a zero or no load reading can be made at this temperature.

AUTHOR'S NOTE:

The following proposed commercial construction of gages was received from R. J. Carleton, Jr., GILMORE INDUSTRIES, "I would use simple expendable frames to hold bare wire gages and leads. With additional development, a semi-flexible wafer probably could be made with the later modified Quigley ceramics used."

REFERENCES

1. L. M. Ball — SESA Proceedings — Vol. III, No. 1 — "Strain Gage Technique."
2. R. S. Barker — SESA Proceedings — Vol. XI, No. 1 — "Self Compensating SR-4 Strain Gages."
3. Kemp, Morgan & Manson — NACA TN-1174 — "High Temperature Strain Gages, etc."
4. Kemp, Morgan & Manson — SESA Proceedings — Vol. V, No. 1 — "High Temperature Strain Gages, etc."
5. Kemp, Morgan & Manson — SESA Proceedings — Vol. VIII, No. 2 — "High Temperature Strain Gages, etc."
6. D. J. DeMichele — Product Engineering, October 1950 — "Strain Gages for Elevated Temperature Service."
7. R. E. Gorton — Pratt & Whitney Aircraft Report, 1950 — "An Electrical Strain Gage for Measurement of Static Strain Up To 1600°F."
8. R. E. Gorton — SESA Proceedings — Vol. IX, No. 1 — "Development and Use of High Temperature Strain Gages."
9. J. E. Carpenter & L. D. Morris — SESA Proceedings — Vol. IX, No. 1 — "A Wire Resistance Strain Gage for Measurement of Static Strains at Temperatures up to 1600° F."
10. E. E. Day — SESA Proceedings — Vol. IX, No. 1 — "Characteristics of Electric Strain Gages at Elevated Temperatures." (Note: To 200°F only.)

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ETCHED FOIL HIGH TEMPERATURE STRAIN GAGES

BY

FRED N. SINGDALE, SENIOR PROJECT ENGINEER RESEARCH
AND RAYMOND A. ALLEMAN, PROJECT ENGINEER RESEARCH
BALDWIN-LIMA-HAMILTON CORPORATION
Philadelphia 42, Penna.

At the present time, Baldwin-Lima-Hamilton Corporation, is making foil type strain gages which are applicable to high temperature operations. These gages are manufactured on a strippable backing material, (EC-1220 MMM) which permits handling the grids without damage. During application of the grid to a test specimen, the backing material is stripped from the grid leaving it embedded in the cement or adhesive chosen for that particular application.

At this writing, these gages are made from 0.0005" thick nichrome or nichrome V foil. This does not necessarily limit the making of the grids to these particular foils. Other foils have been used and are being considered for use at a later date. The foil as received from the manufacturer is cut into suitable lengths which are then thoroughly degreased and chemically cleaned. After the cleaning operation, a light-sensitive coating is applied to one side of the foil and spread evenly by use of an infra-red whirler. During the whirling operation, infra-red lamps dry the coating. After coating, an image of the desired strain gage is printed on the sensitized foil. This operation is accomplished by contact printing from a line negative in a vacuum press using an arc lamp to obtain proper exposure. After exposure, the image of the gage grid is developed by photographic means forming an acid resisting coating on the foil. The acid resisting coating is dried then the reverse side of the foil is carefully cleaned a second time in preparation for the application of the backing material. This backing material (EC-1220 MMM) is sprayed onto the back surface of the foil to form a uniform coating. When the backing material is thoroughly dried, the prepared foil is placed in a spray etcher to etch away the excess foil surrounding the grids which are protected by the acid resisting coating. The strippable backing material is not affected by the acid and holds the grids in proper orientation during this etching operation. After etching the sheets are thoroughly washed to remove traces of the etchant. The acid resisting coating is then removed by use of solvents. The final operation is to cut the sheets into individual gage grids. These are then optically inspected and checked for resistance.

DETAIL APPLICATION PROCEDURES

Although the use of the method described above utilizes many various types of cements and adhesive materials, for the purpose of brevity and simplicity, the detailed steps below describe only four of the cements which have been used.

I. For Use Up To 700°F

In this application a cement designated RX-1 is utilized. This cement is a sodium-silicate base material.

1. The surface to which the gage is to be applied

- should be sandblasted and chemically cleaned.
2. Stir the RX-1 until the consistency of cream.
3. Paint a thin coating of RX-1 on test specimen, allowing 1 hour drying time at 150°F.
4. Apply second coating, and, while the cement is still wet, place gage face down into the coating, strip backing material from the gage using a pair of tweezers and pick to assist in holding down the grid while pulling the backing material free.
5. After a drying period of 1 hour at 150°F, if in the judgment of the technician the bond is not complete, a third coating is applied over the complete assembly. DO NOT COAT TABS.
6. Allow assembly to dry slowly at a temperature of 150°F for a period of 24 hours.
7. After the drying period, attach leads to the gage tabs by means of spot welding. This laboratory uses a Unitek Corp., Pasadena, California, Stored Energy Spot Welder, Model 1016.

NOTE:

Check resistance between the base metal and the gage. If not over 50,000 ohms, heat assembly to approximately 250°-300°F for at least 1 hour. The user will find it necessary to cycle the test assembly both at temperature and load at least three times before it is possible to obtain reproducible readings. However, during the preliminary cycling, if the gage is correctly bonded, the user will find that the resultant differentials in readings are approximately the same value.

II. For Use Up To 900°F

In this application a ceramic coating material prepared at Baldwin-Lima-Hamilton Corporation and designated BLH-388 is utilized. Paired with this BLH-388 is a material BLH-388F which basically is the same ceramic combination suspended in a fire lacquer. This BLH-388F is used as an adhesive to assist in holding down the grid prior to firing.

1. Same as I. in I.
2. Stir BLH-388 until the consistency of light cream, add distilled water if necessary.
3. Using a very fine brush, apply a thin coating (approximately .001") to the surface of the test specimen.
4. Allow 10 minutes to dry. Fire at 900°F for approximately 12 minutes.
5. After the test specimen has cooled to room temperature, apply a thin coating of BLH-388F to the face of the gage grid. It is important that some effort be made to remove any oil from the gage surface that might exist as a result of handling. Most solvents will attack the backing ma-

terial, but a few deft strokes with a cloth that has just been wet with a solvent will usually be effective without harming the backing material.

6. Before the BLH-388F has had time to dry, lay the gage grid face down over the previous coated surface. Press the gage flat, then strip the backing material from the gage. It is helpful to use a pair of tweezers and pick.
7. Dry for 1 hour at 150°F. Longer drying will be helpful.
8. Apply a thin coating of BLH-388 over the gage assembly, approximately .001". DO NOT COAT TABS.
9. Allow 10 minutes drying time. Fire at 900°F for 12 minutes.
10. Same as 7. in I.

NOTE:

This method is intended for use primarily on aluminum. Again the user will find it helpful to cycle a few times prior to taking static data.

Figure 1 — Etched-foil strain gage grid.

III. For Use Up To 1100°F

In this application a standard commercially available cement is utilized. This material is designated AL-P1 and is manufactured by the Robert G. Allen Company, Mechanicville, New York.

1. Same as 1. in I.
2. Stir AL-P1 well prior to using, making sure all color is green.
3. Apply a thin coating to the test specimen and allow to dry, then cure by bringing to a temperature of 600°F for approximately 1 hour. It is not necessary to cure at temperature if assembly will reach this temperature in operation.
4. Apply a second thin coating of AL-P1 to the test specimen. Place the gage grid face down into the coating. Strip backing material from the gage grid using a pair of tweezers and pick to assist in holding down the grid while pulling the backing material free.
5. Allow to dry, apply a third thin coating, allow to dry. DO NOT COAT TABS.
6. Cure at 600°F for at least an hour.
7. Same as 7. in I.

NOTE:

As in above, it is helpful to cycle a few times prior to taking static data.

IV. For Use Up to 1800°F

In this application as in II a ceramic coating material is prepared at Baldwin-Lima-Hamilton Corporation. The designations of this coating and adhesive are BLH-418 and BLH-418F.

1. Same as 1. in I.
2. Stir BLH-418 until the consistency of a light cream, add distilled water if necessary.
3. Using a very fine brush, apply a thin coating (approximately .001") to the surface of the test specimen.
4. Allow 10 minutes to dry, fire at 1800°F for approximately 12 minutes.
5. After the test specimen has cooled to room temperature, apply a light coating of BLH-418F to the face of the gage grid. It is important that some effort be made to remove any oil finger marks that might be present. Most solvents will attack the backing material but a few deft strokes with a cloth that has just been wet with a solvent will usually be effective without damaging the backing material.
6. Before the BLH-418F has had time to dry, lay the gage grid face down on the previously coated surface. Press the grid flat, then strip the backing material from the grid immediately, using a pair of tweezers and pick to assist in holding down the grid while pulling the backing material free.
7. Allow 1 hour for drying at 150°F.
8. Apply a thin coating of BLH-418 over the gage assembly, approximately .001". DO NOT COAT TABS.
9. Allow 10 minutes drying time, fire at 1800°F for 12 minutes.
10. Same as 7. in I.

NOTE:

This application is intended for dynamic measurements only.

In the use of the above described grids as high temperature strain gages it has been found necessary to use a "dummy gage" of the same nominal resistance in the circuit. This dummy gage compensates to a large extent for temperature variation. In order to obtain stability of the gages at high temperatures the "dummy gage" is essential. However, for dynamic work where less accuracy is required, single gages may be used.

Shown in Fig. 1 is an example of one type of an etched-foil strain gage grid.

WORK OF WESTINGHOUSE ELECTRIC CORPORATION

CONTRIBUTED BY
E. J. WISNIEWSKI
HEAD, EXPERIMENTAL MECHANICS SECTION
WESTINGHOUSE ELECTRIC CORPORATION
AVIATION GAS TURBINE DIVISION
Lester, Pennsylvania

Fig. #1, illustrates a static calibration at elevated temperatures, of a pair of Baldwin-Lima-Hamilton AB-11 strain gages.

The curve, Fig. 2, furnished by Westinghouse Electric Corporation, Aviation Gas Turbine Division, shows "Correction for Gage Factor" for Baldwin SR-4 Bakelite Strain Gages, Type CB-11, plotted against temperature in degrees F representing typical correction factor charts as used by Westinghouse. The interesting feature about this chart is the fact that following prescribed temperature cycles, as indicated on the chart, the gages were run to 700°F and above before they failed, and that on the last incomplete

circles represent the plotted points for the two gages on bar No. 1 (which ran to 850°F before they were des-

Figure 1.

cycle in some cases the correction factor above 400°F flattened out. Further, gage No. 1 (bar No. 2), exhibited a flat curve, not exceeding $K = 1.5$.

The correction factor K , as shown, is the ratio of millivolts output at 80°F to output at the specified elevated temperature.

This chart is a composite curve of four gages, two on test bar No. 1 and two on test bar No. 2. Closed and open

Figure 2.

Figure 3.

Figure 4.

Figure 5.

troysed); dot-dash line and dash line represent the plotted points of the two gages on bar No. 2 (which ran to 700°F and 750°F).

The lead to grid connection of this standard CB-11 gage was conventional. Cement was Bakelite No. BC 6035. The wire in C type gages is Iso-Elastic material. Gages were held at 600°F to 700°F for one half hour without retrogression.

It was learned that precautions necessary to assure the successful use of "B" gages at high temperature were:

- Lay down a precoat of a ceramic insulating material.

Figure 6.

Figure 7.

- Keep the Bakelite cement BC 6035 refrigerated prior to use.
- Always insist on a fresh batch of cement when purchasing.
- When using the cement, take only enough out of the refrigerator to take care of the needs at the moment. *Do not put excess cement back into refrigerator.*

Another fact brought out which assures successful operation of the gages at high temperature is to cure cement at 50°F higher than intended use for approximately 30 minutes. For example:

To use at 500°F — cure at 550°F.

To use at 600°F — cure at 650°F.

Other pertinent information supplied by Westinghouse concerning the CB-11 gages may be observed in Figs. #3 through #14.

All of the curves supplied by Westinghouse are relatively self-explanatory. It may be observed in Fig. #15, the type of calibration assembly used to test strain gages at high temperatures. Fig. #16, shows the construction of the Westinghouse high temperature strain gage. Then

in Figs. #17 through #20, pertinent test data on the Westinghouse gages are shown.

The author suggests that any additional information on the Westinghouse high temperature strain gage program, be obtained by writing to the Head of the Section that contributed this work.

AUTHOR'S NOTE:

The General Electric Company, Schenectady, New York, through their representative, Mr. D. J. DeMichele, contributed the following information in regard to using Baldwin-Lima-Hamilton Corporation Bakelite gages at high temperatures:-

- Bakelite gages have been used at G.E. at temperatures up to 700°F for periods of 4 to 5 hours.
- The technique includes laying down an undercoat of an insulating material prior to installing the

gages in the conventional manner. General Electric has used a ceramic material designated as Allen's cement P-1, manufactured by Robt. G. Allen Company. In later test work a ceramic material, designated by the Bureau of Standards as L6AC was favored. A still later development included the use of a General Electric ceramic material designated either LP-28 or LP-29.

- It is contended that the Bakelite gages work satisfactorily but do not have a good appearance at 700°F.
- Lead connection to the gages was made by resistance welding.
- When the gages failed, it was noted that failure occurred at the lead junction and the leads were heavy with oxidation. It was concluded that the excessive oxidation was a result of the use of Advance wire in the gage construction.

Figure 8.

Figure 10.

Figure 9.

Figure 11.

Figure 12.

Figure 13.

Figure 14.

In mounting gage in Fig. 16 vapor blast portion where gage is to be located. Apply undercoat of ceramic and fire to 1750°F for ten minutes. Cool gradually. Mount strain gage and apply several thin coats of cement. Bake each coat a minimum of 30 minutes at 150°F and 30 minutes at 500°F. Attach lead wires.

Figure 15.

Figure 16.

Figure 17.

Figure 18.

Figure 19.

Figure 20.

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GLASS WOVEN STRAIN GAGES

CONTRIBUTED BY
JONES, STROUD & CO., LTD.
Vida Mills, Long Eaton
Nottingham, England

Glass woven strain gages or ribbon gages are made by braiding and weaving glass insulated wire. The wire used in this process is .0005" Nichrome or Karma (the latter is preferred) braided with 4 strands of glass and woven into a ribbon (See Fig. 1). It may then be cut to desired lengths to form high resistance medium — high temperature gages. These are made up of four different structures,

Figure 1 — Vida 1006 Cloth Sample Magnification x10
Warp is vertical; woof is horizontal.

namely; Vida 1006, 1008, 1014 and 1016. With regard to making gages from the woven ribbon, it requires dexterity in handling because of the characteristics of the glass fiber structure.

Narrower widths of ribbon, $\frac{1}{2}$ ", $\frac{1}{4}$ " and $\frac{1}{8}$ " of glass covered and bare oxidized wire are being investigated.

The firm which has had the broadest experience with these gages are Messrs. Rolls-Royce. They have found that Quigley Blue No. 1925 AAA cement is quite satisfactory for turbine blades whose temperature may go up to 1250°F or 675°C and, therefore, they have been using exactly the same cement on the glass gages although they have not taken these much above 1000°F or 540°C.

Rolls-Royce have not attempted to use them on the hotter parts of turbine blades, but they have been put on turbine discs, on the later stages of compressor blades, and also on jet engine exhaust systems where the temperature is above 1000°F or 540°C or even a little higher.

The parts to be gaged have been smeared with a thin layer of Quigley which has been dried over an incandescent lamp for a half hour. The dried cement is then coated by brush with a further thin layer of cement. After the

cement is cured an additional extra thin layer of cement is brushed on and the gages laid down.

The temperature of the completed job is gradually raised to 212°F or 100°C and then in increments up to 650°F or 340°C. The total drying process lasts for about 36 hours.

Messrs. Rolls-Royce are of the opinion that this time could be cut to a shorter period, but they still feel that it

Figure 2 — The Woven Glass Fabric Strain Gage.

is vitally important that the initial drying out of the moisture from a gage should not be hurried.

The gages are easily cut to length with an ordinary pair of scissors and the wires welded to the connecting leads in the usual manner. The weld presents no greater difficulty than that of any other form of strain gage.

Information concerning these gages furnished by Mr. Dennis Drew of Rolls-Royce, Ltd., Derby, England, and Mr. H. Jones of Jones, Stroud & Co., Ltd., is gratefully acknowledged.

AN OPTICAL STRAIN GAGE FOR USE AT ELEVATED TEMPERATURES

CONTRIBUTED BY
AMERICAN INSTRUMENT COMPANY
Silver Spring, Maryland
IN COOPERATION WITH
P. R. WEAVER
NATIONAL BUREAU OF STANDARDS
Washington, D. C.

INTRODUCTION

The optical gage described in this report is capable of operating at temperatures up to 500°F. It was designed and developed at the National Bureau of Standards for use in determining the mechanical properties of material at elevated temperatures and for evaluating the performance of remote-reading strain gages at high temperatures.

Work is in progress on the development of this type of gage for use at higher temperatures.

DESCRIPTION OF GAGE

The optical strain gage employs a double mirror arrangement in conjunction with the autocollimated projection and observing system. The light path is shown in Fig. 1. Readings taken with the autocollimator perpen-

Figure 1 — Double Mirror Collimated System.

dicular to the line of intersection of the two mirrors depend only on the angle between the two mirrors.

Since the coefficients of expansion of the gage body and the specimen will differ, the reading of the gage will change with temperature. After preliminary tests, the gage reading at room temperature is adjusted to the value required to give the correct reading at the test temperature.

Fig. 2 shows an American Instrument Company drawing of a gage for high temperature use. The gage bodies were constructed of cold rolled steel and they have a nominal gage length of $\frac{1}{2}$ ". The fixed mirror is shown at A and the hinged mirror at B. When the specimen to which the gage is attached is strained, the hinged mirror rotates in the 110° notch provided by the side plates shown at D in Fig. 2. These mirrors, made of stellite, have knife edges (C, Fig. 2) which define the gage length. The gages are held in place by a small clamping force.

The gages have a maximum strain range of .024 with a blind spot at midscale equal to .004. They have a strain sensitivity of .000008 when used with an autocollimator

OPTICAL STRAIN GAGE ASSEMBLY
HIGH TEMPERATURE TYPE

Figure 2.

Figure 3 — Observing field as seen through the eyepiece of the autocollimator.

equipped with a vernier reticule. The viewing field, showing the reflected image and its vernier as seen through the Tuckerman autocollimator, is shown in Fig. 3.

CALIBRATION OF GAGES

When the gage is used at 500°F, a change of considerably less than 1% in gage factor results.

By means of a transfer system, accurate to about 1%, the high temperature gage was compared with a standard Tuckerman optical gage for temperatures up to 500°F. The two gages agreed within the experimental error of 1%. There was no evidence of a systematic error.

DEVELOPMENT OF GAGES FOR HIGH TEMPERATURES

A start has been made toward the development of a strain gage for use at higher temperatures by developing a suitable reflecting surface. Two combinations of materials have been found satisfactory for use as mirrors at temperatures above 1000°F. One of these, fused quartz coated with silicon, had good reflectivity up to 1000°F. The other, fused quartz coated with rutile, was satisfactory up to 1800°F.

AUTHOR'S NOTE:

"The interest of Baldwin-Lima-Hamilton Corporation in undertaking this high temperature strain gage project, without fee for itself, stems from its early activity in 1939 in proposing self contained temperature compensated gages employing two filaments of different materials and of different and opposite coefficients of electrical resistance. (Ruge Patent No. 2350972) This principle offered the possibilities of high temperature static measurements but, unfortunately, the metallurgical composition of present types of wires limited its temperature range. This suggests a further fruitful source of research in the field of metallurgy to find suitable wires."

Because of the lack of metallurgical progress sufficient to make the temperature compensated strain gages suitable for high temperature applications, Baldwin-Lima-Hamilton Corporation then proposed that the two filaments should have temperature coefficients of resistance, as measured when the strain gage is attached to the test surface, of the same algebraic sign. (Ruge patent No. 2,672,048.)

"Another principle employed by Baldwin-Lima-Hamilton Corporation in 1947 which appears to offer promise in the high temperature field is that of using a removable supporting member for the gage filament during its transfer to a test member."

HIGH TEMPERATURE STRAIN GAGES

SUBMITTED BY

MESSRS. G. C. KUCZYNSKI; P. F. STABLEIN AND E. A. PERETTI
DEPARTMENT OF METALLURGY
UNIVERSITY OF NOTRE DAME
Notre Dame, Indiana

REVIEW OF PREVIOUS WORK

R. E. Gorton¹, working for Pratt and Whitney Aircraft, developed a strain gage operating on the same principle as the SR-4 gage and used it for measuring stresses in turbine blades. The results of the field tests were not reported. The gage has a flat grid $5/16'' \times 5/16''$ of closely spaced .0007'' Nichrome V (Ni-80, Cr-20) wire and was mounted in refractory cement by a specially constructed jig. The resistance and gage factor at 1200°F to 1500°F were about 650 ohms and 2.0 respectively. It should be noted, however, that the gage factor was found to decrease linearly from about 2.5 at room temperature. This decrease was found to change appreciably from gage to gage. The greatest disadvantage of this gage is that it has to be prepared on the spot by a specially constructed, complicated jig. It is quite obvious that under these conditions it is difficult to compare the readings of two different gages.

J. E. Carpenter and L. D. Morris² describe a gage almost identical to Gorton's, which has been used in the determination of static strains at temperatures up to 1600°F . The gage was a Nichrome V wire grid mounted on the test member by a special jig, perhaps less complicated than that used by Gorton, but troublesome enough. Carpenter and Morris found much greater changes in the gage factor. According to them, it decreases from about 2.0 at room temperature to 1.0 at 1500°F ³. The electrical resistivity measurements performed by J. C. Wilson⁴ on Karma alloy (Ni-73, Cr-20 and Al + Fe) seem to indicate that all alloys of compositions close to Ni-78, Cr-22 undergo an ordering transition in the vicinity of 800°F and, therefore, should not be used in the gages operating at elevated temperatures. Carpenter's gage, like Gorton's, has no temperature compensation.

The main disadvantage of the gages built on the SR-4 principle for use at elevated temperatures is an unreliability caused by rather awkward mounting techniques, limiting their use to certain narrow fields of laboratory applications. The need is for a gage which could be manufactured and calibrated outside the structure under test and then be simply mounted on it. This was our goal in the preliminary investigations described in the following sections of this report.

Two different types of high-temperature gages, the extensometer type⁵ and optical gage⁶ will not be described here as they are so specialized that they could only be used in certain distinct laboratory problems and do not lend themselves to easy modification for more general use.

Thus far, all efforts in the construction of a high-temperature strain gage, seem to be slavishly chained to the design of the SR-4, so successful at room temperature. Although, in the opinion of the authors of this report, this type of gage is not the best suited for high tempera-

ture use, it could be built and operated, but in a different manner than suggested by Gorton or Carpenter and Morris. Discussion of such a gage will be found in the following section.

EXPERIMENTAL PROCEDURE

The tensile type of test was decided upon in which a 100,000 lb. Baldwin-Tate-Emery Tensile testing machine would be used. A split tube furnace operating in a vertical position was used with the test bar screwed into the tension grips of the machine.

The test member was a 24'' length of 1'' diameter 18-8 stainless steel (Fig. 1) threaded to fit the grips of the tensile machine. The rectangular test section, (A in Fig. 1) $.5'' \times .1'' \times 3''$ long, is milled at the center of this bar.

The test member mounted in the split furnace, is shown in Fig. 2. A chromel-alumel thermocouple, used for temperature measurement, was located in the test area between the heating elements and the test section. The furnace maintained control in the test area of $\pm 5^{\circ}\text{F}$ at all temperatures of test.

Figure 1 — Test beam with gage.

The gages investigated consisted of 3 or 4 loops of 5 mil wire strung between two ceramic posts. The post, $1/8''$ in diameter and $1/8''$ high, were fastened with Bakelite cement in a standing position about $1 1/4''$ apart, to a strip of paper which is, in turn, firmly bonded to a small glass or metal plate for rigidity and ease of handling. In each case the object is to provide a surface to which the high temperature cement would not bond. Then gage wires could be

Figure 2 — Test beam mounted in split furnace.

strung taut between the posts, and the ends tied down on the Bakelite. When this was inverted over the test section, Sauereisen cement was used to carefully cement each post and the end loops firmly in place and the unit was left to dry at room temperature. The process of mounting a wire gage is represented in Fig. 3. After drying for 24 hours, the backing strip could be easily removed with a razor, leads attached, and the gage made ready for testing. The leads were connected to a Wheatstone bridge and resistances measured at the testing temperature as a function of the mechanical strains applied. Readings were taken for increasing and decreasing strains. The circuit was capable of reading a 30 ohm resistance to five significant figures. Longitudinal grooves were ground in the heavy section of the bar and ceramic insulators cemented into place. Electrical connections were then made without causing chimney effects in the furnace.

Figure 3 — Close-up showing the mounting of a wire gage.

The problem of attaching leads to the test wires was a difficult one. Spot and gas welding were tried, but the large lead wires (25 mils) could not be effectively welded to the small test wires. Large lead wires had to be used to reduce lead resistance. As a result, silver soldering was used for connections. Since the wires used for testing were not available in large sizes, lead wire of a different composition was used in each case. These wires were chosen experimentally to give as low a thermo-electric power as possible, so that connections could be made wherever con-

venient, in the test area or outside, without an emf causing permanent deflections of the galvanometer in the bridge circuit.

EXPERIMENTAL RESULTS

a) Wire Gage Mounted on Posts

In the previous section the idea was expounded that many of the problems involved in designing a high temperature strain gage could be met by mounting the measuring elements of the gage on refractory posts. These refractory posts, in turn, would be cemented to the test structure. The obvious advantages of such an arrangement are:

- 1) the gage could be manufactured and calibrated outside the test structure,
- 2) the problem of cementing would be greatly simplified, as it is easier to secure a good adherence of cement to metal on a comparatively small area of the post's cross-section than on a much larger one comprising the whole grid, and
- 3) the temperature compensation device could be mounted on the same posts.

The simplest gage of this type is represented in Fig. 4A. It is composed of two ceramic posts around which .005" diameter wire is wound. Such a gage can easily be prepared on a piece of paper-covered Bakelite and mounted on the structure under investigation with some refractory cement previously tested for good adherence at elevated temperatures. After the cement has set, which usually takes up to 12 hours, the gage can be detached from the paper with a thin razor and made ready for performance. As the distance between the two posts increases due to the thermal or mechanical strains, the wire wound around them increases its electrical resistance in proportion to the distance moved.

A change of resistance will be observable only if the temperature coefficient of expansion of the material in the tested member is equal to or higher than that of the gage wire. This condition is easy to meet. The gage has, however, obvious disadvantages; namely, it is not applicable to situations involving large compressive strains and it is limited in the facility with which it can be mounted on sharply curved surfaces.

Another limitation exists because of the mechanical properties of the wire material used in the gage. After the

Figure 4 — (A) Simple wire gage; (B) Wire gage with temperature compensation; (C) Wire gage with thermal-stress compensation.

yield point of this material is exceeded, a permanent extension of the wire will occur, manifesting itself as a permanent increment of electrical resistance. We shall see later in the report how this factor can be minimized.

The materials selected were among the alloys which can withstand temperatures up to 700°C-800°C without excessive oxidation. Such material can be found among nickel-chromium-iron or nickel-copper alloys. The selected alloys were Wilbur B. Driver Company products such as Tophet A (80-Ni; 20-Cr) otherwise known as Nichrome V (Driver-Harris Company nomenclature); Tophet C (60-Ni; 15-Cr; 25-Fe); Evanohm (75-Ni; 20-Cr; 2.50-Cu; 2.50-Al); and Cupron (45-Ni; 55-Cu). Evanohm corresponds roughly to the composition of Driver-Harris Karma, investigated by Wilson⁴, and Cupron corresponds to Advance. Tophet A and C wires were tested in air between room temperature and 700°C and Evanohm and Cupron between room temperature and 400°C. Their physical properties which are pertinent to the high temperature gage are listed in Table I. In the second column of the table the values of specific resistivity as measured at room temperature are given. The third column is filled with the data on thermal coefficients of expansion as measured between room temperature and 100°C. In the fourth column the temperature coefficients of electrical resistance, $\frac{dR}{RdT}$, and in the fifth column, the gage factors, g , at room temperature are listed. In the last column the temperature coefficients of the gage factors as measured between room temperature and 700°C are given. The latter values for Tophet A and C were obtained from the plot represented in Fig. 5. The values of the temperature coefficients of gage factors for Evanohm and Cupron were determined only for temperatures up to 450°C. The values of the gage factors, g , fall from 2.33 at room temperature to about 1.2 at 550°C for Tophet A and from 2.75 to 1.0 at 700°C for Tophet C. It should be noted that $g = 0.70$ for Cupron at 350°C. The values of the gage factors at elevated temperatures are close or even lower than 1.0, indicating that this effect is not due to the shape change, but to the intrinsic changes in the alloy itself.⁷ This is quite probable since all alloys discussed here are magnetic and undergo ferro to paramagnetic transitions at various temperatures, which may cause profound changes in the sensitivity of the electrical resistance to strains.

TABLE I
Characteristics of the Gage Materials

Material	$\rho \times 10^{-6}$ ohm-cm	$\alpha \times 10^{-6}$ per degree	$\frac{dR}{RdT} \times 10^{-4}$ per degree	g at room temp.	$\frac{dg}{gdT}$ per degree
Tophet A	108.0	12.5	1.37	2.33	-1.00×10^{-3}
Tophet C	112.0	13.5	1.59	2.75	-1.00×10^{-3}
Evanohm	134.0	14.0	.2	0.5	-2.10×10^{-3}
Cupron	48.4	15.0	.2	2.0	-2.00×10^{-3}

Measured temperature coefficient of resistance of Tophet C
(25° — 700°C):
 $1.48 \times 10^{-4} - 1.74 \times 10^{-4}$ per degree.

The gage factor temperature coefficients are high for all of these alloys, introducing about 10% error in strain readings if the temperature fluctuation is of the order of 100°C. It should be noted that Gorton¹ found that the gage factor temperature coefficient is only -2×10^{-4} or five times smaller than observed by us. However, the data of Carpenter and Morris² indicate that it is between -3.0×10^{-4} and -2.3×10^{-3} . They also noticed a great decrease of the gage factor above 500°C, due to the disordering of the alloy. These rather large variations of gage factor with temperature, even if temperature compensation is available, make the wire gage an inherently inaccurate measuring device.

Table I reveals that the temperature coefficients of electrical resistance of all alloys tested are reasonably small. Wilson⁴ found that in the case of Karma (Evanohm in our case) this coefficient remains reasonably constant up to 400°C, but above this temperature it undergoes large changes. Gorton¹ found that the temperature coefficient of resistance of Nichrome V (our Tophet A) decreases steadily from 1.37×10^{-4} at room temperature to 0.64×10^{-4} at 750°C. We measured the coefficient for Tophet C, the most promising alloy of the whole group and found it increasing very little from 1.50×10^{-4} at room temperature to 1.74×10^{-4} at 700°C.

TEMPERATURE COMPENSATION

The greatest advantage of a gage mounted on posts is that it can be supplied with an adequate temperature compensating device. The simplest device of this kind is a loose coil of wire of the same composition and same length as the gage wire. This coil can be suspended between two posts as in Fig. 4 B. In such an arrangement both gage wires and coil wire will always remain at the same temperature. If this coil is placed in a Wheatstone bridge circuit, as the dummy gage in the Baldwin indicator, it will eliminate any change of resistance due to the fluctuation of temperature in the vicinity of the gage. It is possible also to eliminate any change of resistance induced in the wire by thermal strains and measure only the strains set up in the material by mechanical means.

The gage which can do this is represented in Fig. 4 C. It is composed of two refractory posts with wire wound

Figure 5 — Gage Factor, g , as a function of temperature.

around them. Inside this coil is another smaller one, of the same wire, wound around one refractory post of the gage and another refractory post attached to the end of the rod made of the material of the tested member. The other end of this rod is built into the gage post. With a change of temperature, the material of the tested member expands, stretching the wire in the main gage. But at the same time, the wire of the second internal coil is stretched by the same amount because the rod is of the same material as the tested member. If, therefore, both coils have the same original resistance and are placed properly in the measuring electrical circuit, the reading on the galvanometer will be zero, unless the main coil is stretched additionally by strains mechanically applied in the tested member. Thus, the influence of the thermal stresses can be eliminated if so desired. Of course, the same gage can have both temperature and thermal stress compensation.

It has been mentioned before that the wire gages mounted on the refractory posts have the disadvantage of poor stability due to the permanent deformation of the component wires. This permanent deformation produces a permanent increase of resistance and subsequently an undesirable hysteresis in the resistance versus strain curve. This disadvantage can be minimized either by selecting a high yield point alloy for the gage wire or by modification of the gage itself. The search for high yield point material should be encouraged irrespective of the modification mentioned above, because the latter will reduce greatly the sensitivity of the gage itself. A gage in which the thermal strains are reduced by a known factor is represented schematically in Fig. 6. It is composed of four refractory posts A, B, C and D, of which A and D are cemented to the tested surface. The posts B and C are attached to the ends of two rods, both of the same length a , made of the same material as the tested member. The gage wire is wound around posts B and C. It is obvious that by adjusting the distances a and b we can reduce the strain in the gage wire by a desired ratio. Of course, the sensitivity of such a gage to the thermal strains will decrease in the same ratio.

TEST RESULTS

The wire gages were mounted on the stainless steel beam with Sauereisen cement No. 21. The cement was left to set for 12 hours. Then the beam was placed within a furnace and mounted in the Baldwin tensile machine. The furnace was brought to the desired temperature measured by a thermocouple placed directly over the gage. As soon as the temperature reached equilibrium, the stress was applied. The strains were measured by SR-4 gages attached to the brass strips outside the furnace. All tests were essentially static because the stress was always applied very slowly. The description of apparatus and procedure was given in the section entitled "Experimental Procedure". Typical curves of the increment of the unit electrical resistance, $\frac{\Delta R}{R}$, versus strain, ϵ , for Cupron at 350°C are given in Fig. 7, where the empty symbols (squares, triangles and circles) denote readings during decreasing strains. The curves of Tophet C at 340°C and 540°C are shown in Figs. 8 and 9. It is to be noted that the scatter of the points along these lines is not appreciable. Tophet C at 540°C, after stretching by 6×10^{-4}

inch/inch, exhibits an appreciable permanent increment of electrical resistance. The curve for Cupron is not linear after the same strain is exceeded; however, surprisingly enough, the points obtained on unloading follow the loading curve quite regularly. Therefore, it seems that the simple gage with temperature compensation can be expected to work fairly well up to 500°C. Above this temperature, however, the thermal stress-reducing design, as described at the end of the previous paragraph should perform better.

To test the temperature compensating gage, described in the previous paragraph, the Tophet C gages with the compensating coil were mounted on pieces of stainless steel and these were placed in the furnace at various temperatures up to about 550°C. The gages were strained by expansion of the steel on which they were mounted. As the lengths of the gage wire and compensating coil were never equal, the increments of unit resistance in them were plotted separately.

Figure 6 — Wire gage with stress reducing device.

Four tests in the temperature range 400°C to 500°C gave values of gage factor between 1.50 and 1.70, in agreement with the values previously obtained and plotted in Fig. 5. Typical sets of curves for the resistance of the gage and compensating coil wires obtained are represented in Fig. 10. The changes of resistance of the compensating coil are represented by the lower curve.

Finally, a gage with a thermal stress compensating coil has been made and tested. Again, as in the case of temperature compensation, two coils, the measuring one and compensating one, had different resistances. However, when their resistances were measured as a function of temperature, with mechanical stresses absent, two parallel lines were obtained, proving that the compensating device is satisfactory.

CERAMIC—METAL GAGES

Parallel to the development of the wire gages, some research was conducted on sintered mixtures of cement and powdered metals. The principle of this type of gage is that at a certain metal/cement ratio there is a limited number of current paths through the material. Each path leads through the bonds between two adjacent metal particles. Some of these bonds are only contact bonds and can be easily severed by a small strain, producing large increments of electrical resistance of the whole mass. If the material is elastic enough, the release of strain should produce a system statistically equivalent to that at the beginning of the experiment. The advantage of a cement-metal gage is its simplicity and its ease of application directly to the surface of the tested structure using only a thin layer of insulating cement. It should also be reasonably inert to the atmosphere if proper metallic powders are chosen. With regard to the latter condition, silver and

Figure 7 — Increment of unit resistance, $\frac{\Delta R}{R}$, as a function of strain, ϵ , for a cupron gage at 350°C.

Figure 8 — Increment of unit resistance, $\frac{\Delta R}{R}$, as a function of strain, ϵ , for Tophet C gage at 340°C.

Figure 9 — Increment of unit resistance, $\frac{\Delta R}{R}$, as a function of strain, ϵ , for Tophet C gage at 540°C.

stainless steel powders were selected. The stainless steel was eliminated after a few preliminary experiments because the small particles of powder were oxidized in the process of sintering. This silver-Sauereisen 31 cement mixtures were more successful.

Mixtures containing 5, 10, 15, 25, 30, 35, 40, 50, 60, 70, 80 and 90 weight-percent of silver were thoroughly milled together, stirred with the liquid binder, and rolled into thin wafers with silver grid-like leads inserted in them. After setting for 24 hours on non-bonding material such as Bakelite, they were transferred into a furnace for sintering at 800°C for periods of time ranging from 1 to 3 hours. This sintering temperature was at least 100°C higher than any subsequent testing temperature and, therefore, should have stabilized the compact at lower temperatures. After sintering, the wafers (see Fig. 11) were cemented to the test section and tested at temperatures

Figure 10 — Increments of unit resistance, $\frac{\Delta R}{R}$, of the Tophet C gages and temperature-compensating coil as a function of temperature.

below 700°C. The mixtures containing 50 and 60% Ag were most successful. They exhibited a fairly linear relationship between resistance and applied strain with gage factors ranging from 3 to 7. However, the reproducibility of the readings was poor, due chiefly to the permanent increases of the electrical resistance during testing. These increments of resistance indicate that there was no appreciable additional sintering going on at the testing temperatures, but some reaction of a chemical nature or interdiffusion took place. Future research on cement—metal bonding and chemical reactions between metal and cement should help in selection of the proper cement-binder which could be inert towards metal powder imbedded in it or be more easily stabilized by sintering at high temperatures.

LIQUID METAL AND OTHER GAGES

The liquid metal gage utilizes small changes in the cross-section of the meniscus of liquid metal, and, therefore, its resistance, when suspended between two solid metal electrodes. The arrangement of the simplest gage of this kind is represented in Fig. 12. The electrodes are mounted on

insulating posts which are affixed to the tested member with suitable cement. If we assume that the meniscus of liquid has the shape of one sheet hyperboloid of revolution, then its volume is:

$$V = \pi r^2 x \left\{ 1 + \frac{x^2}{3b^2} \right\}$$

where r = the radius of the neck of the hyperboloid

x = the distance between the electrodes

$$b^2 = \frac{x^2}{4 \left[\left(\frac{r_e}{r} \right)^2 - 1 \right]}$$

r_e = the radius of the electrodes

When the strain is applied to the member upon which the gage is mounted, the electrodes move apart if the stress is tensional or together, if it is compressive. During these operations the volume of liquid does not change. This condition enables us to calculate the change of radius r , dr , as a function of dx it is:

$$dr = - \left[r + \frac{r_e^2}{2r} \right] \frac{dx}{2x}$$

and as $\frac{dx}{x} = d\varepsilon$, where ε is the strain in the tested member

$$\frac{dr}{r} = - \frac{\left[1 + \frac{1}{2} \left(\frac{r_e}{r} \right)^2 \right]}{2} d\varepsilon$$

Figure 11 — Ceramics-Metal Gages.

If it is assumed that the volume of the bridge of liquid is large enough not to take surface effects into consideration, there should be no change in the specific resistivity, and the total resistance of the liquid meniscus, R , would be proportional to $\frac{x}{r^2}$. Therefore, the gage factor of a liquid metal gage will be approximately:

$$\frac{dR}{R d\varepsilon} = 2 + \frac{1}{2} \left(\frac{r_e}{r} \right)^2 \quad (1)$$

As the ratio of the electrode radius to the radius of the neck of the meniscus may be quite large, the liquid metal gage should be very sensitive.

In order to test the feasibility of this idea, a mercury gage was prepared. A little droplet of mercury or mercury-thallium amalgam was placed between two flat copper electrodes about 0.5 mm. apart. The electrodes were mounted on a beam, which was then stressed by bending. The strain in the beam was measured directly by an SR-4 gage attached to its surface. The results were surprisingly uniform. The gage of pure mercury exhibited a gage factor of between 134 and 140. Hg-Tl gages increased the gage factors from 135 to about 240 with increasing Te content. These experiments indicate that our theoretical treatment of the problem given above and resulting in equation (1) is oversimplified, because the gage factor is dependent on the material itself contrary to equation (1). All tested gages showed extremely uniform behavior. A small hysteresis was observed after the first test, but it always vanished after a few stress cycles. Fig. 13 represents the $\frac{\Delta R}{R_0}$ versus strain plot for a Hg gage where the empty circles denote readings during increasing and the full ones during decreasing strains. Due to its high sensitivity (more than 60 times that of the SR-4 gage) the mercury gage could be applied in some laboratory experiments involving measurements of very small strains. It is, however, difficult to see how it could be standardized and used outside of the laboratory.

Figure 12 — Principle of a liquid metal gage represented schematically.

The success with the mercury gage at room temperature warranted some experimentation with this type of gage at elevated temperatures. Unfortunately, all experiments conducted so far have failed. The materials tried for the liquid bridge were tin, lead, thallium and their alloys. The electrodes were made of tungsten, molybdenum, constantan and nichrome. In all cases the dissolution of the electrode material in the liquid metal was very fast at temperatures just above the melting point of the liquid component of the gage. Therefore, for the present time, barring the development of entirely new ideas overcoming these difficulties, the experimentation on this type of gage has been abandoned.

Another type of device tried was a thermoelectric gage. A few experiments were performed on the influence of strains on the thermoelectric power generated by chromel-alumel and constantan-copper thermocouples at room, as well as at elevated, temperatures. The results were negative. If an effect was present, it was too small to be detected by our measuring devices (Wheatstone bridge).

Finally, a few exploratory experiments were performed on the sensitivity of semiconductors to strains. Thin plates of germanium changed greatly, although somewhat irregularly, their electrical resistance with even the lightest tapping. This observation seems to agree with the predic-

tion⁸ made previously by purely theoretical calculations that semiconductors should have large gage factors.

TESTS OF REFRACTORY CEMENTS

The adhesive quality of various easily-obtained or easily-prepared refractory cements was tested on small pieces of stainless steel (18-8), which were 2" long by 3/8" wide and 3/32" thick. The test pieces were first sanded on a belt grinder with a 100 grit abrasive and then cleaned in water, rinsed in alcohol and dried. A thin layer of cement (about 1/16" thick) was spread on each piece of steel and allowed to air harden for the proper time for each composition. All materials tried gave very good bonds at room temperature.

After the proper hardening interval, the specimens were placed in a muffle furnace and their behavior noted as a function of temperature and cooling rate. The muffle furnace used had a natural cooling rate from 1400°F of 5°-10°F per minute. Some specimens were taken out of the furnace and air-quenched. A thermocouple welded to a test piece that was air cooled showed that the temperature changed at the rate of 1500°F per minute for the first 20 seconds. The temperature of the air-quenched piece dropped from 1400°F to 400°F in 2 1/2 minutes.

Ten test pieces were prepared with the following cements: Sauereisens No. 31, 19, 32, 35, 76 and 7; fused quartz, Alfrax 58, litharge and glycerine, and copper oxide plus phosphoric acid. These were placed on a ceramic plaque and put into a cold electric muffle furnace. The current was then turned on and the temperature controlled and held constant for 1-1 1/2 hours at each of the following temperature points: 250°, 350°, 450°, 550°, 650°, 750°, 850°, 950°, 1050°, 1150°, 1250° and 1350°F. In each instance, before increasing the temperature, the specimens were examined visually.

After holding at 1250°F for 1 hour (preceded by 1-1 1/2 hours at each of the other temperatures) the specimens were all allowed to furnace cool. At temperature all of the cements seemed to be in good shape and adhering to the steel; but when they were cold enough to handle, the

fused quartz, Alfrax 58, copper oxide, Sauereisen 35 and the litharge specimens flaked off the steel when forced with the finger. The others were more strongly bonded, and the refractory could not be forced off with the fingers or by dropping.

The intact specimens (Sauereisens 31, 19, 32, 76 and 7) were put into the cold furnace muffle, brought to 1350°F and held at temperature for 2 1/2 hours. They were then removed and air-quenched (1500°F/minute). The Sauereisen 31 and 32 popped loose from this treatment, leaving Sauereisen 19 and 76 in good shape. These three were then heated for 8 hours at 1400°F. They remained intact, with a very good bond, after another drastic air-quench to room temperature.

Three pieces were tested containing Sauereisens 7, 19 and 76 at a thickness of 1/8 inch. They were heated at 1400°F for 5 1/2 hours and then air-quenched. The refractory on each piece pulled loose. The bond was apparently broken by the air-quench because the metal surfaces beneath the refractories were unoxidized.

Duplicate specimens containing Sauereisen cements 7, 19 and 76 were prepared and heated for 8 hours at 1400°F. After furnace cooling, both Sauereisen No. 7's were in good shape, both No. 19's had flaked loose and one of the two with No. 76 had broken loose. The three intact specimens were again heated at 1400°F and then air-quenched. Both of the Sauereisen No. 7's survived, but the No. 76 had pulled loose.

A few additional tests were carried out in which the steel, after the usual cleaning, was swabbed with Sauereisen thinning liquid and allowed to dry before the cement was applied. In these tests all of the cements popped off upon cooling, leaving a clean surface underneath.

Sauereisen cement No. 31 was used for mounting of the gages described in this report because it is in a convenient powdered form while most of the other suitable cements were ready-mixed paste which tend to harden with time.

As it is obvious that almost any kind of a high temperature gage which might be devised will have to be temporarily attached to the surface being tested, the development of suitable materials for this purpose is a necessity. Because of the physical requirements of the measuring devices, the gage will generally have to be insulated from the tested material, if the latter is metallic in nature. This means, then, that if temperatures as high as 1400°F are involved, the adhesive material will have to be made of ceramic.

Research should be carried out to develop cements with better adherence, longer life and reasonable plasticity at elevated temperature. It is quite obvious that this development should be a part of any high temperature gage research project.

CONCLUSIONS AND RECOMMENDATIONS

The results of various tests discussed in this report bring forth the following conclusions as to the feasibility of the development of a high temperature gage.

A) The Wire Gage

A wire gage similar to the SR-4, as developed by Gorton¹, and Carpenter and Morris², has two great disadvantages. It cannot be prepared outside the structure to be

Figure 13 — Increment of unit resistance, $\frac{\Delta R}{R}$, vs. strain for a liquid mercury gage at room temperature.

tested and is lacking in temperature compensation. The second disadvantage is difficult to overcome in this type of gage; however, it seems to be possible to prepare a wire grid embedded in a thin wafer of the cement, which in turn could be cemented, like the SR-4 gage, to the tested member.

The development of a wire gage mounted on two refractory posts was successful. It was possible to build a gage operating satisfactorily up to 700°C with a temperature-compensating coil and thermal stress compensating device if necessary. The use of this type of gage is chiefly limited to tensional strains, therefore it cannot be regarded as universally applicable.

B) Cement-metal Powder Gage

The preliminary experiments on a cement-metal powder gage seem to be encouraging. However, more research should be done upon the ceramics-metal bond.

C) Liquid Metal Gage

Although very sensitive and dependable at room temperature, this type of gage failed to give satisfactory results at even moderate temperatures.

Based upon these results, the following recommendations for future research and development could be made:

1. The wire-type gages will never be completely satisfactory when operated at elevated temperatures. At best, they could be used in special problems and under certain favorable conditions.
2. The cement-metal powder gage may be developed into a satisfactory measuring device, provided the proper materials, stable at elevated temperatures, could be found. This would involve a study of the metal-ceramics bond and the chemical and sintering characteristics of their mixtures.

D) Semiconductor Gage

Semiconductors are materials of very high electrical resistivity and negative temperature coefficients of electrical resistance. Basically a semiconductor is an insulator which, in most cases, owes its electrical conductivity to the impurities dissolved in it. These impurities supply the additional energy levels not too far removed from the top of the completely filled band, or from the bottom of the upper empty band, to allow a small scale transition of electrons from the completely filled, non-conductive band to the impurity levels or from the impurity levels to the empty, conductive band. The former type of semiconductor is called P type, the latter N type. In both types, a small energy gap ΔE separates the impurity levels from the conduction levels. Therefore, if an electron in a semiconductor is to become a conducting electron, it has to possess at least this energy ΔE , as energy of activation. This leads to the following equation for the specific resistivity ρ of a P or N type semiconductor:

$$\rho = \rho_0 e^{\frac{\Delta E}{2KT}} \quad (2)$$

Where ρ_0 is a constant, K Boltmann's constant and T the absolute temperature. Equation (2) yields immediately, the temperature coefficient of resistivity for these materials.

$$\frac{d\rho}{\rho dT} = - \frac{\Delta E}{2KT^2}$$

The quantity on the right side of the last equation is always negative. For pure metals one can obtain the following approximate relationship:

$$\frac{d\rho}{\rho dT} \approx \frac{1}{T}$$

which means that for conductors the temperature coefficient of resistivity is always positive. Semiconductors possess yet another interesting and useful property. They can rectify, or be able to pass electric current in one direction and inhibit it almost entirely in the opposite. Both properties, their electrical resistance and rectification, can be utilized in designing a high temperature strain gage.

The sensitivity of the electrical resistance of semiconductors to strains is not known. However, it is not difficult to show that the resistance should increase with the strain application. Equation (2) yields at once

$$\frac{d\rho}{\rho d\varepsilon} = \frac{1}{2KT} \frac{d\Delta E}{d\varepsilon}$$

Any change in ΔE is due to the wider separation of the electron bands and changes in the electron levels of the impurities. Both effects, the separation of the bands and changes in electron levels always increase or decrease together, resulting in the increment in ΔE . A rough computation based on the separation of electron bands alone yields values for the coefficient of specific resistivity $\frac{d\rho}{\rho d\varepsilon}$ (which in this case is practically equal to the gage factor) in the vicinity of + 200. The contribution due to the impurity levels should increase this value still further, although at elevated temperatures when the semiconductor becomes intrinsic this contribution should be negligible. It is, therefore, probable that the semiconductors have high gage factors.

The temperature coefficients of resistivity of semiconductors are not excessively high. Thus, for germanium containing small concentrations of tin, the value of $\frac{d\rho}{\rho dT}$ is $4 \times 10^{-4}/\text{degree}$, over the temperature range of 200° to 700°C.

Semiconductors are brittle but they possess some elasticity. Silicon and germanium, the most popular semiconductors in the electronic industry, do not seem to be suitable for our purpose chiefly because they are easily oxidized. However, copper oxide or zinc oxide or a host of other oxides have proved to be good semiconductors and should be tried. Even materials like silicon or germanium could be used if proper protection against oxidation could be devised.

Preliminary measurements of the changes of electrical resistance of germanium under strains were very encouraging, indicating that the electrical resistance of the semiconductors is greatly sensitive to strains. Some of these materials, such as copper oxide, would never deteriorate when heated in air at elevated temperatures. A thin layer of semiconductor between two refractory posts may prove sufficient to indicate even small strains. Such a gage, as any mounted on the posts, can be easily compensated for resistance changes due to temperature fluctuations. All the information we have about these materials seems to indicate that they could be developed as a component if the gage operated at elevated temperatures.

Rectifier Strain Gage — It has been pointed out in the previous section that the semiconductors possess the property of passing the electric current in one direction and inhibiting it in another. This action is called rectification. The main characteristics of every rectifier are: the forward current and the breaking potential, at which the current is able to pass in both directions. There are no experimental data which would shed light upon the behavior of rectifiers at elevated temperatures or under stresses or both. It is, however, quite feasible that the rectifying characteristics would change with strain. The gage would consist of a small diode mounted on the stressed part. The semiconductor of the diode would be mounted on posts or directly cemented to the part under test. The induced strains would change the rectifying characteristics of the semiconductor which could be easily calibrated in terms of strain. It is difficult to say off-hand but it seems that the upper range of working temperatures of the rectifier gage would be somewhat lower than that of other gages discussed before. Again, as in the case of resistance semiconductor gages, the best rectifying materials such as silicon and germanium would not be the most suited materials, due to their high affinity for oxygen, but oxide rectifiers would probably suffice if the idea appeared to be workable.

E) Metal Film Gage

Such a gage would be made of very thin plates of mica, porcelain, or other suitable refractory material, on whose surface a thin layer of metal is deposited by evaporation, sputtering or other means. The requirement of good mechanical properties of the deposited metal is no longer important because very thin metallic films have elastic properties approaching those of the substrate. Mica suggests itself as the best material for such a substrate but other materials, such as certain enamels or porcelain, may prove themselves to be superior. The important factor is the elasticity of the substrate. This type of gage is ideally suited for mounting on posts as described in the first section of this report.

The electrical properties of such thin metallic films have been extensively investigated and appear to be extremely attractive for our purpose. The electrical resistivity of such films increases enormously, with decreasing thickness of the film, and in most cases an appreciable decrement of the temperature coefficient of resistivity has been observed.^{9, 10, 11, 12, 13, 14} For very thin nickel films, for instance,^{9, 10, 12} negative temperature coefficients of resistivity were reported. The same was observed¹⁴ for much thicker films of bismuth. 1.5 micron thick films of iron, nickel, lead and gold evaporated on glass revealed greatly reduced temperature coefficients (see Table I). It is believed that with still thinner films much lower temperature coefficients of resistivity could be obtained. The gage factors of these films are expected to be low, but surprises are not excluded.

From our point of view the most suitable metals for a gage would be noble metals such as gold, silver, platinum, palladium, etc., and their alloys because of their ideal resistance to oxidation, but it will probably be possible to use chromium or some chromium alloys. Experiments should also be carried out on metallic films of low melting point metals such as bismuth or tin. Very thin film of these metals should adhere well even in the liquid state.

In such liquid gages the gage factor will depend upon the influence of stresses on the surface tension of these metals, ultimately registered as a change of resistivity.

Another variant of metal film gages would be metals evaporated on asbestos or quartz threads.

TABLE 2

Metal	Thickness (microns)	α ($\times 10^{-4}$) film	α ($\times 10^{-4}$) bulk
Bi	1.0	- 27.7	40
	6.5	- 16.8	40
Fe	1.0 - 5.0	19.0	50
Ni	1.0	16.0	60
Pb	2.0	29.0	43
Au*	2.0	11.7	34

α = temperature coefficient of resistivity.

All data reported above refer to room temperature.

* evaporated on celluloid

MAGNETIC MATERIALS

A very promising idea for a high temperature gage is the utilization of magnetic materials. The electromotive force induced in a circuit by the alternating magnetic flux within it is proportional to the flux density or magnetic induction. The magnetic induction is the quantity which changes in a strain field¹⁵ because magnetic induction is proportional to magnetic susceptibility, and the latter quantity is a function of elastic strain. By straining the magnetic material within a solenoid, energized by A.C., the current is induced in a pick-up coil around the solenoid. This current can be directly calibrated against the strain applied to the magnetic core. The requirements for the core material are: (a) high Curie temperature, (b) low hysteresis, (c) high magnetic susceptibility, and (d) elasticity at elevated temperatures. There are a number of magnetic alloys which may satisfy some of these conditions, but they usually are brittle and have little elasticity. The best materials would probably be the ferroxcubes¹⁶. The ferroxcubes are non-metallic substances having the general chemical formula $MO \cdot Fe_2O_3$, in which M stands for a bivalent metal ion. This bivalent metal ion is usually Mg, Zn, Cu, Ni, Fe, Co or Mn. Ferroxcubes have extremely low hysteresis which, if appreciable, would render our gage impracticable on account of irreversibility. The elastic properties of the ferroxcubes could be perhaps improved by the addition of some high melting point non-magnetic metals or alloys. The ferroxcube cores, with or without metallic additions, could be hot pressed from powders into the form of thin plates, and around them the coils of fine wires could be easily wound. The contemplated gages would have the shape of either plates or small magnetic loops, cemented to the base, or, better still, mounted on refractory posts, with proper temperatures compensating solenoids.

The ferroxcubes so far developed have Curie temperatures in the range of 300° — 550°C, but higher Curie points do not seem impossible.

This gage has been tested at room temperature using an iron core with positive results.

The discussion above marks only the beginning of efforts to devise a satisfactory gage capable of working at elevated temperatures. Careful scrutiny of the properties of solids may reveal new devices based on the correlation of the changes of some physical property with strain. The electrical resistance gages may utilize certain order-disorder alloys which have very high ordering temperatures. Chromium-nickel and cobalt-manganese are such systems. This type of gage would be advantageous if the gage factor of ordered alloys would increase with approach of the transition temperature.

TEMPERATURE COMPENSATION

All the types of gages discussed above would be useless without adequate temperature compensation. The readings would be meaningless without knowledge of which part of the measured property change is due to strains and which part to temperature change. We have seen previously that in all proposed gages the temperature changes, which under most operating conditions are unknown, would produce effects indistinguishable from those generated by deformations. It is, therefore, imperative to secure a good temperature compensating device. It is at once obvious that the successful temperature compensating arrangement used in Baldwin strain indicators cannot be

used in this case, because it would be difficult to adjust the temperature of the piece of metal, on which the compensating gage is mounted, to exactly the temperature of the measured object. However, it is possible to modify this arrangement to make it work properly under the difficult conditions created by elevated temperatures. It is proposed then to mount two gages of the same type, but of different gage factor and different temperature coefficients, side by side on the selected area of the measured object. If the gage factors of these gages will be denoted by a_1 and a_2 , their temperature coefficients (or magnetic fluxes) by b_1 and b_2 and their total resistances by R_1 and R_2 respectively, then the changes ΔR produced cumulatively by strain increments $\Delta \epsilon$ and temperature increments ΔT will be

$$(\Delta R)_1 = a_1 R_1 \Delta \epsilon + b_1 R_1 \Delta T$$

$$(\Delta R)_2 = a_2 R_2 \Delta \epsilon + b_2 R_2 \Delta T$$

From these two linear equations ΔT can be easily eliminated and the relationship between $(\Delta R)_1$, and $(\Delta R)_2$ and $\Delta \epsilon$ obtained.

$$\Delta \epsilon = \frac{b_2 R_2 (\Delta R)_1 - b_1 R_1 (\Delta R)_2}{b_2 a_1 - b_1 a_2}$$

It is possible to design a circuit which would solve these equations automatically and after proper calibration yield readings directly in terms of strain increments.

It is needless to add that this device can be applied with equal success to the resistance as well as rectifier or magnetic gages.

REFERENCES

1. R. E. Gorton, *Experimental Stress Analysis*, V. 9, 163, (1951).
2. J. E. Carpenter and L. D. Morris, *Experimental Stress Analysis*, V. 9, 191, (1951).
3. A. Taylor and K. G. Hinton, *J. Inst. Metals*, V. 81, 169, (1952).
4. J. C. Wilson, Private communication.
5. G. Guarnieri and J. Miller, *Metal Progress*, p. 692, (November, 1948).
6. P. R. Weaver, *Experimental Stress Analysis*, V. 9, 159, (1951).
7. G. C. Kuczynski, *Testing Topics*, (to be published).
8. G. C. Kuczynski, *High Temperature Strain Gages* (Mineographed Report, 1953).
9. A. Colombani, C. R. Acad. Sci. Paris, 215 17-18 (1942).
10. A. Colombani, Ann. Phys. Paris 19 272 (1944).
11. A. van Itterbeck. Physica 15 433 (1949).
12. A. van Itterbeck. Nature 156 634 (1945).
13. B. Vodar and N. Mostovetch. C. R. Acad. Sci. Paris 226 167 (1948).
14. W. J. Tulley. Nature 157 372 (1946).
15. F. Bitter, *Introduction to Ferromagnetism*, McGraw-Hill Book Company, (1937).
16. J. L. Snoek, *New Developments in Ferromagnetic Materials*, Monographs on the Progress of Research in Holland, 1947.

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APPENDIX 1

NEW STRAIN SENSITIVE ALLOYS

BY
B. D. CULLITY AND G. C. KUCZYNSKI
DEPARTMENT OF METALLURGY
UNIVERSITY OF NOTRE DAME

INTRODUCTION

The heart of an electrical resistance strain gage is a material whose resistance changes considerably when the material is strained by a small amount, i.e. it is a material with a high *gage factor*, defined as the fractional change in resistance per unit change in strain. Such strain sensitive materials may be sought for among pure metals, alloys of a wide variety of kinds, and semiconductors. We confine ourselves here to a consideration of alloys of two specific types, *interstitial* and *martensitic*, both of which appear promising from the viewpoint of strain sensitivity.

INTERSTITIAL ALLOYS

Metallic solid solutions can be either substitutional or interstitial: in the former, solute atoms replace solvent atoms on the lattice points of the solvent, and in the latter, solute atoms fit into positions between the solvent atoms. Since these interstitial positions are generally small, interstitial solid solutions are only formed when the solute atom is much smaller than the solvent atom. Carbon in alpha iron is an example of such a solution.

In a dilute unstrained interstitial solution, the solute atoms are randomly dispersed among the various interstitial positions available. When the alloy is strained, however, the solute atoms are forced into preferred positions relative to the applied strain and, when the strain is released, they return to their former random distribution. Considerable fundamental information is already available about such alloys through the work of Snoek¹, Zener², Wert³ and others on damping capacity, but practically no information on their electrical properties is available. Their electrical resistivity should depend markedly, however, on the extent to which the solute atoms are in preferred rather than random positions, which, in turn, depends on the degree of strain.

The fragmentary data available support this belief. Thus, Lopuhkin⁴ found that the gage factor of iron-carbon alloys increased from about 1.7 to about 2.4 as the carbon content decreased from 1.0 to 0.08 per cent. On the other hand, Kuczynski⁵ found a gage factor of 2.0 for pure iron. These data point to a maximum in the gage factor curve at a carbon content between 0 and 0.08 per cent. It is precisely in this region that one would expect the gage factor to be a maximum, since this maximum (of unknown magnitude) should be reached when the iron is just saturated with carbon and this occurs at a carbon concentration much less than 0.08 per cent.

Iron-carbon alloys are only one example of this phenom-

enon. An investigation should be made of a whole series of binary alloys, made up of such metals as iron, tantalum, columbium, vanadium, chromium, molybdenum, etc. as solvents and carbon, nitrogen, oxygen, boron, etc. as interstitial solutes. Low temperature coefficients of resistance could probably be obtained by designing ternary alloys, e.g. major amounts of iron and tantalum and a small amount of carbon.

MARTENSITIC ALLOYS

Martensite has been known for years as a metastable constituent of quenched steel, a constituent to which such steel owes its high hardness. Only recently, however, have martensitic phases been found in other alloy systems and in some of these systems the formation of martensite has been found to be reversible under certain conditions. The term "reversible" is here used in the particular sense that the martensite can be made to transform back into its parent phase at a temperature at which the parent phase is, itself, unstable. In no other solid state transformation has such reversibility been found.

Martensite is normally formed simply by cooling the parent phase through a certain temperature range, but it can also be produced by the application of strain at constant temperature. Most phase changes are accompanied by a sudden change in electrical resistivity which means that, if martensite can be made to form reversibly as the result of strain, one would have a promising strain gage material. The possibilities here are attractive and there are enough martensitic alloys already known to form a solid basis for investigation.

For example, martensite can be formed in copper-zinc, copper-aluminum, copper-tin, copper-manganese, iron-nickel, indium-cadmium, lithium-magnesium, chromium-manganese, etc. alloys as well as in iron-carbon alloys, and this is only a partial list. Strain-induced martensite transformation has been found in a number of alloys, for example by Scheil⁶ in iron-nickel alloys; by Greninger and Mooradian⁷ in copper-zinc alloys; by Kurdjumow⁸ in copper-aluminum alloys, etc. And finally, Reynolds and Bever⁹ have shown that the strain-induced martensite reaction is reversible in copper-zinc alloys, i.e. that martensite formed by strain can be caused to disappear by release of strain. This field of martensitic alloys, and that represented by the interstitial alloys discussed above, appears to have been left untouched in the search for strain-sensitive materials and fully warrants careful investigation.

LIST OF REFERENCES

1. J. Snoek. *Physica*, 8, 711, (1941).
2. C. Zener. "Elasticity and Anelasticity of Metals." Univ. of Chicago Press (1948).
3. C. A. Wert. *Trans. A.I.M.E.* 188, 1242 (1950)
4. E. Lopuhkin *Tech. Phys. (U.S.S.R.)* Vol. IV. No. 1, p. 31 (1937).
5. G. C. Kuczynski. Sc. D. Thesis. Mass. Inst. of Technology (1946).
6. E. Scheil, *Z. anorg. allgem. Chemie.* 207, 21 (1932).
7. A. B. Greninger and G. Mooradian. *Trans. A.I.M.E.*, 128, 337 (1938).
8. G. V. Kurdjumow. *J. Tech. Phys. (U.S.S.R.)*, 18, 999 (1948).
9. J. E. Reynolds, Jr. and M. B. Bever. *J. of Metals*, p. 1065, Oct. 1952.

A STUDY OF TECHNIQUES OF MEASURING MECHANICAL STRAINS AT HIGH TEMPERATURES

SUBMITTED BY
PROFESSOR SAMUEL T. CARPENTER
SWARTHMORE COLLEGE
Swarthmore, Penna.

IN COOPERATION WITH
JOHN L. EVERETT
E. H. SMITH AND COMPANY
Silver Spring, Maryland

As many electrical effects as possible were studied in order to determine which offered the best hope for future work. From the point of view of electrical properties of most materials, the range from room temperature to 1000°F is an enormous one. In general, magnetic, dielectric and resistive properties change their character completely in this interval. It is because of this that the use of ceramic materials as components of strain gages, for example, does not look too promising.

The basic conclusion reached after this study was completed is that a satisfactory answer to our problem can best be found in a gage whose performance depends mainly upon its physical dimensions, rather than upon its physical properties. Such a gage will perform in exactly the same way at all points in the required temperature range and any changes due to temperature can be predicted. Furthermore, such a gage offers good potentialities for extension into higher temperature ranges.

Two types of gages which have the desired property of depending chiefly upon mechanical dimensions are described in this report. One of them was fabricated and tested, the test showing that the performance of the gage was as predicted.

THE SERRATED PLATE STRAIN GAGE

The basic theory of the serrated plate strain gage lies in the separation of two flat plates of conducting material by a fixed distance and filling this intervening space with a dielectric material or a semiconductor. See Fig. 1. In the case of the dielectric, the gage is a condenser and the electrical property measured is the capacitance. On the other hand, if the intervening material is a semiconductor, the gage is a resistor and the electrical property measured is resistance. The physical operation of the gage is the same for both forms in that the gage is designed so that a strain will displace plate A of Fig. 1 with respect to plate B in the manner shown in Fig. 1. Because the equations describing the gage are identical in form for both

Figure 1 — Principle of capacitance — resistance gage.

types, we shall discuss only the capacitance type in the rest of this section. However, it should be remembered that the same considerations, particularly the sensitivity, apply to both types.

Considering now the gage in its capacitance form, let us assume that in the zero strain condition the two plates are directly opposite one another. The effect of moving one plate with respect to the other will be a reduction of the capacitance. The relationship between capacitance and the strain is shown in Fig. 2. This relationship departs from linearity because of bending of the lines of force at the edges of the plates. However, there will be a portion of the curve in which the relationship between capacitance

Figure 2 — Relationship between capacitance — resistance of gage in Fig. 1 and the relative displacement due to strain.

and strain is approximately a straight line and it is this region which can be expected to be the basis for a useful high temperature strain gage.

The chief drawback of the two-plate gage just described is its low sensitivity. In fact, this gage has a strain factor of unity. While this is not a theoretically insurmountable difficulty, nevertheless, the practical use of this gage would probably require extremely sensitive and expensive measuring equipment.

The sensitivity limitations of the two-plate gage can be easily overcome by a serrating procedure, Fig. 3 (a) and (b) and Fig. 4. The serrations will form a parallel set of condensers, each with a gage factor of unity. However, the total sensitivity of the gage will be represented by the sum of the individual factors. Accordingly, if, for example, there are fifty serrations, the gage as a whole will

Figure 3a — Enlarged cross-section showing displacement of gage.

Figure 3b — Pencil gage.

Figure 4 — Two-plate gage showing serrations.

have a factor of 50. This increased sensitivity greatly simplifies the measurement problem.

A gage of the serrated capacitance type was built and tested. This gage had the following specifications:-

- Total plate area — 0.500 sq. in.
- Number of serrations — 38
- Serration width — 0.014"
- Dielectric — Mica (Muscovite)
- Dielectric thickness — 0.002"
- Plate material — duralumin

The testing of this gage was carried out in a device which held one plate fixed and permitted the other one to be moved through known distances by means of a screw. The screw was provided with a dial head, the smallest division of which corresponded to a screw displacement of 0.0001". It is estimated that the screw position could be measured to within 2×10^{-5} inches. Figs. 5 and 6.

Fig. 7 shows the observed relationship between the capacitance of the gage and the relative displacement of the plates. Data were taken under two temperature conditions, namely; room temperature and with the gage heated by

Figure 5 — Device for testing gage of serrated-capacitance type. One plate is held in a fixed position and the other is permitted to move through known distances by means of the screw.

Figure 6 — Calibrating device showing gage disassembled.

infra-red heat lamps. The capacitance measurement was made using a resonance type Q meter. This meter did not read absolute capacitance, but rather the change in capacitance which occurred when the plates were moved with respect to one another. The reference level from which these differences were measured was the capacitance when the serrations in the top plate were in line with the corresponding serrations in the lower plate. Since the capacitance is at a maximum when the plates are in that condition, the changes in capacitance are actually negative.

The slope of the straight portion of the room temperature curve is 0.77 micro-micro farads per ten thousandth of an inch. In the heated condition the slope increases to 0.95 mmf per ten thousandth inch. No means were available for measuring the actual gage temperature, but it is certain that it was not greater than 100°C.

The actual cause for the increased slope with temperature was not determined from the test. Thermal expansion thereby leading to increased capacitance must contribute very little to the effect. The best possibility for ex-

plaining the change probably lies in temperature variation of the dielectric properties of the mica.

It is believed that the serrated type of gage possesses excellent potentialities for use in measurement applications where a considerable temperature range is to be encountered. Some of the developmental difficulties which are discussed in the next paragraph appear to be amenable to solution.

Figure 7 — Response curves of serrated capacitor strain gage showing relationship between capacitance of gage and relative plate displacement. Slope of linear portion is 7500 mmfd per inch at room temperature and 9500 mmfd per inch when heated.

All the materials of which the gage is made are mechanically stable up to 1000°F. Whether electrical stability will occur over these temperature ranges will depend upon the way the mica is affected by temperature and this is not predictable from any information available. There is no doubt that the dielectric constant will be temperature sensitive. If the variation of the dielectric constant with temperature is predictable, then this effect may be easily taken into account by suitable corrections. On the other hand, a different material than mica may be needed. See Fig. 8 which illustrates how dielectric constants change with temperature and indicates the possibility of obtaining "tailored" properties.

Probably the most important limitation in the operation of this gage at high temperatures will result from the decreased resistivity of the mica. This decreased resistivity will tend to lower the "Q" factor of the measuring circuits and thereby impose a limit on the smallest displacement which can be detected. Here too, the information covering the effect of temperature on the power factor of mica does not appear to be available, so no reliable estimate of the "Q" factor at high temperatures can be made.

Should the mica dielectric cause difficulties at high temperatures, it would be possible to replace it by an air dielectric. The major result of this would be to decrease the sensitivity of the gage by a factor of about 6 or 7. Thus, for the gage which was tested, the sensitivity at room temperature would be reduced to the order of 1000 mmf per inch. The gage factor would not, however, be changed to this extent. In fact, by suitable precautions such as deeper serrations and a closer plate spacing, the

gage factor could probably be maintained at its present value of 38.

One compensating effect of the air dielectric would arise from its high resistivity which would be reflected in high "Q" measuring circuits. Since the magnitude of the smallest detectable displacement depends upon the "Q" of the measuring circuit as well as the sensitivity, the higher "Q" of the air dielectric may compensate for the lower gage sensitivity. Consequently, from a practical point of view, an air dielectric may be as satisfactory as the mica one.

No special problems were encountered in the manufacture of the experimental gage which might cause apprehension concerning the mass production of this type of gage. The serrations were made by a slitting saw which cut one groove at a time. In the case of production manufacture, all the grooves could be cut at one time by mounting a suitable number of slitting saws on a mandrel with appropriate spacers. The formation of the serrations can thus be accomplished quickly and inexpensively. Fab-

Figure 8 — Dielectric constant vs. temperature for various compositions of barium titanate dielectric materials. Wide variety of curve forms available indicates possibility of choosing auxiliary dielectric for capacitance gage which will act to compensate variation with temperature of dielectric constant of mica.

rication of the blanks appears to be straight-forward with no requirement apparent for expensively close tolerances on the flatness of the plate surfaces.

This type of strain gage would be adaptable to measuring strains in two right angle directions.

THE RESONANT CAVITY STRAIN GAGE

The need for a gage whose characteristics are more independent of temperature than the types previously described is met, to a great extent, by the resonant cavity strain gage. This device is, essentially, a wavemeter operated in a reverse manner so that a known frequency is used to measure an unknown dimension. The size of the

Figure 9 — Schematic diagram of resonant cavity strain gage.

device depends upon the frequency at which it is operated. The higher the frequency, the smaller it may be made.

Fig. 9 shows one form of a resonant cavity strain gage.

A variable frequency is introduced into the cavity by the probe of the coaxial line. The piston is displaced by the amount of the strain to be measured. For a cavity of this type, the resonant frequency will be linearly related to the piston displacement, the sensitivity depending upon the mode which is excited.

The great advantage of the resonant cavity for measurement of strain is that its behavior depends only upon physical dimensions whose change with temperature can be accurately known. There are no such quantities involved as resistivity and dielectric constant which are temperature dependent. A second important advantage is that these devices have extremely high "Q" factors which means that their ultimate sensitivity is high.

A gage of reasonably small dimensions will necessarily resonate at extremely high frequencies. For example, if the diameter of the cavity is 0.90" and its length is also 0.90" it will resonate at a frequency of ten thousand megacycles per second, if the TE₁₁₁ mode is utilized. A displacement of the piston of 10⁻⁴ inches will produce a frequency change of 0.430 megacycles per second. Reducing the diameter to 0.45" will increase the resonant frequency to 16.7 megacycles per second. The formula which connects the cavity dimensions and the resonant frequency is the following:

$$f = 10^4 \sqrt{\frac{0.4781}{D^2} + \frac{0.3480}{L^2}}$$

where f is the TE₁₁₁ resonant frequency in megacycles per second.

D = diameter of cavity in inches

L = length of cavity in inches.

The response of the gage, namely; the slope of the frequency versus displacement curve is

$$\frac{df}{dx} = \frac{0.3480}{fL^2} \times 10^8$$

Since f changes more slowly than $\frac{1}{L}$, this formula means

that the smaller the gage the greater will be its response or sensitivity. The gage factor, too, will increase as the gage becomes smaller, but at a slower rate than does the response.

Having discussed the gage, itself, let us now consider the auxiliary equipment which is required. This consists of a source of power and a means of measuring frequency. The requirements imposed on the source of power are that it furnish the frequencies that we need and it must be able to be tuned. Fortunately, the power requirements are

small and there are suitable power sources in the frequency ranges we need.

Some of these tubes are listed in the following table. These are of the klystron type and would probably be suitable for our purposes.

TABLE I

Number	Frequency in megacycles per second	Output Milli- watts	Tuning range megacycles per second		
			Mechanical	Electron	Thermal
2K25	8500-9660	30	1160	32	
2K45	8500-9660	30		50	1160
2K50	23,215-24,750	10		65	935
2K39	7,500-10,300	250	2800	44	

In using these tubes, mechanical tuning is accomplished by changing the dimensions of the tube cavity mechanically, electronic tuning by adjustment of electrode voltages and thermal tuning by changing the cavity dimensions thermally.

It is of interest to compute the tuning range which we need to see which of the three tuning methods will be satisfactory. The maximum range is based upon the maximum deflection which we wish to measure. Suppose for example, that this maximum deflection is 0.010" and that we wish to use a gage operating in the 10,000 mcps region, whose length is 0.90". The response of this gage will be 0.430 megacycles per second per 0.0001". Thus, the total change in frequency for a response of 0.010" is 43 megacycles per second. It is clear from Table I that two tubes, the 2K45 and the 2K39 meet this requirement with electronic tuning alone. This is an enormous advantage for it means that our strain measurement is in terms of a voltage difference which may be read directly and precisely, that voltage difference being the change in repeller voltage needed for the strain gage to become resonant again. This means that precise and complicated methods for determining the actual frequency of the oscillator will probably not be needed.

In actual practice it appears that the simplest way to solve the measurement problem is by means of a signal generator operating in the desired frequency range. The generator consists of the appropriate tube of the type listed in Table I and also contains an output meter. The signal generator is coupled to the strain gage by means of a coaxial cable. In order to determine the resonant frequency of the gage, the signal generator is tuned until the output is at a minimum.

One of the principal difficulties which can arise in utilizing this gage in practice would be when it is necessary to measure strains in rotating members. Since slip rings are not satisfactory electrical devices at the frequencies we need, the problem of energizing the gage may be considerable. One solution might lie in mounting a rotating joint on the axis of the member's rotation. Another basis for a solution lies in providing intermittent contact (for instance, once per revolution per gage). This might be done by using a wiping type of contact.

THE ROLE OF CERAMICS IN STRAIN GAGES

This section summarizes a study made of the possible applications of ceramic materials to a strain gage. The

Figures 10a & 10b — Relationship of resistivity and loss factor to temperature of several ceramic insulating materials.. Source: Russell and Mohr, J. Am. Ceram. Soc., 30, 32-35 (1947) Code: A, Sintered Alumina; B, 75% Alumina Body; C, Special Zircon Porcelain; D, Zircon Porcelain; E, Ultra Steatite; F, Fused Quartz; G, Regular Steatite; H, High Voltage Porcelain.

study consisted of interviews with research people at the Bureau of Standards and a review of the literature.

Both ceramic coatings and ceramic materials were studied.

The conclusion which resulted from the investigation is that ceramic materials in general do not appear to lend themselves easily to strain measuring devices. For one thing, all their electrical properties are, more or less, uncontrollable and, in general, they vary widely with temperature. Secondly, virtually all of them undergo phase transformation in the region between room temperature and 1000°F. When these phase changes, which are Curie points, occur, the electrical properties of the material undergo a considerable change in character. This is usually shown by a very rapid increase of power factor with temperature so that at 1000°F the materials become, in fact, conductors. It would appear, therefore, that materials which change their characteristics so markedly in the temperature range of interest would be difficult to use in a device controlled by these characteristics.

As an example of how these characteristics vary, Fig. 10 (a) shows the power factor of various ceramic insulating materials as a function of temperature. Fig. 10 (b) shows the relationship between resistivity and temperature. It is evident that these materials change from insulators at room temperature to conductors at high temperature.

Discussions at the Bureau of Standards indicated that no known ceramic materials were free of this property. It is true, of course, that a vast number have had their electrical properties extensively studied, particularly in the range above 200°C.

The prospect, therefore, of utilizing ceramic materials in electrical strain gages does not appear bright in view of currently available knowledge and materials.

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HIGH TEMPERATURE STRAIN GAGE FOR MEASUREMENT OF STATIC STRAINS

CONTRIBUTED BY
WILLIAM O. PASSARELLI, Jr.
PROJECT ENGINEER
WESTINGHOUSE ELECTRIC CORPORATION
ATOMIC POWER DIVISION
Bettis Field
Pittsburgh, Pennsylvania

This gage has been developed expressly for the measurement of thermal strains at high temperatures by the Westinghouse Atomic Power Division for the Atomic Energy Commission under Contract AT-11-1-GEN-14.

STRAIN GAGE DESCRIPTION

The gage consists of a small grid of 0.001" diameter Karma wire imbedded in Quigley AAA 1925 ceramic cement which has been painted onto a metal pad $1/16$ inch thick, $2-3/16$ inch long, and $1\frac{1}{2}$ inch wide. The grid is located on the longitudinal center line of the pad, but is displaced towards one end to provide sufficient room for a terminal strip and gage leads. The gage is protected by a small, rectangular, flexible, sheet metal cover.

This assembly, once it is cured and aged, is a complete strain gage ready for installation. Installing the gage involves welding it to the component to be tested. The use of a small, hollow, copper block covering the gage allows the making of a sound fillet weld around the entire periphery of the gage; protects the gage from damage during welding; and allows pressing it close to the component during installation.

The temperature compensating gage design is the same as that of the active gage excepting only the inclusion of a spacer strip on the bottom of the gage at one end, and the smaller overall dimensions. The spacer permits tack welding the gage in place, but still leaves the end with the strain sensitive grid free to expand or contract with changes in temperature.

NOTE:

The gage evolved is an adaptation of one developed by Messrs. Kemp, Manson, and Morgan at the National Advisory Committee on Aeronautics Laboratories in Cleveland, Ohio. This gage was developed to measure dynamic strains at 1600°F on gas turbine blading. As used by the NACA Laboratories, it did not have the stability required for static strain measurements, and in addition had to be built and installed under laboratory conditions (this involved much tedious work).

GAGE CHARACTERISTICS

Resistance & Sensitivity

The present strain gage has an electrical resistance of 200 ohms, a gage factor of 2.36 and is stable enough to

Figure 1.

permit making long-term measurements at temperatures up to 500°F .

Stability

Using gages which have been cured and aged, (see curing procedure on attached drawings) the total drifts observed, when using two gages connected in a temperature-compensated bridge network, have varied from 10 micro-

Figure 2.

inches per inch to 70 micro-inches per inch over a total period of 1700 hours of operation.

Deviations of the "zero" (or reference readings) from the initial zero readings after the gages had been maintained at a constant 500°F (at zero stress conditions) were a maximum of 50 micro-inches per inch.

Figure 3.

The proper curing of the gages (specified on the drawings cited previously) is necessary to attain stability. It was observed that gages cured according to the NACA instructions were unstable, and drifts of several thousand micro-inches per inch occurred within a few hundred hours. However, it was discovered that after approximately 2,000 hours of operation at 500°F the gages became very stable. To accelerate the curing of the gages, they are now subjected to a series of excursions from room temperature to 700°F and are baked for several days at 700°F.

TEMPERATURE COMPENSATION

The gages built are similar enough in characteristics that the errors due to temperature changes in a temperature compensated circuit are as small as those observed in commercial strain gages. However, because the WAPD developed gage was designed to be used in the measurement of thermal strains, and the temperature changes

involved are approximately 400°F, the actual errors can be large.

But because almost all of the gages have stainless steel pads (to match the coefficients of expansion of the gage pads and the component to be tested), it is possible to determine the temperature coefficients of single gages or pairs of gages before they are installed.

Tests revealed that the effects of welding the active gages in place are small enough that the maximum errors are approximately 75 micro-inches per inch.

STATE OF DEVELOPMENT

The gage in its present state of development is useful for the measurement of strains on large components at temperatures up to 500°F whether the strains are induced thermally or by direct mechanical loading.

It is highly probable that the gage will be satisfactory for use up to 700°F although no testing of its characteristics has been done in the range of 500°F to 700°F.

The gage is limited in its use to testing of components having relatively simple shapes because the gage pad must be pre-formed to fit the test component; and because the metal pad affects the strength of the part to which it is attached. However, the gage would not ordinarily be used on small parts, and consequently the effect is small. (The strengthening effect produced by a gage with a stainless steel pad on the flexural strength of a stainless steel beam 2 inches by 4 inches with bending about the axis of minimum moment of inertia, is less than 5%.)

The gage at present is still considered a laboratory instrument. But observing the usual precautions taken in making strain measurements, a great deal of useful information can be obtained through its use.

NOTE:

The preparation of this report for Mr. F. G. Tatnall of the Baldwin-Lima-Hamilton Corporation has been authorized by Mr. Lawton D. Geiger, Pittsburgh Area Office Manager, AEC, in his letter to Mr. W. Dee Shepherd, Contract Manager, Westinghouse Atomic Power Division.

Reference Drawings

Westinghouse 56-A-9826

Westinghouse 56-A-9827

HIGH TEMPERATURE DIFFERENTIAL TRANSFORMER

SUBMITTED BY
AUTOMATIC TEMPERATURE CONTROL CO., INC.
Philadelphia 44, Penna.

Prototype models of a differential transformer designed for high temperature operation was constructed and subjected to elevated temperature runs for evaluation. Reasonably satisfactory operation (at 2000 cycles) was obtained up to 600°F. Thereafter, the rapid decrease in the primary-to-secondary resistance resulted in a loss of sensitivity.

Preliminary investigation indicated that the following constructional features might have some promise and they were, therefore, incorporated in the later units tested:

1. High temperature ceramic bobbin
2. Hollow cobalt armature
3. Enclosure of the transformer in a ceramic shell with complete sealing from the furnace atmosphere being achieved by the use of #78 Sauer-eisen refractory cement.
4. Aluminum oxide insulated tungsten wire. (Subsequent observations revealed disadvantages in using this coating.) Efforts to obtain a better substitute are continuing. Pending more concrete results in this direction, the transformer design is largely based on overcoming the effects of the following characteristics of the aluminum oxide coating:-
 - (a) The discrepancy between coefficient of expansion of the tungsten and the aluminum oxide, resulting in its loosening and flaking off.
 - (b) Its rigidity, resulting in transverse cracking during winding.
 - (c) Its deterioration in a reducing (furnace) atmosphere.
 - (d) Its susceptibility to attack by the Sauereisen refractory cements used for sealing purposes.

Figure 1 — One inch long, tungsten wound, ceramic enclosed differential transformer.

As a consequence of the above: the radial dimensions of the transformer were increased to minimize cracking during winding; a ceramic shell to exclude the furnace atmosphere to obviate its deterioration due to deoxidation was

employed; and the use of refractory cement restricted to parts not touching the windings. One of the auxiliary problems that appears (the answer to which is still evolving) was the manner of connecting lead wires to the tungsten coil windings. At first, a double crimp in a piece of nickel tubing was used, but this proved unsatisfactory, when the circuit opened at high temperature. A high temperature silver solder was then tried and a successful connection maintained at 1200°F. In an attempt to first secure satisfactory transformer performance at 1000°F before going higher, a terminal for withstanding 1600°-1800°F has not yet been made.

At elevated temperatures, three factors tend to decrease the output of a differential transformer:

1. The intrinsic magnetization of the cobalt armature at 1000°F decreases to approximately 80% of its ambient temperature value.
2. Increase of the primary and secondary resistance due to the positive temperature coefficient of resistance of tungsten results in a current decrease of the order of 3:1. It was found that when the sensitivity vanished (as stated below) no voltage increase was able to restore sensitivity, hence, as a basis of comparison, constant primary voltage was considered satisfactory.
3. The primary-to-secondary insulation resistance decrease from 10 megohms at 74°F to 30,000 ohms at 900°F effects a complete loss of sensitivity somewhere between 600° and 700°F.

The attached tables and curves illustrate the above points.

When this transformer was heated by the flame of a Prestolite oxy-acetylene torch (3000°F) for 2 minutes and 40 seconds, it was observed that the armature was red hot, the null voltage was halved and its sensitivity appeared to be unimpaired. From it, may be deduced the fact that a long furnace soak with its gradual temperature rise from ambient to 1000°F was a more severe test than the rapid heating. Inasmuch as the short-time test corresponded to the intended application, it was obvious that this 1" long transformer was a first answer to the problem. However, it was felt that a differential transformer which would withstand the destructive effects of both the rapid and slow heating cycle would be even more desirable. As a consequence, a transformer was fabricated from a standard 6204 ceramic bobbin, #36 gage glass insulated copper wire and the same cobalt armature employed in the 1" long transformer. Inasmuch as the individual primary and secondary resistance was approximately 20 ohms, one-fifteenth that of the 1" long transformer, a considerably smaller primary excitation voltage (6 volts) was required. Impregnation with sodium silicate to exclude air from the glass insulation proved somewhat unsatisfactory since the primary-to-secondary distributed resistance decreased from 800,000 ohms to 800 ohms in traversing from the ambient to 1000°F temperature range. Despite this, the transformer operated satisfactorily from

ambient to 1000°F as the attached table shows. It may be reasonably assumed that such a transformer, if encased in a ceramic shell, could withstand the effects of a rapid

Figure 2.

Figure 3.

heat cycle. Inasmuch as it was experimentally proven that the glass insulation could withstand heating to 1000°F in a vacuum, the next transformer will have the following construction:

1. 2" long ceramic bobbin
2. #36 copper, glass insulated, windings
3. 1½" long, 5/16" O.D. 1/8" I.D. cobalt armature
4. Ceramic enclosing shell.
5. Nickel lead wires brazed to windings with high temperature silver solder.

RECOMMENDATIONS

A differential transformer constructed as above with operation at the optimum voltage and frequency (to be determined for the given design).

Figure 4.

Figure 5.

Figure 6.

CONCLUSION

Of the several prototype differential transformers tested, the following showed promise:

1. The one inch long, tungsten wound, ceramic enclosed transformer performed satisfactorily when subjected to a rapidly-rising temperature (from

Figure 7 — Differential transformer calibrator for furnace use.

Figure 8 — Front view of calibrator.

- ambient to at least 1000°F), but failed at about 600°F when subjected to a slow temperature rise.
2. The two inch long, glass insulated, copper wound, unenclosed transformer, performed satisfactorily up to 1000°F with a slow temperature rise. This transformer was not put through a rapid heating cycle but the next design involving a ceramic enclosure will be.

High Temperature Transformer Characteristic Data

Armature Displacement	Output Voltage
0	.00104
.010	.00425
.020	.0083
.030	.0119
.040	.0159
.050	.0198
.060	.0235
.070	.0272
.080	.0305
.090	.0340
.100	.0370

Primary Excitation Voltage — 5.0 volts, 1000 cps.
Temp. = 80°F

Temperature Versus Output Data For High Temperature Transformer

Freq. cps.	Primary Voltage	Null Voltage	0.1" Voltage	Temp. deg. F	Quality
2000	20.0	.0042	.04	78	8.56
2000	20.0	.0065	.044	300	5.77
2000	20.0	.0072	.045	500	5.24
2000	20.0	.009	.059	600	5.55
2000	20.0	.020	.095	700	3.75
2000	30.0	.036	.14		2.88
2000	20.0	.111	.135	800	.216
2000	30.0	.185	.22	900	.19
No output at any voltage					

Transformer wound with tungsten wire.

Temperature Versus Output Data For High Temperature Transformer Wound With Glass Insulated Copper Wire

Freq. cps	Null Voltage	0.1" Dis- placement Voltage	Temper- ature deg. F	Quality = $\frac{V_{0.1"} - V_{null}}{V_{null}}$
2000	.006	.058	74	8.66
2000	.0039	.059	200	14.1
2000	.0037	.066	300	16.8
2000	.0034	.07	400	19.4
2000	.0026	.07	500	26.1
2000	.0024	.066	600	26.7
2000	.0019	.062	800	31.5
2000	.0016	.059	900	35.4
2000	.0016	.053	700	31.8

Initial: — Prim. Res. = 22 ohms, Sec. Res. = 18 ohms.
Primary — Secondary Res. = 800,000 ohms.

Final. — Same as above except Prim. — Sec. Res. = 800 ohms at 900°F and increased to 18,000 ohms at ambient.

Frequency Versus Output Data For High Temperature Differential Transformer

Fre- quency cps	Primary Voltage	Null Voltage	0.1" Arm. Motion Voltage	Quality = $\frac{V_{0.1"} - V_{null}}{V_{null}}$
100	20	.0023	.004	.736
200	20	.0023	.0069	2.0
400	20	.0023	.014	5.1
1000	20	.004	.026	5.5
2000	20	.0044	.046	9.42
5000	20	.0044	.07	14.9
10000	20	.0044	.098	21.3

NOTE: This data was taken at ambient temperature of 76°F.

At this temperature the Primary Res. = 310 ohms and the Secondary Res. = 310 ohms.

Armature (cobalt) Length = 0.5"; O.D. = .3125"; I.D. = .125."

Capacity from 0 — .0008 mfd between a primary and secondary lead inserted to give lowest null.

Wound with tungsten wire coated with Al₂O₃.

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BREWER REPORT

SUBMITTED BY
GIVEN BREWER
CONSULTING ENGINEER
Marion, Mass.

SEMICONDUCTIVE FILMS

In recent years a great deal of research and development work has been accomplished in the realm of printed circuitry. There was a possibility that certain semiconductive films might be suitable for high temperature strain gages. The investigation made so far indicates that a number of these films are strain sensitive, but that the existing deposits would oxidize long before the temperatures of 1000° to 1500°F were reached. Despite the great amount of work accomplished on printed circuitry, there is still very little known as to the actual properties of the ceramics and the films at high temperature. Some work is now going forward at Aerovox Manufacturing Company, New Bedford, Mass., in an attempt to produce materials to retard or prevent oxidation of the printed films at higher temperatures. At this stage in the development of printed circuits it does not seem hopeful that a high temperature strain gage can evolve from the techniques and developments so far accomplished. See references 1, 6, and 7 at the end of this report.

CERAMICS

Although a great deal of developmental work and practical experience has been gained with existing ceramics used in the field of electric strain gages, there is still no satisfactory ceramic cement today. The early work was accomplished with the Sauereisens, the Quigley AAA cements, and, most recently, the General Electric cements of the silica-oxide and the alumina-oxide types. The existing cements, until the advent of the GE types, were unpredictable in their viscosity and in their performance. The General Electric cement overcomes some of the earlier defects but is still highly corrosive and porous. The General Electric cement, however, is consistent and can be kept in two solutions almost indefinitely without deterioration. It is, at present, the most satisfactory strain gage cement, to the best of my knowledge. See references 2, 5 and 8.

After a conference with Professors Norton and Kingery of Massachusetts Institute of Technology (see references 9 and 10) the possibility of using one of the sesquialuminum phosphates (manufactured under the proprietary title of "Alkophos" by the Monsanto Chemical Company) was investigated. The Alkophos type ceramics are far less corrosive than the General Electric type and presumably would have equal or better bonding and physical strengths. Experiments are just now under way evaluating the Alkophos type of ceramics.

Prerequisite for a successful capacity type strain gage is that the dielectric constant of the ceramic remain essentially constant from room temperature to the working temperature. So far, I have been unable to obtain any data on the dielectric characteristics of conventional ceramics

at high temperature. There is some possibility that reconstituted mica sheet, which can be plasticized and formed, might be useful as a medium for dielectric type or even a wire type strain gage at high temperature. As yet, however, no work has been done on this possibility.

The ideal ceramic binder for an electric strain gage would be about the thickness of heavy paper, nonporous, and completely neutral chemically, before its high temperature curing. It should also have good adherence to stainless steels and should have a thermal coefficient of expansion of the same order of magnitude as do these stainless steels. Moreover, the ideal ceramic should have good properties of electrical insulation in the temperature range of from 1000°F to 1500°F.

A number of frit glasses and low temperature fusing glasses have been developed particularly by E. I. DuPont. Some of these fusing glasses will melt at temperatures low enough to be deposited upon aluminum and aluminum alloy materials. These glasses, for the most part, are conductive at high temperature and have other disadvantages, particularly in application. However, there is still a possibility that these glasses might be used as a final sealing coat to offer a barrier to oxygen and other corrosive gases.

Professor Kingery has pointed out that most of the electronic tube manufacturers employ a ceramic coating over their filament wires. These ceramic coatings are of the Alundum type and resist temperatures up to 1800°C. Also, they withstand very large thermal change in dimensions of the filaments without cracking. Samples of these coated wires have been obtained from the manufacturer and they seem to be quite durable and reasonably flexible. At present most of these Alundum type ceramics are cured at very high temperatures. However, the Norton Company does make a variant of the high temperature ceramic in a lower temperature setting type.

It was suggested by Professor Norton that some of the Sauereisens might be used as a final sealer to prevent oxidation of the strain gage. The Sauereisens were used earlier in the development of ceramic strain gages but have now been abandoned in favor of the improved ceramics. As a sealant, however, the Sauereisens might be quite useful. This, however, has not been checked.

WIRES

The type of wire filaments most commonly used for high temperatures are the Karma and the Nichrome V types. Both of these wires have high coefficients of resistivity with temperature. As a consequence of this large coefficient, very large zero shifts are encountered in testing high temperature structures.

The existing ceramics are very corrosive. Until they have been chemically set, the wire filaments are badly

corroded and often change resistance during the period before curing.

There is a possibility that a high temperature strain gage, or, at least, a strain gage operating in the range of from 500° to 800°F, might be made from Advance type wire. The copper-nickel wire now used, for the most part, on conventional room temperature strain gages has been too subject to corrosion in existing ceramics for consideration. If the Alkophos ceramics prove to be suitable mechanically and, if they are as less corrosive as their relative pH values indicate, it may be that a medium-range strain gage can be made using Advance (Cu-Ni) wire. At present little seems to be known as to the characteristics of Advance in the temperature range above 500°F. However, if a successful strain gage could be made from this wire in the higher temperatures, this gage would presumably enjoy far less zero drift than present gages employing Karma and Nichrome V wires. In this respect, too, it is possible that a medium temperature strain gage might be made utilizing reconstituted mica sheet in plastic form, see references 4 and 4a.

HIGH TEMPERATURE GAGES

Both of the two most commonly used types of gages now depend upon embedding the wire filaments into a ceramic paste. In the first method, the gage is wound conventionally on a frame with a sheet of teflon paper underneath the filaments and the interstices of the grid filled with ceramic. With the ceramic pledget in place, the gage is dried at low temperature to drive off the vehicle whereupon the gage is removed from the winding jig and is ready for application.

If some time is to evolve before the strain gages will be applied, these gages are sometimes put in small containers with silica-gel to reduce moisture and the corrosive effect as much as possible. The gage is next applied to the part to be tested and then fired at the curing temperature which is usually in the 700° to 800°F range.

For application of the second type of strain gage, the surface of the part is cleaned and a pledget of the ceramic placed upon the area of investigation. The strain gage is then wound on a special jig which is then pressed down into the ceramic on the part. Using tweezers or some other mechanism, the strain gage filament is fished off the jig and embedded into the ceramic. The ceramic is then dried and cured on the part itself. This second type of strain gage has the advantage that it can be applied to surfaces having mild compound curvature, whereas the first type strain gage, which has no flexibility, cannot be applied to surfaces other than flat.

Some work has been done by the NACA using single strands of platinum wire applied to a previously coated surface of the part under test. The single strand wire is then cured down to the base material. This type of strain gage was not investigated.

Leads to the strain sensitive filaments are of several types including foils, hollow tubular leads and heavier wires of the same material. Joints are accomplished by tweezer welding or by mechanical means; the latter used particularly in the case of tubular leads.

PROPOSED STRAIN GAGE DEVELOPMENTS

A. Utilizing the Alkophos ceramics with their higher pH and therefore less corrosive environment, it is pro-

posed to make conventional gages. The conventional gages made of Nichrome V would be made employing Alkophos ceramic in place of the present General Electric cement. Also conventional gages employing Advance wire in place of the Nichrome would be used for evaluation at moderate temperatures. If encouragement is received utilizing the Alkophos ceramics, they may be further improved by additions of clay or other oxides to alter the thermal coefficient of expansion of the ceramic.

B. Using reconstituted and plasticized mica sheet, it may be possible to produce a medium temperature range

Figure 1.

strain gage that would be quite durable and flexible. In this case, the wire grid would be placed in a mold; the reconstituted mica plasticizer filled into the mold; and the entire chamber brought up to pressure and temperature so that the grid wires would be completely embedded in the plastic. (See reference 4a.)

Work conducted by the Electrotechnical Laboratory, Bureau of Mines, Norris, Tennessee, has shown that it is possible by means of pressure and temperature to form mica papers and blocks. It might be possible to design a die containing a strain gage grid and, by filling the die with the reconstituted mica powders, apply pressure and temperature producing a strain gage of a considerable durability.

The reconstituted mica sheet with the strain gage filaments would be capable of withstanding temperatures in the range of 1000°F to 1500°F as far as it is now known. This mica strain gage would then be cemented down to the part to be tested either using ceramic cement or some other type of high temperature cement. Whether ceramics now exist which will bond satisfactorily to mica has not yet been determined. It may be possible that the gage could be coated with reconstituted mica sheet powder and, by applying temperature and pressure, be bonded to the metallic part itself.

C. A successful strain gage might be made of the foil type. It was my thought to coat strain sensitive grids with Alundum ceramic which would be then fired onto the grid. Once the firing was completed, there would be no corrosive attack on the wire, since the volatile substances had been driven off in the curing processes. This wire could then be coated in and cemented down to a thin stainless steel perforated or non-perforated foil base. The perforated foil permits egress of the vehicle from the final cementing operation.

With the wire grid fired down to the foil base, the under part of the foil could be again coated and a strain gage of this type cemented onto test structures in a manner very similar to that now employed for bakelite gages. A foil type gage would also have the advantage of being durable for shipment and would permit cementing to mildly compounded surfaces. In the foil type gages it should be possible to keep the ceramic thicknesses very small. With these small thicknesses the ceramic will enjoy a certain

amount of flexibility. In this respect the flexibility would be similar to that noted in glass fibers. As a consequence the resultant gage would be reasonably flexible and could be cemented to compound surfaces. The corrosive attack on both the foil and the gage wire would be limited, since curing would take place quickly after the gage was manufactured.

D. Professor W. D. Kingery, of Massachusetts Institute of Technology, has suggested the development of a strain gage of the core type. A strain gage of this nature might be manufactured by wrapping around a mica core the strain sensitive filaments and mechanically anchoring the terminal points of the filament to the mica. This gage, as wound, would then have no ceramic whatsoever on it. As a consequence, there would be no attack on the wires during the time between winding and the time of application. Application would consist of painting a ceramic base on the part; curing this base; painting another layer over the cured portion; submerging the gage in ceramic; and, then, pressing the entire gage down onto the part, clamping it and curing it at once. In this method of application we would use Pyrex or glass cloth and conventional procedures for curing the gage on the part. With this core type of gage there is almost no opportunity for corrosion of the wire or the base metal, since the time between application of cement and curing is almost negligible. Also with a core type gage and pressure pad we could fit the gage to moderate curvatures without great difficulty as there is no ceramic involved in the cured or semicured condition.

E. It is possible also that a satisfactory single wire gage might be made from a platinum wire. The wire could be coated in the conventional manner by one or the other of the two filament companies and delivered in the coated and fired condition. Clippings of the wire could then be cemented down to a perforated foil and fired once more. The foil gage of this type could be attached to severely compounded surfaces. The single wire type foil gage, of course, poses far less problems in manufacture than does the grid type gage. However, accurate control of gage length of the single filament type might be difficult.

F. Still another possibility for a strain gage utilizes a radioactive source. The gage would be manufactured by depositing two screens of lead lines. The strained elements would be hooked up mechanically to grids in order to cause motion between these grids. This would permit more or less radiation to pass. This signal could then be picked up and amplified.

ADDENDUM TO GIVEN BREWER'S REPORT

We made 8 mica strain gages. The best gage seems to be one made of a sandwich of two pieces of mica paper each about .007" thick, heated to 2100°F and pressed at 1000 to 2000 psi in a graphite die. Three such gages were made using Nichrome V wire and tubular leads. In each case, upon cooling, we found the gage open circuited. Inspection at about 90 power with a binocular microscope revealed grid and leads apparently intact. I suspect the joint between the leads and the grid failed.

I made one gage with a single loop of the .005" Nichrome V tube at 2100°F and 2000 psi. This gage retained continuity, indicating that perhaps a grid wire of .002" or .003" is necessary. I also think the leads should be ribbons instead of tube. In other words, I think the mica gage will

be successful and that the failures are due to poor mechanical design which we can rectify.

I made one gage of hot pressed mica ceramic. This gage requires a fitted die but makes a hard, tough, machinable gage. This gage is as hard as dense, unglazed porcelain, but has the advantage of machinability. It might be good for turbine blades in an abrasive gas stream. Leads also broke inside die, microscope shows them intact. Formed at 2100°F about 1000 psi.

One gage was made of a mica sandwich . . . Nichrome V .001" wire cemented at room temperature with Sodium Silicate cement and dried overnight at about 200°F. This gage was then subjected to 1000°F for about 15 minutes and held continuity.

Two other gages were made using a low melting lead glass, low pressure, and about 1100°F for 25 minutes. These gages, one of Platinum and the other Nichrome V, were good at the end of test, but are obviously not as strong or dense as the gages made at higher temperature and pressure.

A graphite die and about 7½KW at 9600 cps is required to heat the synthetic mica for fusion. High pressure is also required. We used the facilities of the U. S. Dept. of Interior ElectroTechnical Lab for this with Dr. Hatch directing the work.

I will try some brief evaluation experiments with those I have now, but as previously explained, these gages are but crude prototypes. Both Dr. Hatch and I believe a much better gage can be built with .003" Nichrome V grid tweezer-welded to Nichrome ribbon. (See Fig. 1.)

We have ideas on combinations of synthetic mica, temperature, pressure and method of laying down the grids that we wish to explore.

These gages could be made 10 or 15 at a time in a press with induction or dielectric heating.

We have some ideas on cementing the gages down. One quick test indicates that where the part can be put in a die and raised to the proper temperature and pressure we

Figure 2 — Various Gages made in cooperation with Dr. Hatch, using reconstituted mica.

can get bonding strengths equal to the ceramic i.e. about 5000 psi adherence.

We have shown that a durable gage can be made of hot-pressed synthetic mica and that it will stand temperatures above 1500°F. Our work indicates that we cannot make a gage with grid wire as thin as .001" . . . that is, when it is to be welded to .005" tubing. These gages are non-corrosive to the wire and fairly impervious to gas migration, etc. How well they will cement down to a structure is not known. We can control thermal coefficient of expansion to just about equal that of stainless steel.

REFERENCES

1. "Characteristics and Applications of Resistance Strain Gages", U. S. Department of Commerce, National Bureau of Standards, Circular 528
2. "Dynamic Stress Measurements in Turbines" by R. A. Berger and A. W. Brunot, General Electric Co., West Lynn, Mass.
3. "Fundamental Study of Phosphate Bonding in Refractories: I, Literature Review; II, Cold-Setting Properties; III, Phosphate Adsorption by Clay and Bond Migration" by W. D. Kingery, Divisions of Ceramics, Department of Metallurgy, MIT
- 3a. "Fundamental Study of Phosphate Bonding in Refractories: IV, Mortars Bonded with Monoaluminum and Monomagnesium Phosphate" by W. D. Kingery, Division of Ceramics, Department of Metallurgy, MIT
4. "Synthetic Mica Investigations: I, A Hot-Pressed Machinable Ceramic Dielectric" by J. E. Comeforo, R. A. Hatch, R. A. Humphrey and Wilhelm Eitel, Electro-technical Laboratory, Bureau of Mines, Norris, Tennessee
- 4a. "Samica Mica Paper" by Roland D. Jackel in Monthly Research Report of the Office of Naval Research, December, 1951
5. Interview with R. A. Berger and A. W. Brunot at Thompson Laboratories of the General Electric Company, West Lynn, Massachusetts
6. Meeting with Mr. G. M. Ehlers, Chief Research Engineer, The Aerovox Corporation, New Bedford, Massachusetts
7. Interview with Miss Elise Harmon, The Aerovox Corporation, New Bedford, Massachusetts
8. Interview with Mr. Frank Hines of Ruge-deForest, Cambridge, Massachusetts
9. Interview with Professor Norton, MIT
10. Interview with Professor Kingery, MIT

CORNING GLASS WORKS REPORT

SUBMITTED BY
DR. W. W. SHAVER AND MR. WESTON H. JENKINS
CORNING GLASS WORKS
Corning, New York

The Corning Glass gage is a micro-sheet glass sandwich, .008" thick, enclosing a thin gold resistor coating between the sheets. The operating temperature is rated at 450°C. It is applied in the form of a clip gage or semi-circular arc attached with No. 78 Sauereisen cement to the test specimen at the ends of the arc. Arc ends will separate under plastic strain to attain a maximum elongation of 10%.

Leads of silver foil were welded to the resistor using a pointed carbon rod at 10 Volts DC.

Gages are very fragile and several were broken during installation on test members.

A second set of gages used .001" Constantan foil sealed in glass with silver foil leads. Improved resistance-temperature characteristics were noted. The strain limit between the ends of the arc was retained at 10%. The temperature limit was 550°C. The wires to the external circuit were welded to silver leads to minimize local heating at points where the leads are attached to the glass.

Sealing of Nichrome or Karma wires to glass could probably be accomplished with less difficulty than with Constantan.

The semi-circular arcs of .008" micro-sheet lime optical glass are both 1½" diameter and 2⅜" diameter. These have the following properties:-

Softening point	716°C
Annealing point	527°C
Strain point	493°C
Coefficient of thermal expansion	91×10^{-7}

A program of evaluation of glass gages was established by W. D. Manly, Metallurgy Division, Oak Ridge National Laboratory, as follows:-

1. Measurement of resistivity as function of temperature:
 - (a) Reproducibility
 - (b) Temperature cycling
2. Determine best voltage input.
3. Bonding plain glass sheet to the test bar.
4. Effect of base metal on resistivity measurements.
5. Determination of compatibility of the wire and glass over a temperature range by wrapping wire around a glass rod. Glass rod and glass tube of lime optical glass was furnished by Corning Glass for these tests.
6. Determine effect of different base metals on the resistivity of the strain gage wires by placing a metal rod inside a glass tube that has been wrapped with the resistance wire.

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BRIEF ABSTRACT OF PAMETRADA CONTRACT REPORT No. C. 59 MAY, 1953, ENTITLED "PROGRESS REPORT ON DEVELOPMENT OF HIGH TEMPERATURE GAGES"

BY J. MORGAN, B.Sc.
CONTRIBUTED BY
DR. T. W. F. BROWN
PAMETRADA RESEARCH STATION
(PARSONS AND MARINE ENGINEERING
TURBINE RESEARCH AND DEVELOPMENT ASSN.)
Wallsend, Northumberland, England

The Summary in the report named in the above title is quoted as follows: "The progress made in the development of a strain gauge suitable for measuring static strains in

Figure 1 — The gauge wire is woven in the form of a grid into one side of a fiberglass tape former. The wire is not allowed to penetrate through the tape and is only taken under sufficient warp threads to ensure its remaining in position. This photo shows a grid $\frac{3}{4}$ " x $\frac{1}{8}$ " on a $\frac{3}{4}$ " wide tape.

Figure 2 — The lead wires are woven into the opposite side of the tape holding the gauge wire. They are placed astride the grid and project slightly beyond the edge of the tape. The ends of the lead wires are flattened into palms and spot welded to the gauge wire ends. The lead wires are then withdrawn until any slack in the gauge wires is taken up.

steam pipes at temperatures up to 900°F is reviewed. A suitable gauge form has been developed having very good sensitivity, Figs. 1 and 2. Progress has been made with the development of a suitable cement, and the problem of the interaction of cements, gauge wires and test bars. No suitable gauge wire material has yet been found."

A very brief abstracting of the extensive report follows:

Cements, L-6AC, Quigley No. 1925 Blue, Sauereisen No. 19 and Sauereisen No. 31 were reported upon. A total of twelve cements were tested including three from literature, one of which was successful up to 1700°F. The composition of the latter on drying is $K_2O \cdot Al_2O_3 \cdot 3SiO_2$, showing good adherence to mild steel and electrical resistance of infinity at room temperature.

The wires, Nichrome V, Advance, 10/90 Iridium Platinum, 10/90 Rhodium Platinum, Staybrite, Kanthal D, Tophal Z (20-30% Cr. — 5% Al.) were studied.

Preliminary information from tests casts some doubt on whether any conventional resistance alloy would be suitable. The possibility of using pure metals was considered. However, it was concluded, after study, that the degree of care necessary to ensure proper temperature

Figure 3 — The fiberglass tape is stretched taut and clamped. It is then impregnated with a thin solution of high temperature cement. When dry, the tape is removed from the clamp and is trimmed close to the gauge leads, thus leaving the finished gauge. The grid dimensions are $\frac{3}{4}$ " x $\frac{1}{8}$ " and the overall size is $\frac{3}{4}$ " x $\frac{1}{4}$ ".

compensation when using pure metals would be unattainable in the field. Binary alloys and noble metal alloys will be investigated such as 40/60 AgPd, 50/50 AgAu, 40/60 AuPt, although the latter is almost impossible to draw to fine wire.

A Supplement to the above contract report details tests on seven additional synthetic mixtures for high temperature cements. These tests were carried out at length. Tests were also made on the adhesiveness of some cements to wires of different compositions.

DEVELOPMENT OF A GAGE FOR MEASUREMENT OF STRAIN AT HIGH TEMPERATURES

SUBMITTED BY
MESSRS. K. W. MILLER, F. MINTZ, J. T. NICHOLS,
E. A. ROBERTS, J. A. STAVROLAKIS AND G. STEVEN
ARMOUR RESEARCH FOUNDATION
ILLINOIS INSTITUTE OF TECHNOLOGY
TECHNOLOGY CENTER
Chicago, Illinois

This is a preliminary report issued under Venture No. R3055-1, "Development of a Gage for Measurement of Strain at High Temperatures," by Armour Research Foundation, Department of Mechanism and Dynamics Research.

Foundation personnel who contributed materially to the work covered in this report include: K. W. Miller, F. Mintz, J. T. Nichols, E. A. Roberts, J. A. Stavrolakis and G. Steven.

INTRODUCTION

This report is a digest of the preliminary thinking of staff members at the Armour Research Foundation (ARF) regarding methods for the measurements of strain at elevated temperatures.

SENSING METHODS

Resistance-Variation Techniques

In spite of limitations which characterize the present resistance strain gages of drawn wire at temperatures above 500°F, we believe that the electrical resistance variation principle is one of the most promising for the high temperature measurement of strain. Resistance elements other than drawn wire may be developed to have suitable characteristics. Etched foil elements have already been used under standard ambient conditions.

Vapor-Deposited Conducting Films

We believe that vapor deposition of resistance elements is a most promising technique for fabrication of high temperature gages.

The process offers the following advantages in elevated temperature application:

a. It obviates the need for workable materials that lend themselves to cold drawing into very fine wire sizes.

b. The bond that is produced between certain metals and a dielectric base approaches that of molecular cohesion; it can be severed only by the destruction of the metallic film and simultaneously by a chemical attack of the substrate.

c. A photo reproduction process has been recently perfected for masking the substrate prior to vapor deposition of a micro-precision pattern. This process has been exploited by the Armour Research Foundation in a recent confidential development utilizing miniature circuit elements of vaporized metallic films.

d. Since the process is carried to completion in a high vacuum (0.01μ), it is possible to deposit substances of high purity.

e. It offers the possibility of utilizing variations of physical constants with film thickness which have been observed for very thin vapor deposits.

Some determinations over a narrow temperature range have shown that the temperature coefficient of resistance, αR , for several sputtered metals is a function of the film thickness.¹ A plot of this coefficient versus the log of the film resistance (film thickness) produced a straight line ranging from a positive to a negative value and passing through a point of $\alpha R = 0$. A sensing element with a coefficient of resistance either equal to zero or very small and constant would be a very important contribution.

Although it is evident that the process offers many advantages, it does have inherent drawbacks also. For example, the precision that can be obtained at present from the photomasking procedure is not comparable to the dimensional tolerances that can be achieved with fine wire resistors. It may be possible, however, to compensate for greater dimensional tolerances by varying the film thickness in order to deposit to a predetermined resistance. In some regions, film thickness may not critically affect gage characteristics.

The vacuum deposition process also requires extremely close process control to insure consistent characteristics in the product. Preparation of samples, degree of vacuum, vaporizing temperature and time, and the temperature to which the substrate is preheated are all control factors. Certain limitations exist, too, in the control of the chemical composition of some vapor-deposited alloys.

There is still the problem of gage element oxidation. Surface protection of the metal, i.e., by ceramic coatings, is considered a temporary expedient, since atmospheric gases will rapidly penetrate to the metal surface by diffusion through the coating. Protection is probably not feasible. It may be possible, however, to eliminate the need for protection by utilizing a stable component system that approaches thermodynamic equilibrium with its environment in the temperature range for which strain measurements are desired. The oxides, carbides and nitrides of the transition metals offer one possible area where a solution to this problem might be found.

For the past three years, phase diagram studies have been conducted at the Armour Research Foundation on binary and ternary alloy systems of titanium and zirconium. These could serve as the basis for the initial exploration of the semiconductors. For instance, the monoxide of titanium is isomorphous with titanium nitride and has been found to form a continuous solid solution

band across the ternary phase diagram. It is conceivable that a narrow composition range Ti-N-O is chemically stable in air at a predetermined temperature level.

In many instances the deposited films can be vaporized from vacuum-melted buttons of the desired composition. An alternative method is the vaporization of the pure metal followed by a carefully controlled high temperature diffusion treatment. This heat treatment would be carried out in a stream of purified neutral atmosphere, containing the active gases in the desired ratio of partial pressures. A similar process has been utilized at the Armour Research Foundation for the nitrogen surface hardening of titanium components.

At this point it should be emphasized that there are serious gaps in our understanding of the mechanism of the deposition from the vapor phase. There are, for example, many unusual relations between the physical constants of the bulk material and those of thin vapor-deposited films of the same material.^{2,3} Lack of stability of these properties at room temperature that cannot be explained by macro-phenomena associated with the bulk material have been observed. In many instances it is possible, however, to stabilize the metallic vapor film by a room temperature aging treatment or by an accelerated treatment at moderately elevated temperatures.

SEMICONDUCTOR APPLICATIONS

It has been reported recently that stressing germanium crystals in tension will produce resistance changes of the order of magnitude that is found in metallic resistors.⁴ It would not be unreasonable to assume, however, that many different effects might be produced with other semiconductors. An analogy could be drawn with the thermoelectric effect that is obtained from non-metallic thermocouples. For example, the thermoelectric emf output of the graphite/silicon-carbide thermocouple is ten times that generated by the conventional metallic thermocouples.

No data has been uncovered yet pertaining to the gage factors that might be obtained from semiconductors that are of interest in this investigation. The theories of solid state physics have not been developed to the point where it is possible to predict the strain sensitivity of resistance from the crystallographic structure of the materials. It should be emphasized, therefore, that a search for a solution in this field does enter into areas of research where there is little available supporting theory or large body of experimental data.

MAGNETIC SENSING TECHNIQUES

The gage we now envision is similar to available double gap magnetic strain gages. Two E cores oppose each other in a common frame. Both cores are bridged by a common bar between them. Gage signal would vary as the common bar moves closer to one of the E cores and away from the other. Metallic alloys, such as hypersil, magnetic iron and permendur have Curie points above 1000°F and may, therefore, be used in magnetic circuits as high-permeability elements at this temperature. Some high-permeability alloys such as permalloy and mu-metal presumably would be less acceptable because of Curie points below the 1000°F range being considered.

The main problem in this development would be the

fabrication and maintenance of the inductance coils. The noble metals, gold and platinum, would probably be suitable as electric elements from the standpoint of low resistance and stability, but quantity requirements and their cost limit their application for commercial gage quantities. Nickel or nickel-chromium wire, while slightly less conductive than similar wire of the noble metals, may be feasible for the stable high temperature inductance coils required in a magnetic gage.

It is necessary that the inductance coils of such a gage be wound around the high-permeability portion of the magnetic circuit with individual turns insulated from the core and from each other. Since the coils will not be heavily strained mechanically, the requirements for an insulating material are chemical inertness and high electrical resistance in the desired temperature range and sufficient resistance to thermal strain to remain intact.

We believe there are possibilities for development and use of suitable fired ceramic coil forms and also for the use of coil wire insulated by ceramic coatings which could then be wound directly on the core. Some commercial coatings such as solaramic are already available; others are under development. Work on this problem is also being successfully pursued now at the Armour Research Foundation.

CAPACITIVE SENSORS

Variation in capacitance of two opposed condensers can be used to sense relative motion, and hence, strain, through shifts in frequency where the capacitors control resonant electric circuits.

PIEZOELECTRIC SENSORS

Resonant piezoelectric elements may be considered for measurement of strain by being bonded directly to the test specimen. A piezoelectric material such as quartz, for example, might be satisfactory since it retains mechanical and piezoelectric properties up to 1000°F. Other than selection of material, factors to be considered for achievement of optimum strain sensing properties include dimensioning and orientation of cut and the mode of vibration.

An electric driving circuit would be provided to resonate the sensing element and discriminating circuits would be provided to sense the frequency changes. As in the case of the balanced mount mentioned earlier, it may be possible to provide temperature compensation by heterodyning signals from like crystals at the same temperature. In this case one would be strained, the other unstrained. It would also be possible to mount resonant crystals in place of capacitors in the capacitance gage discussed earlier. One element would be compressed while the other would be allowed to expand.

Bonding gage elements to the mounting surfaces is a prime problem which must be solved in order to assure the success of these methods for measuring strain. Bonding and mounting problems, generally, are discussed in a subsequent section of this report.

INDUCTANCE SENSING

The change in inductance of a coil is approximately proportional to small changes in the length of the coil. When a coil is elongated or compressed along its longi-

tudinal axis, changes in its inductance may be used to determine the amount of compression or elongation. A possibility for measuring strain at high temperatures is that of sensing the change in inductance of a bonded coil fabricated from materials which would not deteriorate under the test conditions. Such a gage could take the form of a platinum or platinum-rhodium coil wound on a wafer of artificial sapphire or hot pressed alumina. The coil could be secured to the wafer by dipping or spraying the unit with a suspension of fine-grained, high-purity alumina and sintering at about 2300°F.

Sensitivity would probably be low, unusual precision would be required in the measuring instrumentation and the effect of stray inductance would have to be very carefully controlled.

GAGE BODIES AND MOUNTING TECHNIQUES

For the vapor-deposited resistive strain gages, the principal requirements are that the gage body or backing material be resistant to high temperature oxidation and that it have also a high electrical resistance. Mica appears to fulfill both requirements and has been proved to be a desirable substrate for vapor deposition. Mica is a complex aluminum silicate held together by hydroxyl ion bonds. We believe now that mica could be suitable as a gage body for some sensing methods including resistance variation in the region of 1000°F although in the region of 1300°F it begins to disintegrate because of the departure of the chemical water which bonds the material together.

Artificial mica as well as natural mica is a possibility. Greater control can be exercised over artificial mica in regard to the shapes in which it can be made available. Special shapes of artificial mica can be fabricated from mica flour either by cold pressing and sintering or by hot pressing. Mica flour shapes may be cold pressed in dies under pressures of about 10,000 — 15,000 psi. The desired shapes may be made mechanically and dimensionally stable by sintering at temperatures in the region of 800°F. Additives to the mica flour can be used to give the resulting material a chemical bond stronger than that achieved by an air set. Additives which have been used with success are the oxychlorides of magnesium and the oxyphosphates of aluminum, zirconium and barium.

It is evident that materials for gage bodies should possess chemical and physical inertness at operating temperature in order to be considered for strain gage applications. Noteworthy examples of materials that are inert beyond the 1100°F limit of mica are single crystals such as sapphire, quartz, or periclase. All of these materials are readily available in shapes that might be required and can be fabricated by diamond grinding, and possibly by grinding with carborundum. For bonding the materials mentioned to non-metallic specimens we would investigate the applicability of fine powders of these same materials mixed with small quantities of ball clay. A precaution required is that the cement selected should not react with alumina at high temperatures. Fortunately, pure alumina is inert to most materials. The addition of ball clay to the powdered material will assure that the cement has a high plasticity before firing and high strength after firing.

The limiting strain to which a strain gage may be used

is often determined by the limiting shear stress of the cementitious medium. While some information is available on the compressive and tensile yield stresses of applicable ceramic materials, information on the shear yield stress is probably unavailable. Investigations would have to be conducted to determine the yield of the bond between gage and specimen as a part of the research program making use of these materials. The field of this investigation is related to various experiments that have been conducted with high temperature mortars and it is possible that some work already performed might have application to the problem of bonding mica to test specimens at high temperatures.

For bonding sapphire, quartz, or periclase to a metallic specimen, a good possibility would be a fine powder of the specimen metal, in effect, a brazing powder. The characteristics of such a bond can be controlled by minor additions of other metals designed to enhance wetting of the major component powder and to lower the softening point. Depending upon requirements, mixtures can be achieved for brazing over the temperature range between 1000°F and 2000°F.

Thermo-setting bonds, such as sodium silicate or borosilicate glasses might also have possibilities for cementing mica, sapphire, quartz, or periclase. Particular exploratory work would have to be conducted depending upon the gage and specimen materials which are likely to be used. Sodium silicate, for example, would probably not be suitable as a bond in any gaging situation where platinum was an important component either of gage or specimen. The presence of sodium at high temperatures causes recrystallizing of the platinum through its mineralizing action.

The balanced mechanical constructions described for magnetic, capacitance or resonant element sensing lend themselves to some bonding techniques which are already available such as welding or brazing. Resistance brazing appears especially applicable for the formation of the pad type bonds required; good control over the area of contact can be achieved. Shims of the brazing material, fluxed on both sides, would be clamped between gage and specimen. High electric currents between gage and specimen, through the fluxed shim, would generate heat for brazing the two together.

If the specimen and gage mounting tabs represent compatible thicknesses, spot welding might be employed as a bonding method. Re-use of these types of gages would be desirable from the standpoints of calibration and protection of the investment in the gage. Intermediate mounting tabs which could be cut away to remove the gage could be used. Between calibration and use, or between uses, it would be necessary, in this procedure, to machine away mounting tab remnants and weld or braze new ones.

Should the specimen in which a measurement of strain is desired have a gross section, electric brazing or spot welding might be unfeasible. Torch brazing would then be tried. Metal surfaces clad with brazing material have already been used to facilitate rapid and uniform fabrication of brazed bonds.

In accordance with the concepts proposed in the preceding sections the experimental program should consist of a number of exploratory investigations.

1. Establish the vapor deposition method and the ensuing thermal treatments best suited to the fabrication of the multi phase semiconducting films described above.

2. Determine the stability of these films in air by prolonged exposure to atmospheric conditions at temperatures in excess of 600°F. In this study X-ray diffraction will be employed to follow any chemical changes that may take place in the film material.

3. Establish the temperature coefficient of resistance of these materials over a temperature range as a function of film thickness.

4. Test the strain sensitivity of resistance at various temperatures and determine the stability of this physical property as a function of time and environment.

5. Determine the elastic strain which can be imposed upon the materials without exceeding the rupture strength of the films.

6. Fabricate experimental inductance coils and measure

their electrical characteristics and stability at elevated temperatures.

7. Investigate the field for selection of suitable dielectric material with stable or predictable high temperature characteristics.

8. Fabricate and test ceramic bonds between various cermets such as titanium carbide or high temperature porcelains and possible gage body materials such as mica, periclase, sapphire or quartz. (Cermets is a word commonly used in the ceramic industry to denote a combination of oxides, nitrides or borides with pure metals or alloys.)

9. Test brazed bonds between metallic alloys designed for high temperature service and the possible gage body materials mentioned in 8 above.

REFERENCES

1. A. Schulze and H. Eicke, "Ueber das electrische Verhalten duenner Metallschichten" *Metall.* V.7, No. 5/6 (1953), p. 171.
2. L. Holland, "The Production, Properties and Uses of Thin Films Condensed in Vacuo," *Vacuum*, V. 1, No. 1, (Jan. 1951) p. 23.
3. Nicholas Mostovetch, "Etude Experimentale de la Conductibilite Electrique des Depots Metalliques tres Minces Obtenue par Evaporation Thermique," *Annales de Physique*, V.8, (1953) p. 61.
4. Bulletin of the Am. Phys. Soc., Washington Meeting 1953, Paper No. WA3, C. S. Smith and J. R. Hayes (Bell Telephone Lab.). "Piezo-resistance Effect in Germanium."

SYKORA HIGH TEMPERATURE STRAIN GAGE

CONTRIBUTED BY
GEORGE E. SYKORA
WELL SURVEYS, INC.
624 East Fourth Street
Tulsa, Oklahoma

A base material to be a slab, bar or rod of ceramic or a coating of ceramic on a metallic backing.

1. A slab — meaning a small leaf or slice of ceramic (such as synthetic sapphire)* using one or two surfaces for a grid.
2. A bar — meaning a rectangular section of ceramic (such as synthetic sapphire) to use one to four surfaces for a grid. The grid can be arranged to give the different directional effects of strain on the four surfaces or for temperature compensation from one grid to the next.
3. A rod — meaning a round stock of ceramic (such as synthetic sapphire) .002" in diameter up, having the grid as a spiral around the rod so that a torsional effect on this rod is measurable. These can be mounted in oil holes or in tubes by using spider rings for holding them in place. A lever arm attached to one end or both ends (in case of center anchoring) may be used for spot deflections. Torsional motion can be indicated by the increasing and decreasing of resistance of the metallic coating. One or more longitudinal grids may be applied to the periphery of the rod stock. (The rod, bar or slab can be heat formed to the contour for application to the surface of the test specimen.)
4. A coating — meaning a covering of ceramic (such as synthetic sapphire, fired ceramic or an anodic surface) on a base material of metal or ceramic. Apply metallic resistance alloy grid to surface of the coating. A cover plate could be used to prevent oxidation by using the same type of coating without a grid.

The anodic coating may be applied to other than aluminum base materials (such as the low expansion high temperature alloy metals) by sputtered aluminum on surfaces, then anodize those surfaces.

A band or border of metal (applied at the same time grid is applied) around the outer edge of grid area may be used to hold cover plate in place. If the cover plate is made of ceramic, the same metal band or border can be

applied to it so the two can be soldered or fused together.

Metal coatings for resistance grid may be applied by using the following methods:

1. A metallic oxide may be reduced onto the aluminum oxide in a hydrogen atmosphere. This coating can be done by surface coating or by printed circuitry methods. Another method which could be used involves the putting of one or two ten-thousandths scratches on the surface of the ceramic which scratches or grid cuttings can then be filled or wiped full of metallic oxides. These, in turn, can be reduced to metal. Of course, the right proportion of oxides must be used for the combination of oxides and metallic dust to give the above-explained self temperature resistance compensation for a particular temperature application.
2. Using a powdered metal and/or an oxide composition which can be coated, plated or wiped in grooves to be oxidized and then reduced onto the surface.
3. Wire or foil pressed on surface that has been chemically treated to give a molecular bond adhesion so that high or moderate temperatures will not cause grid to peel. It is possible in all the above cases to have aluminum oxide or sapphire cover plates.
4. A cover plate that cannot be fused on, but merely put in a metallic envelope which is, in turn, welded or spot welded around its outer edge to give anchoring points or areas to the test specimen.

Second phase — This pertains to the properties of the twinned areas of sapphire and their piezoelectric effect, due to strain. Further investigation is necessary to find out the effects of high temperature on this phenomenon.

Third phase — Create in the manufacture of the sapphire boules an interface in the sapphire itself by the addition of impurities in the aluminum oxide powder. It would be necessary to experiment with these impurities which cause interface. They may be as simple as powdered iron particles or other metallic oxides or merely metallic salts.

*Industrial Sapphire can be obtained from Linde Air Products Co., 30 East 42nd St., New York, N. Y., or from Union Carbide and Carbon, Tonawanda, N. Y.

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SHALER REPORT

SUBMITTED BY
MESSRS. AMOS J. SHALER, VICTOR F. ZACKAY
AND WILHELM BUESSEM
State College, Pennsylvania

In order to develop electrical-resistance strain gages which might be useful for experimental stress-analysis work at temperatures in excess of 1000°F, it appears necessary, first, to find answers to a few questions on the mechanism of action of conventional room-temperature gages. For example, it has been stated that specimens mounted with strain gages can be extended beyond the elastic-strain limit (measured on gross specimens) of the gage wire without causing its zero-point to drift. We need to know the reason for this behavior before a material can be intelligently selected for high temperature application on the basis of its elastic limit. One of the possible answers is that the presence of a coating may raise the elastic limit, particularly that of thin wires. If this is one of the functions of the coating, the intelligent selection of coatings and adhesives for high temperature use also depends on prior understanding of the room-temperature behavior of ordinary gages.

The second part of the report contains a description of a possible type of construction, described here as "ceramic-fiber construction" which might greatly extend the utility of materials of low elastic-strain limit for high temperature gages and might also make possible the use of metallic adhesives, for mounting, if they are preferable to non-conducting materials.

Much necessary information may be scattered in the literature concerning topics other than that of strain gages.

Investigation of the Mechanism of Action of Electrical-Resistance Strain Gages and of Materials for High Temperature Gages The Mechanism of Action of Room-Temperature Gages

It has been stated by the makers of electrical-resistance strain gages that a specimen mounted with one of these gages can be extended some 10% beyond the published elastic-strain limit of the metal of which the wire is made, without causing the electrical zero-point of the gage to drift. If this statement is correct, the reason for such behavior is important in the selection of wire-materials for high temperature gages. The following information should therefore be sought in the literature; or by experimental measurement.

Strain-Behavior of Room-Temperature-Gage Wire

The statement quoted above must be verified. Slow strain cycles of increasing amplitude should be applied to the specimen to detect the following values: The point of maximum extension leading to no electrical zero-point drift; the point, if any, at which the strain in the wire deviates from the strain in the specimen; and the elastic-strain limit of the coated wire. An auxiliary measurement must be made of the stress-strain curve of bare strain-gage wire and a bulk specimen of the same composition.

Possible Results of Experiments And Their Interpretation

If (first possibility) the elastic-strain limit of the wire is greater than that of the wire-metal in bulk-form, measurements of strain limits of materials having promise for high temperature service must be made on wires of small diameter. It is possible that a refractory metal or alloy may be found which, in the form of fine wires, possesses a satisfactory strain limit. Evidence pointing to such a possibility may be found in the work of Kuczinsky⁽³⁾ and in that of Rightmire and Wulff⁽⁴⁾. Wires having diameters much less than one thousandth of an inch should not be excluded if techniques exist for making them (see below).

The experiments described above may lead to other conclusions. If neither bare constantan wire nor bare refractory-metal wire shows an elastic-strain limit substantially in excess of the bulk-specimen values, but the mounted gage suffers elastically strain of greater magnitude, it is possible that the coating of the wire may appreciably affect its behavior. There exists experimental evidence making it unwise to exclude such a possibility. Recent work by Benedicks⁽⁵⁾, Barrett⁽⁶⁾, Parker⁽⁷⁾, and Udin and his collaborators⁽⁸⁾ show both the great influence of surface energy on the mechanical behavior of fine wires and the great influence of environment on the surface energy. Wire diameters in the sub-industrial range should not be excluded here either, because the finer the wire, the greater are the roles of the surface and of its environment. It is difficult to predict whether a fine wire of a ductile metal or a fine wire of a refractory brittle metal ought to show the greater change in mechanical behavior when an effective coating is applied to it. Much of the work of the authors cited above has been performed on ductile metals. Nevertheless, similar conclusions have been reached for some brittle materials; the mechanisms may be different in the two groups.

A third conclusion is possible even if mechanical tests show that neither a reduction in diameter nor the application of a coating has a substantial effect on the elastic range. This conclusion is that the recovery of electrical properties may be rapid in comparison with the rate of recovery of mechanical properties. Thus, the wire in a conventional gage may become plastically or anelastically deformed to a slight extent at extreme extensions and yet show no electric zero-point drift. The presence of a coating may considerably modify the rate of recovery of both classes of properties. In recent work, Barrett⁽⁶⁾ has demonstrated the great effect of environment on the rate of anelastic recovery. No work has come to our attention concerning a similar effect on the recovery of electrical conductivity after cold work, but Druyvesteyn⁽⁹⁾ has shown that the two recovery mechanisms are very different.

Possibilities If Experiments Are Negative

Finally, it may be that the experiments will indicate

that no appreciable augmentation of the elastic range can be obtained by either reducing the diameter of the wire or coating it and that zero-point drift must exist if the elastic limit is exceeded. In that event, it is probable that no material of sufficient chemical and mechanical stability can be found for high temperature operation of electric strain gages of conventional design. Gages for such work will then have to be developed by a different approach. Two possibilities are described in greater detail below under the title "Gages With Wire Under Hydrostatic Compression". One involves a mechanical diminution of the strain to be measured; i.e., the strain gage wire is subjected to a strain that is proportional to that of the specimen but smaller. Materials of limited elastic range might then become useful. The design described also has the advantage of removing some of the limitations on mounting media for high temperature use. The other suggestion concerns the possibility of extending the elastic range of the metal by maintaining it under hydrostatic compressions.

MATERIALS FOR HIGH TEMPERATURE STRAIN GAGES

Both wire and mounting materials that may show promise in bulk could fail when used for strain gages at high temperature. Metals which are metallurgically stable when in the form of large specimens may become recrystallized at much lower temperatures and in much shorter times when in the form of wires. Adhesives which may show static chemical stability at service temperatures may be subject to stress-induced transformations.

Materials for Wires

Materials for wires for high temperature gages may be chosen from three groups of metals; ductile refractory metals and alloys, brittle refractory metals and alloys, and cermets. Techniques for making wires of ductile metals and alloys are of course, simpler, by far, than techniques for making fine wires of brittle materials. Yet the history of the electric lamp filament industry shows that by the exercise of ingenuity one can develop techniques for making wires in any size out of practically any material. A study of that history may be rewarding in any attack on the present problem. It may be noted that a new method has been recently developed which may bear investigation here. It is the technique of die-less wire drawing, developed in England by the British Iron and Steel Research Association⁽¹⁰⁾. Any material that can be made to "neck" in a tensile test can potentially be made into wire as fine as is desired by this process — and even cemented carbides may be made to "neck" in a tensile test conducted under hydrostatic pressure.

Accordingly, the elastic range, thermal stability, and chemical stability of all refractory metals, alloys, and cermets should be investigated; not one of them must be disregarded on the ground that fine wires cannot be made from it, nor on the ground that its elastic range is too limited.

Materials for Adhesive

Materials for mounting high temperature strain gages should not be selected before the behavior of the adhesive in conventional gages has been studied more thoroughly

than it has been. It is important to know whether or not the adhesive cracks when the gage is extended. If the film of adhesive does not crack, but becomes extended elastically as much as the wire, it follows that the high temperature mounting material should be chosen, not on the basis of its bulk mechanical properties, but on the basis of the properties shown when it is in the form of a thin film. Little data exists on film properties of any materials, least of all, perhaps, on those of ceramics. If the adhesive of conventional gages cracks under strain without diminishing the effectiveness of the gage, then it is evident that a material could be used at high temperatures which may be applied in the form of "islands" bonded on one side by wire, on the other by the specimen. Such an "island" structure might be obtained, for example, if a fine metal or cermet wire were soldered onto the specimen by means of silicon metal powder or titanium hydride powder, the "solder" being then given an oxidizing heat treatment to convert it to silica or titania; these oxides would then probably be present in the "island" structure described above.

GAGES FOR SERVICE AT HIGH TEMPERATURES

Techniques used in the manufacture of metal-ceramic electric heating elements have applications here and the advice of an engineer experienced in that field would be advantageous.

GAGE WITH WIRE-TO-SPECIMEN STRAIN-RATIO LESS THAN ONE

A type of gage is suggested here in which the specimen-strain is reduced by a fixed ratio before it is applied to the wire. The gage consists of a bundle of ceramic fibers interwoven with the resistance wire. One end of the bundle is soldered to the specimen with a thin coating of an adhesive such as Sauereisen. The other end of the bundle may be capped, coated, or left loose. At some distance between the two ends of the bundle, the gage wire is woven among the fibers in such a way that it lies everywhere in a plane parallel to the bundle-ends, (Figs. 1 & 2). The ratio of strain in the wire to strain in the specimen may be made almost unity if the wire is woven near the specimen, or almost zero if the weaving is near the other end of a long bundle. The ratio is chosen for the best compromise between high sensitivity and high strain-capacity. The manufacture of the gages would probably consist of the following steps: the first operation might be the simultaneous extrusion of a single parallel row of a sufficient number of ceramic fibers having diameters of the order of 0.3 to 0.5 mm, using known techniques. The green fibers might be dried and fired in a continuous furnace-operation as they emerge from the extrusion die. They would then be interwoven with the wire at intervals corresponding to the selected bundle-length. The parallel array might next be folded as many times as necessary along fold lines parallel to the fibers and lying between every fourth (or more) fiber, to provide a bundle in which each gage wire travels among a row of four (or more) fibers in one direction, then is woven back among a parallel row next to the first, and so forth, as many times

fibers and wires in place and could then be sheared to length, the shear plane being kept parallel to the planes of the wires and at a distance from each such plane so

Figure 1.

Figure 2.

as is required for high sensitivity. The entire bundle might then be impregnated with an organic binder to hold the chosen as to provide the selected strain ratio. The organic binder might be burned out of each gage during the operation of soldering it to the specimen.

GAGES WITH WIRE UNDER HYDROSTATIC COMPRESSION

Wires of a metal having a unidirectional elastic-strain range too limited for useful gaging purposes might be used for large deformations if they are embedded in a material which constrains them laterally during extension. First, the hydrostatic compression thus imposed would extend the elastic range of the metal. Second, it might be possible to extend the strain to which such wires are subjected even further by allowing them to suffer plastic or anelastic deformation, provided the surrounding material has sufficient bulk, a low modulus, and a wide elastic range; the surrounding material might then cause recovery of the plastic strain when the gage is unloaded, and at high temperatures the metal might recover its electrical, if not its mechanical, properties if a short rest were given to it between strain cycles.

Gages of the type described above might be manufactured in one of two ways. First, a metal tube might be filled with ceramic material, a heavy wire of the selected metal being threaded along the axis of the tube through the ceramic fill. The whole assembly might then be swaged and drawn severely down to the desired diameter. The metal tube and ceramic might then be stripped from the wire except for a short section which would serve as the gage; the stripped portions functioning as leads. The remaining length of outside tube might be soldered to the specimen. The wire inside the unstripped portion would be under hydrostatic compression during both manufacture and testing, so that its elastic range would be considerably extended.

A similar gage might be made by oxidizing a heavy wire of the desired metal until only a thin core of metal is left unoxidized. The surface of the wire might then be reduced to metal again for joining purposes. To provide hydrostatic compression of the central core, the oxidized-and-reduced assembly might be swaged as in the previous design, and the ends might be similarly stripped to provide leads.

REFERENCES

1. Technical Report ONRL-1-51, Office of Naval Research, London Office, by A. J. Shaler.
2. Chalmers, B., *Proceedings Royal Society (London)* 156, (1935), 427.
3. Kuczynski, G., Massachusetts Institute of Technology, ScD Thesis, Department of Metallurgy, 1945.
4. Rightmire, B., and J. Wulff, to be published, 156, (1936), 427.
5. Benedicks, C. A., in *Pittsburgh International Conference on Surface Reactions*, (1948), 196.
6. Barrett, C., *Acts Metallurgica*, 1 (1953), 2.
7. Parker, E. R., and M. R. Pickus, *Trans. A.I.M.E.*, 191, (1951), 792.
8. Udin, H., A. J. Shaler, and J. Wulff, *Journal of Metals*, 1, (1949), 186.
9. Molenaar, J. and W. H. Aarts, *Nature*, 166, Oct. 21, 1950, 690 and other papers.
10. Annual Report, British Iron and Steel Research Association, 1951.

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AUTHOR'S NOTE:

**THE MATERIAL FOR THIS NOTE WAS CONTRIBUTED BY
CONTROL ENGINEERING CORPORATION
Norwood, Mass.**

Control Engineering Corporation, Norwood, Mass., manufactures a water-cooled pressure transducer suitable for use at gas temperature up to 5000°F and liquid temperature up to 1000°F, maintaining an accuracy stated as follows:

“Output linear to input to $\pm 1\%$ of full pressure

range” and resolution “better than one part in one thousand.”

Cooling water requirement $\frac{1}{2}$ gpm at 10 psig.

This pressure gage uses a catenary type 304 stainless steel diaphragm acting upon a thin wall tube dynamometer upon which is placed two 700 ohm strain gage windings made of conventional materials.

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STRAIN INDICATING DEVICE USING VOLUME CHANGE TO DETERMINE STRAIN LEVEL

CONTRIBUTED BY
W. D. MANLY
METALLURGICAL DEPARTMENT
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee

This method encompasses the welding of a small tube (Superior Tube Company, Norristown, Pa.) to the part that is under load and this tube is connected to a sensitive manometer or pressure indicator cell like an SR-4 diaphragm type low pressure cell. See Fig. 1.

The part could be brought to temperature with the pressure cell sufficiently far away from the part at the elevated temperature so it will not become inoperative. The pressure-transmitting liquid for an application of this type could be liquid sodium, liquid mercury, or some type of

molten salt.

The manner in which the apparatus measures strain lies in the fact that the tubing welded to the strain member will be elongated which will cause an accompanying increase in the volume of the tubing. By a careful calibration of the tubing, the volume change of the tubing can be correlated with the strain in the member to which it is welded. This apparatus works best under tension and for this type of loading, the ends of the tubing could be welded to raised lugs from the part under load.

Figure 1 — Strain indicating device using volume change to determine strain.

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THE USE OF CERAMIC, COATED WIRE BONDED BY MEANS OF ELECTRO-PLATING

CONTRIBUTED BY

R. B. WILLI

CHIEF ENGINEER, SOUTHWARK DIVISION

BALDWIN-LIMA-HAMILTON CORPORATION

Philadelphia, Penna.

The major problems to be overcome in the development of this principle include the application of a thin heat-resistant insulation (see Brewer Report) and the selection of a suitable electro-plating metal which will have the property of depositing itself over impurities and voids, yet have the same coefficient of expansion as the test specimen.

There are a number of insulating materials which may be considered, such as glass, silica, mica, quartz, asbestos, porcelain, alumina, fire clay, etc. as well as various means of application. This might be done by the use of the powdered form of the material applied in a spray, somewhat as is now used in metal coatings, or the vaporized form of the material could be deposited by condensation. While dipping might present the simplest solution, there is danger that such material might char under operating temperatures, affecting the insulating properties. Over top

of the insulation it may be desirable to add a thin coating of a conductor to assist in the bonding process.

For convenience in handling, the insulated wire could be mounted on a perforated plate and the complete assembly electroplated to the specimen.

The process of electroplating can be readily performed in any laboratory, or under normal field conditions, by means of a rubber diaphragm held firmly against the specimen to retain the electrolyte and a source of low voltage direct current, such as a storage battery. Many metals will not deposit over cavities or impurities, but tend to magnify these conditions. Such a deposit would be unsuitable, since it would fail to give the desired bond. Nickel should accomplish this, although its temperature coefficient may introduce an objectionable error. On thin specimens the layer of electroplating may even be unsatisfactory because of its effect on stress distribution.

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NOTES ON STRAIN GAGE TECHNIQUES

CONTRIBUTED BY
R. A. BERGER AND A. W. BRUNOT
GENERAL ELECTRIC COMPANY
THOMPSON LABORATORIES
West Lynn, Mass.
AS REPORTED BY GIVEN BREWER

In the early days of development of ceramic strain gages, all of them involved the use of Sauereisens, which are really porcelain cements. The early porcelain cements were not very practical, since the bond between the Sauereisens and the metal was very poor. Next in line of use were the Quigley AAA paints which were somewhat successful for a while. Unfortunately, the Quigley cements varied substantially in viscosity and there was no practical method of controlling this quality. The Quigley Manufacturing Company recommended that the cements should not be diluted and since the viscosities varied from that of water to that of a thick pigment and since there was no control at all over the Quigley cements, General Electric eventually gave up their use.

Meanwhile, a Robert Girard of the General Electric Company, Schenectady Division, developed two General Electric cements known as 473B (LP28) and 71B (LP29). These ceramic cements are quite consistent in viscosity and, moreover, can be diluted to a good brushing consistency by using a solution of orthophosphoric acid as follows:

Diluting solution for 473B and 71B:

Four parts of water to one part orthophosphoric acid. Add $1\frac{1}{2}$ to 2 cc "Rodine 77" per 100 cc of above solution.

General Electric ceramic, as mixed, lasts about a month, but there is a certain amount of shelf aging. However, it will be possible to get both of these ceramic cements from General Electric in their original unmixed form. General Electric believes that there will be no aging processes at all if the cement is not mixed until the time of application.

Referring to the GE ceramics, the 473B is the silica-oxide type; whereas, 71B is the alumina-oxide type. These cements made into gages and attached to the steel part are improved by temperature and stress cycling which is analogous to the cycling required for Bakelite and paper gages to gain maximum stability.

The thermal coefficient of expansion for the LP28 material is 7.9×10^{-6} in./in./°F, whereas the LP29 material has a thermal coefficient of 4.2×10^{-6} in./in./°F (this is at room temperature. By mixing the two General Electric ceramic cements together, it is possible to obtain a composite mixture having a thermal coefficient of expansion fairly close to that of the base metal on which the gage will be attached. This is most important, if the bonding shear stresses are to be kept as low as possible.

In the case of the Quigley cements the biggest disadvantages were lack of consistency in viscosity, porosity and the fact that it was very hygroscopic and poor in bonding retention. As a consequence, due to gage porosity, the base metal under the strain gage oxidized quickly and after 1 to 10 cycles in actual use, in the range up to 1100°F, the strain gage would come loose from the metal to which it was attached.

All the present ceramics in use exhibit a porous barrier to oxidation, including the latest GE cements. In fact, the greatest single deficiency of the ceramic gages, at the moment, is this matter of porosity. The gage factor and other variables which affect the efficiency of the gage in use are minor as compared to the failure of the bond. In other words, the bond failure and the subsequent oxidation of the metal underneath the gage, is the biggest problem.

The General Electric cements are first put on and then cured at about 600°F (non-glazing). There are ceramic glazes that can be fired at temperatures of approximately 1100°F, these glazing type coatings might be useful for cover coating and for sealing the ceramic cement. By glazing, it might be possible to substantially eliminate the porosity now encountered. These low temperature coatings are obtainable from DuPont's under the nomenclature of "Ceramic Coatings For Aluminum".

The common range of General Electric's present testing is from 1250° to 1500°F.

The wires themselves, which comprise the electric strain gage, do not give General Electric much trouble at this point. Variations in gage factor have not been checked too closely, but what little work has been done indicates that the gage factor does not vary too much. General Electric uses the Nichrome V .001" diameter wire. Karma wire exhibited less resistance change with temperature in the range below 800° F., (showing a 1 ohm change in 800°F on a 500 ohm gage with a gage factor of 1.8). However, above 800°F, the Karma wire exhibits bad terminal resistance hysteresis. It appears, therefore, that Nichrome is better.

When static tests are desired, General Electric uses the following procedure:

- a.) A test device is instrumented with strain gages.
- b.) The device is spun and brought up to temperature.
- c.) Strain gage readings are taken.
- d.) The device is braked to a stop as quickly as possible.
- e.) With the maximum temperatures held constant, another strain gage reading is taken. As a result strain due to stress is immediately known without errors due to drift.

A double filament gage having two wires of opposite temperature resistivity would provide the best answer for a ceramic gage having both static and dynamic utility. Perhaps an even better gage could be made by using a double filament gage and also a double filament dummy gage all wrapped together in the same ceramic.

The Bureau of Standards' undercoating type L6AC is useful but it fires at too high a temperature, namely: 1700°F for 1 minute. This temperature is too high to be

used without altering the heat treatment of the metallic surface.

The transfer method of applying strain gages can be described as follows: A winding fixture is made which has small music wire posts at each end of two movable plates. These movable plates are made in the shape of U's with a flat bottom. From the flat base the music wire wrapping posts protrude upward at a 90° angle. In the slots of the "U" are two machine screws which anchor the movable plates and establish the actual linear gage length of the strain gage. A small piece of acetate or teflon paper is put down between the binding posts slightly shorter than the gage length of the strain gage. The strain gage wire is anchored with a piece of scotch tape at one end, wound back and forth around the post and, finally, is secured with another piece of scotch tape. Liquid cement brushed over the grid with acetate paper forming a base upon which to build up the ceramic. The cement is allowed to air dry. If it is an old cement, it is heated to accelerate the air drying. The consistency of the ceramic is varied by additions of an orthophosphoric acid mixture, so that good brushing consistency is obtained. After drying, a spatula is put underneath the teflon or acetate, the screws are released on the pin holders, and the strain gages lifted off the pins. Care was taken not to coat the loops around the pins with ceramic. Next, the surface of the metal to receive the strain gages is cleaned by pickling and, then, sand blasting (not grit blasting). It is also possible to rub the surface with emery paper, if desired. The surface is finally cleaned with alcohol daubed in, not rubbed. It is necessary to repeat this daubing procedure many times to have a completely-degreased, chemically-clean surface. The ceramic cement is then thinned down to the consistency of water and painted over the surface of the metal to form an insulating base. It is desirable to have this base coat as thin as possible. Now the strain gage is applied to the undercoat while the undercoat is still wet. In many instances it will be noticed that even if the strain gage has a thick ceramic coat over it, it behaves as a blotter, taking the water from the undercoat. This is evident by a moistening of the top coat. Because of the migration of water, the undercoat becomes dry and powdery and will not cure properly. At this point, a brush dipped in a bottle of cement can be used to brush away half of the gage in the longitudinal direction, that is, the cement is brushed entirely away from the gage down to the undercoat until the wires are exposed. Then, new cement is brushed over until the wire is again covered up, a small ridge being left in the center. After air drying, this procedure is repeated in the other direction so that the strain gage now has a completely fresh coating of ceramic around the wires and air dried to the original undercoat.

(In another technique the strain gage grid is wound between two steel blocks and then comparatively large normal forces are exerted on the blocks. These forces raise the grid wire beyond its yield and sets the grid into mechanical shape.)

After the gage has been covered with the ceramic and air dried in position, the leads, which are Nichrome V wire or Nichrome V ribbon, 10 mils in diameter, are welded to the extension of the gage wires by a tweezer welder. The leads are then brought through a two-hole ceramic insulator which is mechanically fastened to the test apparatus by spot welded clips. The entire gage and lead-in system is then covered with the same ceramic as

the gage and cured at 600°F for one hour. Some of these techniques are described in a paper by Berger and Brunot entitled "Dynamic Stress Measurements in Turbines".

It is anticipated that experiments will be made by depositing titanium hydride in a vacuum on an air dried gage. This will have to take place at 1100°F, but, if it were possible to get the titanium hydride on the under surface of the gage, it would then be possible to silver solder the gage to the test piece. In this case, the bond should be strong and should resist oxidation. There is a possibility here for making a commercial gage. It would be necessary, however, to make the gage flexible enough so that it could be attached to curved surfaces. The ceramics are brittle and do not bond very well to themselves, hence, a crack in the ceramic after curing, following an attempt to put it on the part, would not heal.

In the ranges of temperature considered, strains are larger for the same stress than they would be at room temperature. The photogrid system of printing an accurate coordinate system adjacent to points of high stress might prove to be useful. Strains of approximately 2% are usually necessary for accurate reading. Work at the University of California has produced photogrids capable of withstanding temperatures encountered in hot pressing of magnesium.

HIGH TEMPERATURE STRAIN GAGE NOTES

EXTRACTS FROM LETTERS TO THE EDITOR

BY DR. J. C. WILSON

SOLID STATE DIVISION

OAK RIDGE NATIONAL LABORATORY

Oak Ridge, Tennessee

DATA ON WIRES NOW USED IN STRAIN GAGES FOR USE AT ELEVATED TEMPERATURE

Driver-Harris kindly contributed some .005" Karma wire for tests, the results of these tests appear in Fig. 1. All the data were taken on one piece of wire. Curve 1 shows the resistance plotted against temperature when the "as-received" wire was heated to 1130°F at a rate of 1000°F/hr. It will be noted that the resistance changes are rather marked. Curve 2 shows the effect of cooling at a rate of about 40°F/hr; upon reheating to 1130°F (Curve 3) and cooling fairly rapidly (a rate of about 2500°F/hr.), the resistance change is rather great (Curve 4). Reheating to 930°F and cooling over a period of about 1 week gave curve 6.

Figure 1.

The following conclusions can be drawn:

- (1) The low temperature coefficient of resistivity exists only up to about 400°F for "as-received" wire.
- (2) The temperature-resistance curve depends on the heating and/or cooling rate between about 500° to 1100°F.
- (3) The sign of the resistance change with temperature is variable from low positive to high negative values.
- (4) The room temperature resistance can vary several per cent, depending on heat treatment.

It appears that Karma can be used only over a narrow range of temperatures (that is all the manufacturer claims for it) with the advantage of a low temperature coefficient of resistivity. The data does show, however, that the temperature range over which the temperature coefficient of resistivity is very low, may be controlled by heat treat-

ment. For instance, Curve 6 shows that a low temperature coefficient of resistivity may be obtained from about 400° to 650°F by very slow cooling. The best range is about - 100 to + 200 for the wire "as-received" from the manufacturer.

At higher temperatures than 1200°F the resistance should rise again but rather slowly. We haven't made measurements above 1200°F yet. The queer behavior of this metal is attributed to ordering of the lattice in the temperature range of 600° to 1100°F.

I have been suggesting the iron-chromium and iron-chromium-aluminum alloys as possibilities for high temperature strain gage wires. I am trying to obtain a couple of samples for test, but, from what appears in the literature, the combination of high-resistivity and low temperature coefficient of resistivity should make them fairly useful. They are, however, not strong at high temperatures.

The best source for information is a Russian book by I. I. Kornilov entitled "Alloys of Iron-Chromium-Aluminum" published by Polegrafkniga (Moscow) in 1945. A good bit of Kornilov's data appear in Case and Van Horn's book "Aluminum in Iron and Steel" (John Wiley, publisher, 1953).

There are several iron-chromium-aluminum alloys on the market:

- (1) Alloy K, manufactured by C. O. Jelliff, Southport, Conn.
- (2) Radiohm, manufactured by Driver-Harris Co., Harrison, N. J.
- (3) Kanthal, manufactured in Sweden and marketed in U.S.A. by Kanthal Corp., Amelia, Conn.

I have a large enough sample of .002" Alloy K to furnish you some if it will aid your work. The resistivity is about the same as that of Evanohm or Karma.

We will soon have temperature resistance curves on the Alloy K and you will be sent a copy. My main concern with these alloys is their lack of high temperature strength, and a suspicion that there will be some peculiar resistivity changes at perhaps 1000°F. The latter effect should not be as great as in Karma or Evanohm.

AIR GAGING METHOD

An air gaging device, Fig. 2, such as Sheffield (or Solex) has been tested at 1200° and 1500°F at Oak Ridge National Laboratory.

Magnification 8000 X, that is, water manometer column movement is about 8000 times motion of plate at exit orifice.

For reference, see Hetenzi "Handbook of Experimental Stress Analysis".

Figure 2 — See Hetenyi, "Handbook of Experimental Stress Analysis" for references.

CAPILLARY-RESISTANCE METHOD

Connect a fine capillary (.005" to .010" I.D.) of stainless steel to stressed member. If, then, a conducting fluid (mercury, sodium, or other) were used in the system, the resistance of the capillary will change as the column of

Figure 3.

conducting fluid changes position with respect to resistance probes. See Fig. 3.

Such a system of measuring changes in fluid level in a tube by means of electrical resistance has been used by L. F. Coffin at G. E. Knolls Atomic Power Lab, Schenectady, N. Y. at 1200°F.

AUTHOR'S NOTE

**THE MATERIAL FOR THIS NOTE WAS CONTRIBUTED BY
GEORGE D. WHITE
CERAMIC ENGINEER
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee**

George D. White, Ceramic Engineer at Oak Ridge National Laboratory (Y-12) has developed a method of rolling a ceramic on sheet metal which provides a thin, strongly-adhering coating.

A ceramic coated sheet was furnished as a sample of the work and it performed well in thermal shock and mechanical deformation tests. The ceramic in question was 70% glass, 30% chromate, was rolled on a stainless steel sheet 1/16" thick and fired at a temperature of

1800°F thus obtaining a finished thickness of 1/2 mil.

Another sample of perforated nickel sheet with a similar ceramic sprayed on it showed similar desirable characteristics.

Mr. White has proposed a technique for embedding a wire filament grid in a ribbon of ceramic coating which would then be applied to the metal surface by hot rolling or hot pressing, depending upon the surface.

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CONTRIBUTED BY
J. E. CARPENTER
HEAD, STRUCTURAL LABORATORY SECTION
AERO-MECHANICS DEPARTMENT
CORNELL AERONAUTICAL LABORATORY, INC.
Buffalo, New York

The successful measurement of strains produced by thermal stresses and by external loads depends upon the absolute elimination of bridge unbalance due to temperature effects. The problem is resolved into the development of suitable external instrumentation.

Figure 1 — A desirable relationship for use in external instrumentation.

The prefabricated strain gage would consist of the components depicted in Figs. 2 and 3. In Fig. 2, leads A are the extensions of the strain-sensitive wire which is embedded in the matrix in the conventional manner. Also embedded in the same wafer is a thermocouple capable of indicating temperatures up to the operating limit of the strain gage. The extensions of this thermocouple are represented by leads B. See Fig. 2.

The temperature compensation is controlled by introducing resistances R_1 and R_2 to the bridge (see Fig. 4) in a manner universally used for balancing strain gage circuits. The output of the thermocouple embedded in the strain gage is amplified and this amplified voltage is used to drive a standard servo-balancing motor. Consequently, as is the case in conventional automatic temperature recorders, a given angular rotation of the motor is directly indicative of, and related to, the temperature of the strain gage. From simple bridge theory, it is then possible to select a rotary potentiometer (R_2 of Fig. 4), to be operated from the output of the motor, and a fixed resistance (R_1 of Fig. 4) so that $\Delta R/R$ is maintained at a zero level throughout the temperature range.

The techniques described above were initiated under an internal research program now in progress at this laboratory. As yet, only preliminary bench testing has been conducted and the results, to date, have been most encouraging. A strain gage, constructed of 1 mil of Evanohm wire and bonded to a stainless steel specimen, was subjected to

Figure 2.

Figure 3 — Typical High Temperature Strain Gage.

Figure 4.

a temperature sensitivity test and the $\Delta R/R-T$ relationship, shown as curve A of Fig. 5 was determined. A pre-calibrated chromel-alumel thermocouple, instrumented into a standard temperature recorder, was then attached to the test specimen. By keying a suitable rotary potentiometer to the shaft of the balancing potentiometer of the recorder (see Fig. 6), and incorporating this resistance into a circuit similar to the one shown in Fig. 4 the $\Delta R/R-T$ relationship shown in curve B of Fig. 5 was obtained. Since no attempt was made to compensate for the non-linearity of the original $\Delta R/R-T$ curve (which could have been done by utilizing a suitably designed rotary potentiometer), the devised circuit merely rotated curve A about the origin until a small slope of the linear portion of the curve was obtained.

This type of instrumentation is believed to be a practical approach to the problem of temperature compensa-

Figure 5.

tion. For example, the proper integration of the servo and associated equipment in a common housing could result in a simple multi-channel instrument which would lend itself readily to commercial production and which would be an invaluable "Black-Box" companion to nearly any type of static strain gage reader. It should be possible to design such a unit so that a dial adjustment will correct for gages having different temperature sensitivities and bonded to various base materials.

Heretofore, the bulk of all high temperature instrumentation has been concerned with the measurement of dynamic strains, for which case the stability characteristics of the gages are relegated to one of only minor importance.

In general, there are two basic methods of calibrating strain gages at elevated temperatures. They may be described as the tension test method and the "constant-stress" beam method.

For the tension test method, the gages to be calibrated are attached, back to back, to a tension strip test specimen. Two platinum targets, usually placed two inches apart, are welded to the specimen, perpendicular to its longitudinal axis, so that the strain gages are positioned between the targets. An optical strain measuring device is sighted on

Figure 6 — Modification to Servo-Balancing System of Brown Recorder.

these targets, through suitable windows in the furnace wall, and simultaneous strain gage and optical gage readings are taken as the test specimen is stressed.

Two common types of constant stress beams are the tapered, constant-thickness cantilever beam and the constant section beam loaded by end moments. In either case, the loaded beam will deflect in the arc of a circle. Consequently, the true strain in the beam, independent of the changes in the material properties, can be geometrically determined by merely measuring the beam deflection.

AUTHOR'S NOTE:

EXTRACTS FROM A LETTER TO THE EDITOR FROM
DR. W. L. HOWLAND
DEPT. MANAGER — FLIGHT TEST SERVICE
LOCKHEED AIRCRAFT CORPORATION
Burbank, California

"... I believe the method which I have developed for making strain gauges (described in Patent No. 2,621,276) has very large possibilities for use at high temperatures, but, to date, we have not run tests at elevated temperatures with this type of strain gauge.

"The primary type of testing that I have done on evaporation and sputtering type gauges was to determine whether or not higher strain sensitivities could be obtained; and was to determine if gauges could be produced that would be much easier to manufacture in quantity. My tests have definitely answered the first question, that gauges with a much higher strain sensitivity than the wire filament type can be produced, and a very large new field has certainly been uncovered by the use of either evaporation or sputtering.

"I actually investigated other methods of depositing gauges, but I think that the evaporation method has the greatest possibility. For very high temperatures, I think it is possible to evaporate a layer of quartz and then to evaporate a conductive coating on top of this that is either very resistant to oxidation or is again covered by evaporating quartz on top of it. I actually conducted tests with evaporation of alloys and found the process very successful. I studied the making of conductive coating strain gauges by evaporation, sputtering, painting or spraying, printing, electro depositing, or chemically depositing. I found that the evaporation or sputtering showed the greatest promise and, therefore, concentrated on running tests on gauges made by this process.

"Some of the advantages of the evaporation process in making strain gauges are as follows: (a) A very careful control of the material deposited can be exercised. Control can actually be maintained to a thickness of a few angstroms, and in an automatic process the depositing could be carried on until a very precise amount of resistance was obtained. (b) A system can be easily designed and developed in which gauges could be manufactured automatically in large quantities. Evaporation processes are already in industrial use producing items in quantity. Many very interesting effects can be obtained by rotating shutters, scheduling the type of material deposited, tapering the material deposited, etc. (c) Strain sensitive portion of a gauge may or may not be cemented down to the base material. I actually evaporated material on paper which

could then be transferred to the object to be tested. (d) Extremely high strain sensitivity factors can be produced, and a wide variation of electrical characteristics can be produced by evaporating layers of different materials.

"Due to the pressure of other work, we have been unable to conduct tests at elevated temperatures with the evaporated type of gauge. I believe that this method holds a great deal of promise for high temperature gauges; but we have only scratched the surface at the present time in the application of this process to strain measurements. The big problem in using this process is that of obtaining a good electrical connection to the gauge or bridge. The best system appears to be where a complete bridge is formed so that the electrical connections are not as important. We have not completely investigated various methods of forming end attachments, but my approach for high temperature gauges would be to form the connections also by an evaporation process. This can easily be done in a vacuum by remote control shutters or masks ..."

The Howland patent No. 2,621,276 of December 9, 1952, covers most completely the producing of "film-like layers of pure metals, metal alloys, metallic salts, mixtures of plastics and pure metals and/or plastics and various metal alloys and/or metallic salts and/or conductive organic and inorganic salts having unique resistances, strain sensitivities, and temperature characteristics". The film-like layers are "built-up from material either evaporated, vaporized, atomized, powdered, or suspended or dissolved in a fluid vehicle and in its finished form is a homogeneous film resembling a fine foil or mirror coating ... The films formed using initially fluid vehicles may resemble plastic resins, rubber or ink coatings. ..."

A typical claim in the patent described the principle of construction:-

"An electrical strain gauge ... comprising an insulating base, terminal lead-in wires defining the length of said gauge, preformed sheet metal foil terminals electrically bonded to said wires, said terminals and that part of the lead-in wires bonded thereto being cemented to said base, and a homogeneous film-like strip of strain sensitive electrically conductive material, overlying said foil terminals and electrically bonded thereto, said strip being self-adhering to both the foil terminals and the insulating base."

AUTHOR'S NOTE:

THE INFORMATION FOR THIS NOTE WAS CONTRIBUTED BY
DR. S. GULBRANDSEN, ASSOCIATE SUPERINTENDENT
THOMAS D. CALLINAN AND ROBERT T. LUCAS
CHEMISTRY DIVISION
NAVAL RESEARCH LABORATORY
Washington, D. C.

Dr. S. Gulbrandsen, Associate Superintendent, Chemistry Division, Naval Research Laboratory, Washington, D. C., advises us that a possible material for strain gages might be quartz paper. The process for making this paper is to leach fine glass fiber (in bulk) with acid to remove the bases, then fabricate it into paper. At this stage, the silica contains about 15% water of hydration which can be driven out by heating to 600°C. The end result from this process produces a composition approximating pure quartz. The following abstract comes from NRL Report 4064 of the Naval Research Laboratory, Washington, D. C. entitled "The Electrical Properties of Silica Fiber Paper" by Thomas D. Callinan and Robert T. Lucas, Chemistry Division.

"The preparation and properties of paper made from hydrous and anhydrous silica fibers are described and the combinations of these fibers with various commercial resins evaluated. Although this paper was found to be mechanically weaker than previously developed glass fiber paper, it had a much greater thermal resistance. Thus, at 670°C the silica fiber paper was in no way distorted; glass fiber paper, however, shrank and became quite brittle. The tensile strength may be greatly improved by the use of a binder. When machine-made hydrous silica fiber paper is impregnated carefully with electrical-grade varnish, papers of good mechanical strength and acceptable energy-loss characteristics are obtained. With respect to electrical losses, the anhydrous paper was superior to the hydrous paper by a factor of ten and had an extraordinarily low dielectric constant; but tensile strength and density were lower than in the hydrous variety."

TABLE 1

Content and Analysis of Hydrous Silica Fiber Paper

Content	
Silica Fiber	100 %
Binder	0 %
Moisture (removed at 110°C)	6.8%
Chemical Analysis	
SiO ₂	82.4%
Impurities	2.0%
H ₂ O	15.6%

TABLE 2

Physical Properties of Hydrous Silica Fiber Paper

Melting Point	1710°C
Thickness (inches)	0.009
Tensile Strength (psi)	12.0
T.S. (50% moisture) (psi)	19.0
Density (g/cc)	0.201
Basic Weight*	22.8
Uniformity	Excellent
Dirt Count	0
Bursting Strength (Mullen) (psi)	1
Tear Number (Elmendorf)	8
Absorptivity	High
Porosity (Gurley-sec)	3.2
Air Resistance (mm H ₂ O/ml)	8.6

*Weight in lb. of 500 sheets, 25 x 40 in.

AUTHOR'S NOTE:

STORED ENERGY WELDING UNIT UNITEK CORPORATION Pasadena, California

It has been ascertained through work performed by some of our sub-contractors that the following piece of equipment manufactured by Unitek Corporation, Pasadena 8, California, has been found very useful in lead connection and experimental attachment of metal back strain gages. The following description of this equipment is for information purposes and it is suggested that many applications in strain gage work might be found for this equipment.

Fig. 1 shows the Unimatic Weldmaster, manufactured

Figure 1 — Unimatic Stored Energy Spot Welder. Used in lead attachment of metal backed strain gages.

by Unitek Corporation. This equipment is now in use for lead connection.

Unimatic welders employ the capacitor-discharge principle, which permits an extremely short weld time (less than 0.001 seconds). This characteristic makes possible the welding of many materials normally considered impractical for joining by this method. Examples are: silver contact buttons to beryllium copper wiper arm; fine resistance wires to terminal lugs or posts; and various spring materials to their supporting structures.

The equipment is intended specifically for manufacturers of electronic and scientific instruments. It produces high strength welds consistently and without discoloration or excessive deformation. The metallurgical nature of the parent material is not altered except within the weld zone itself and there is virtually no "heat affected" zone.

These machines are ideally suited to the joining of fine wires to themselves and to leads or lugs. The Unimatic Model 1015 Weldmaster is especially recommended for this type of work. The Tweezer Type Handpiece Accessory may be simply plugged into the Weldmaster for reaching otherwise inaccessible locations.

The Unimatic Model 1010 Long Lead Welder is a field instrument designed for intermittent use, and is intended for attaching thermocouple junctions or strain gages to test assemblies. It was originally developed for field repair of jet engine insulating blankets, made of quilted metal foil. This machine is now enjoying increased use for strain gage application. A long lead accessory is also available for the Weldmaster, which makes that machine usable as a long lead welder.

AUTHOR'S NOTE:

POSSIBLE MATERIALS FOR HIGH TEMPERATURE GAGE CONSTRUCTION

Glass Fibers, Inc., 1810 Madison Avenue, Toledo 2, Ohio, have recently developed a high temperature insulation material of fibrous form, called Q-Felt, which will re-

sist temperatures up to about 3000°F. It is produced from 98% chemically pure quartz. Densities are as low as 3 lbs. per cubic foot.

AUTHOR'S NOTE:

**THE INFORMATION FOR THIS NOTE WAS CONTRIBUTED BY
J. W. SELDEN, MANAGER
NEW PRODUCTS DIVISION
MINNESOTA MINING & MANUFACTURING COMPANY
900 Fauquier Avenue
Saint Paul, Minnesota**

Our Adhesives and Coatings Division has suggested their adhesive CDL 328251, which in laboratory tests show good aging characteristics at 480°F for 250 hours.

Address: Minnesota Mining & Manufacturing Co.
Adhesives and Coatings Division
411 Piquette Avenue
Detroit, Michigan

Our Abrasives Division Laboratory has been working with specially compounded resins which show good strength characteristics but inferior adhesion at 500°F.

Address: Minnesota Mining & Manufacturing Co.
900 Fauquier Avenue
St. Paul 6, Minnesota

Our Electrical Products Division has developed products and techniques for the application of Teflon to electrical components for protection and insulation at high temperatures.

Address: Minnesota Mining & Manufacturing Co.
900 Fauquier Avenue
St. Paul 6, Minnesota

It has been suggested that our Irvington Varnish & Insulator Division might have interesting materials for test.

Address: Minnesota Mining & Manufacturing Co.
Irvington Varnish & Insulator Division
6 Argyle Terrace
Irvington 11, New Jersey

The Minnesota Mining and Manufacturing Co. state that CDL-328251 may be satisfactory adhesive suitable for installation of strain gages. This material is a high temperature, low strength adhesive. CDL-328251 is a white, putty-like paste which, when used with CDL-328250 primer, gives good high temperature resistant metal to metal bonds.

AUTHOR'S NOTE:

**THE INFORMATION FOR THIS NOTE WAS CONTRIBUTED BY
E. E. SIMMONS
Pasadena, California
ORIGINAL INVENTOR OF THE BONDED
WIRE RESISTANCE STRAIN GAGE**

Radiation from a gamma source improves the rigidity of some kinds of plastic materials by causing cross-linking of the molecules. Therefore, some of the cements used

in strain gages may be improved in rigidity and thus be suitable at higher temperatures by radiating the gage after cementing in place.

LIST OF CONTRIBUTORS INCLUDED IN THIS REPORT

<i>Section</i>	<i>Author</i>	<i>Title</i>	<i>Period Covered</i>	<i>Charge</i>
A	Fred N. Singdale, 2335 Sesmas Street, Duarte, California	DEVELOPMENT OF HIGH TEMPERATURE STRAIN GAGES	May, 1953 to May, 1954	ONR s-c C. & C. s-c
A	D. J. DeMichele, General Engineering Lab., General Electric Company, Schenectady, N. Y.	HIGH TEMPERATURE STRAIN GAGES		ONR s-c
A	John D. Russell, Chief Engineer, Micro-Test, Inc., Los Angeles 36, Calif.	WELDABLE WIRE STRAIN GAGE	Nov., 1952 to Feb. 25, 1954	No Cost
A	R. J. Carleton, Jr., Gilmore Technical Association, Cleveland 3, Ohio	THE GILMORE REPORT	June 1, 1953 to June 4, 1954	ONR s-c
A	Baldwin-Lima-Hamilton Corporation, Eddystone Div., Phila. 42, Pa.	ETCHED FOIL HIGH TEMPERATURE STRAIN GAGES	Ended Nov., 1954	No Cost
A	E. J. Wisniewski, Head, Experimental Mechanics Section, Westinghouse Electric Corp., Aviation Gas Turbine Division, Lester, Penna.	WORK OF WESTINGHOUSE ELECTRIC CORPORATION, AVIATION GAS TURBINE DIVISION		No Cost
A	Jones, Stroud & Co., Ltd., Vida Mills, Long Eaton, Nottingham, England	GLASS WOVEN STRAIN GAGES	Ended June 18, 1953	No Cost
A	American Instrument Co., Silver Spring, Md. In cooperation with P. R. Weaver, National Bureau of Standards, Washington, D. C.	AN OPTICAL STRAIN GAGE FOR USE AT ELEVATED TEMPERATURES		No Cost
B	G. C. Kuczynski, P. F. Stablein, and E. A. Peretti, Department of Metallurgy, University of Notre Dame, Notre Dame, Indiana	HIGH TEMPERATURE STRAIN GAGES	Nov. 21, 1952 to July 31, 1954	ONR s-c C. & C. s-c
B	B. D. Cullity and G. C. Kuczynski, Department of Metallurgy, University of Notre Dame, Notre Dame, Indiana	NEW STRAIN SENSITIVE ALLOYS	Same as above	Included in above
B	Prof. Samuel T. Carpenter, Swarthmore College, Swarthmore, Penna. In cooperation with John L. Everett, E. H. Smith and Co., Silver Spring, Md.	A STUDY OF TECHNIQUES OF MEASURING MECHANICAL STRAINS AT HIGH TEMPERATURES	Ended Oct. 5, 1953	ONR s-c

<i>Section</i>	<i>Author</i>	<i>Title</i>	<i>Period Covered</i>	<i>Charge</i>
B	William O. Passarelli, Jr., Project Engineer, Westinghouse Electric Corp., Atomic Power Division, Bettis Field, Pittsburgh, Penna.	HIGH TEMPERATURE STRAIN GAGE FOR MEASUREMENT OF STATIC STRAINS	Ended June, 1954	No Cost
C	Automatic Temperature Control Company, Inc., Philadelphia, Pa.	HIGH TEMPERATURE DIFFERENTIAL TRANSFORMER	Nov. 21, 1952 to July 31, 1954	ONR s-c
C	Given Brewer, Consulting Engineer, Marion, Mass.	THE BREWER REPORT	Jan. 27, 1954 to July 15, 1954	ONR s-c
C	W. W. Shaver and H. Jenkins, Corning Glass Works, Corning, New York	THE CORNING GLASS WORKS REPORT	Dec. 5, 1951 to June 1, 1952	ONR s-c
C	T. W. F. Brown, Pametrada Research Station, (Parsons and Marine Engineering Turbine Research and Development Association), Wallsend, Northumberland, England	PROGRESS REPORT ON DEVELOPMENT OF HIGH TEMPERATURE STRAIN GAUGE	Ended May, 1953	No Cost
D	K. W. Miller, F. Mintz, J. T. Nichols, E. A. Roberts, J. A. Stavrolakis and G. Steven, Armour Research Foundation, Illinois Institute of Technology, Technology Center, Chicago, Illinois	DEVELOPMENT OF A GAGE FOR MEASUREMENT OF STRAIN AT HIGH TEMPERATURES	Ended June 19, 1953	ONR s-c
D	George E. Sykora, Well Surveys, Inc., 624 East Fourth Street, Tulsa, Oklahoma	SYKORA HIGH TEMPERATURE STRAIN GAGE	Nov. 6, 1953 to Jan. 25, 1954	No Cost
D	A. J. Shaler, V. F. Zackay and W. Buessem, State College, Pa.	THE SHALER REPORT	Ended Jan. 25, 1954	ONR s-c
D	Control Engineering Corp., Norwood, Mass.	AUTHOR'S NOTE		No Cost
D	W. D. Manley, Metallurgical Department, Oak Ridge National Laboratory, Oak Ridge, Tennessee	STRAIN INDICATING DEVICE USING VOLUME CHANGE TO DETERMINE STRAIN LEVEL		No Cost
D	R. B. Willi, Chief Engineer Southwark Division, Baldwin-Lima-Hamilton Corp., Philadelphia, Pa.	THE USE OF CERAMIC COATED WIRE BONDED BY MEANS OF ELECTROPLATING	Ended Nov. 3, 1952	No Cost
E	R. A. Berger and A. W. Brunot, Thompson Laboratories, General Electric Company, West Lynn, Mass. As Reported by Given Brewer	NOTES ON STRAIN GAGE TECHNIQUES	Ended Jan. 27, 1954	No Cost

<i>Section</i>	<i>Author</i>	<i>Title</i>	<i>Period Covered</i>	<i>Charge</i>
E	J. C. Wilson, Solid State Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee	HIGH TEMPERATURE STRAIN GAGE NOTES	Ended Apr. 27, 1954	No Cost
E	George D. White, Ceramic Engineer, Oak Ridge National Laboratory, Oak Ridge, Tennessee	AUTHOR'S NOTE		No Cost
E	J. E. Carpenter, Head, Structural Laboratory Section, Aero-Mechanics Department, Cornell Aeronautical Laboratory, Inc., Buffalo, N. Y.	CORNELL REPORT IG-886-S-1	Ended Aug., 1953	No Cost
E	W. L. Howland, Dept. Mgr., Flight Test Service, Lockheed Aircraft Corp., Burbank, Calif.	AUTHOR'S NOTE	Ended June 25, 1953	No Cost
E	S. Gulbrandsen, Associate Superintendent, T. D. Callinan and R. T. Lucas, Chemistry Division, Naval Research Laboratory, Washington, D. C.	AUTHOR'S NOTE	Ended July 13, 1953	No Cost
E	Unitek Corporation, Pasadena, California	STORED ENERGY WELDING UNIT	Ended Mar. 24, 1954	No Cost
E	Glass Fibers, Inc., 1810 Madison Avenue, Toledo, Ohio	AUTHOR'S NOTE		No Cost
E	J. W. Selden, Mgr., New Products Division, Minnesota Mining and Manufacturing Company, 900 Fauquier Avenue, St. Paul, Minnesota	AUTHOR'S NOTE	Ended May 3, 1954	No Cost
E	E. E. Simmons, Pasadena, Calif.	AUTHOR'S NOTE		No Cost

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APPENDIX

STRAIN MEASURING DEVICES—THEIR THEORY, TECHNIQUES, AND APPLICATIONS (WITH PARTICULAR EMPHASIS ON THE RESISTANCE WIRE STRAIN GAGE)

COMPILED BY
H. F. RONDEAU
AMERICAN METER CO.
Erie, Pa.

BOOKS

- Dobie, W. B. and Isaac, P. C. G. *Electric Resistance Strain Gages*. The Macmillan Company, 60 Fifth Avenue, New York, 1949, \$3.50; or The English University Press, Ltd., London, 1948.
- Hentenyi, M. *Handbook of Experimental Stress Analysis*. John Wiley & Sons, Inc., New York, 1950.
- Koch, J. J.; Boiten, R. G.; Biermasz, A. L.; Roszbach, G. P. and Van Santen, G. W. *Strain Gauges—Theory and Application*. Elsevier Press, Inc., 402 Lovett Boulevard, Houston, Texas; or 300 Park Ave., New York, 1952.
- Roberts, Howard C. *Mechanical Measurements by Electrical Methods*. The Instruments Publishing Co., Inc., Pittsburgh, 1951 (Second Edition).

Technical Journal Articles

- Betts, C. H. "Bonded Resistance Wire Strain Gages Simplify Determination of Creep Measurements," *Steel*, 124, page 115, February 27, 1949.
- Bierman, H. R. "Device for Measuring Physiologic Pressure Phenomena Using the Bonded Electrical Wire Resistance Strain Gage," *Review of Sci. Instr.*, 19, pages 707-710, October, 1948.
- Bierman, H. R. and Jenkins, R. "Hypodermic pressure Manometer Utilizing the Bonded Wire Resistance Strain Gage," *Review of Sci. Instr.*, 22, pages 268-269, April, 1951.
- Brewer, Given. "Determination of Principal Stresses By Use of the Equilateral Strain Rosette," *Aero Digest*, pages 90-97 and 217, January, 1945.
- Carlson, R. W. "Five Years' Improvement of the Elastic-Wire Strain Meter," *Eng. News-Rec.*, V. 114, pages 696-697, May 16, 1935.
- Contini, Roberto. "A Graphic Solution for Strains and Stresses from Strain Rosette Data," *J. Aeronautical Sciences*, V. 12, No. 1, pages 47-50, January, 1945.
- De Forest, A. V. "Characteristics and Aircraft Applications of Wire Resistance Strain Gages," *Instruments*, V. 15, No. 4, pages 112-114 and 136-137, April, 1942.
- Deignan, J. E. "Measuring Bedrock Action Under Tygart Dam with Elastic Wire Strain Meters," *Eng. News*, 116, page 731, May 21, 1936.
- De Michele, D. J. "Wire Strain Gages for Elevated Temperature Service," *Product Eng.*, 21, pages 115-117, October, 1950.
- Dohrenwend, C. C. and Mehaffey, W. R. "Measurement of Dynamic Strain," *J. Applied Mechanics*, March, 1943.
- Dorey, S. F. "Wire-Wound Electrical Resistance Strain Gages," *Engineer*, 177, pages 375-376, May 12, 1944; pages 386-387, May 19, 1944.
- Eaton, E. C. "Resistance Strain Gage Measures Stresses in Concrete," *Eng. News-Rec.*, V. 107, pages 615-616, October 15, 1931.
- Edwards, J. "Electrical Resistance Wire Strain Gages," *Metal Treatment*, Winter, 1947-1948, Vol. 14, pages 213-221; Spring, 1948, pages 17-26.
- Gunning, W. F. and Van Leeuwen, E. G. "Resistance Wire Strain Gage Equipment for Static and Dynamic Testing," *Product Eng.*, 16, pages 608-613, September, 1945.
- Hengstenberg, T. F. "Atom Smasher Tank Stresses as Measured by SR-4 Strain Gage," *The Welding Journal*, pages 363-366, June, 1947.
- Hillman, V. E. "Electric Strain Gages Aid Machine Design," *The Iron Age*, pages 50-53, April 11, 1946.
- Hoff, N. J. "A Graphic Resolution of Strain," *J. Applied Mechanics*, V. 12, No. 4, pages A 211-216, December, 1945.
- Jasper, Norman H. "Instrumentation Problems for the Vibration Field Test Engineer," *Instruments*, V. 23, No. 2, pages 142-143, February, 1950.
- Keenan, A. G. and McIntosh, R. L. "Strain-Sensitive Resistance Wire Manometer," *Review of Sci. Instr.*, 19, pages 336-339, May, 1948. (Contains bibliog. & diagrams)
- Kenyon, R. L. and Tobin, Harry. "Measurement of Stresses in Car Wheels," *Ry. Mech. Engr.*, V. 115, No. 12, pages 516-523, December, 1941; and V. 116, No. 1, pages 6-19, January, 1942.
- Kern, R. E. "Stress Measurement by Electrical Means," *Trans. Electrical Engineering*, pages 100-107, March, 1946.
- Kern, R. E. and Williams, S. B. "Stress Measurement by Electric Strain Gages," *Trans. American Inst. Elect. Engrs.*, V. 65, March, 1946.
- Levesque, G. N. "Bonded Resistance Wire Strain Gages as Components of Machinery and Gaging Equipment," *Product Eng.*, 20, pages 136-137, August, 1949.
- Mindlin, R. D. "The Equiangular Strain Rosette," *Civil Eng.*, V. 8, No. 8, pages 546-547, August, 1938.
- Moyd, L. "Determination of the Coefficient of Linear Thermal Expansion of Rock Specimens by Means of Resistance Wire (SR-4) Strain Gages," *Min. Eng.*, 187, Trans. 683-684, June, 1950.
- Munch, R. H. "Wire-Type Strain Gages and Their Applications to Pressure Measurements," *Ind. & Engr. Chem.*, 37, pages 99-100, October, 1945.
- Murphy, G. "A Graphical Method for the Evaluation of Principal Strains from Normal Strains," *J. Applied Mechanics*, V. 12, No. 4, pages A 209-210, December, 1945.
- Nielsen, D. M. "Strain Gages, Resume of Characteristics of Wire Resistance Gages; Typical Electronic Circuit for Measuring & Recording," *Electronics*, 16, pages 106-111, December, 1943.
- Norton, J. T. and Kuczynski, G. C. "Simultaneous Measurement of Tensional and Electrical Resistance of Fine Wires," *Instruments*, 21, page 328, April, 1948.
- Petrucelly, V. "Resistance Wire Strain Gages as Elements of the Wheatstone Bridge," *Elec. Eng.*, 68, page 331, April, 1949.
- Randels, W. C. and Plane, V. C. "Force Measurements by Means of Resistance Wire Strain Gages," *Jr. Aeronautical Sci.*, 14, pages 59-62, January, 1947.
- Rankin, A. N. "Orientation of Strain Gages in Stress Analysis," *G. E. Review*, V. 50, No. 9, pages 14-21, September, 1947.
- Roberts, H. C. "Electric Gaging Methods for Strain, Movement, Pressure, and Vibration," *Instruments*, V. 17 and 18, April, 1944 to December, 1945.
- Rogers, G. L. "Quick Selection Chart for SR-4 Strain Gage Type Pickups," *Instruments*, page 912, October, 1949.
- Rondeau, H. F. "Miniature Force and Pressure Cells," *General Electric Review*, Vol. 54, No. 11, pages 24-26, November, 1951.
- Ruge, A. C. "Bonded Resistance Wire Gages for Strain Measurements," *Product Eng.*, 20, pages 116-117, January, 1949.
- Rusher, M. A. and Mershon, A. V. "Electric Strain Gage," *Elec. Eng. Trans.*, V. 57, November, 1938.
- Sanson, T. B. "Resistance Strain Gages," *The Electrical Review*, July 1, 1949, pages 3-6.
- Savic, P. "Wire Resistance Strain Gauge," *Research*, Vol. 1, No. 3, pages 98-106, December, 1947.
- Sherlock, R. H. and Belgin, A. "Protection of Electric Strain Gages in Concrete," *The Journal of the American Concrete Institute*, pages 189-192; November, 1947; Discussion, page 192, December, 1948.
- Strong, J. G. "Resistance-Wire Strain Gages," *Roy. Aeronautical Soc. J.*, 54, pages 19-26, January, 1950.

- Tatnall, F. G. "Applications of Bonded Wire Strain Gages," *Tool Eng.*, 26, pages 28-31, April, 1951.
- Van Leeuwen, E. G. and Gunning, W. F. "Resistance Wire Strain Gage Applications and Circuits," *Product Eng.* 16, pages 443-449, July, 1945.
- Wells, A. A. "Multi-channel String Galvanometer for Use with Wire-Resistance Strain Gauges," *J. Sci. Inst.* 27, pages 59-61, March, 1950.
- Woodman, E. H. "Wire-Strain Gage Measures Earth Pressure," *Elec. World* 124, page 95, September 29, 1945.
- "Chart Eases Selection of Resistance Gage," *Aviation Week*, pages 33-34, June 6, 1949.
- "Correcting Lead Wire Errors with SR-4 Strain Gages," *Marine Eng.*, V. 57, pages 77-78, March, 1952.
- "Electric Resistance Wire Strain Gauges," *Engineer* 162, pages 121-123, August 9, 1946.
- "Measuring Creep with Strain Gages," *The Iron Age*, page 59, December 23, 1948.
- "Strain Gage; SR-4 Metaelectric Gage," *Scientific American*, page 265, November, 1940.

Technical Organization or Society Publications or Proceedings

- American Railway Engineering Assoc. Proceedings. "Measurement of Stresses on 115 lb. Rail on Tangent Track — North Western Railway," V. 52, 1951, page 60 (Report of Committee 4).
- American Railway Engineering Assoc. Proceedings. "Measurement of Stresses on 132 lb. R. E. Rail on Tangent Track — Sante Fe Railway," Vol. 51, 1950, page 626, Appendix 11-a.
- American Railway Engineering Assoc. Proceedings. "Lateral Forces Exerted By Locomotives on Curved Track" (A Synopsis), Vol. 52, 1951, page 93.
- American Railway Engineering Assoc. Proceedings. "Critical Review of the Subject of Speed on Curves as Affected by Present Day Equipment," Vol. 52, 1951, page 576 (Report of Committee 5).
- American Railway Engineering Assoc. Proceedings. "Effect of Wheel Unbalance, Eccentricity, Tread Contour and Track Gage on Riding Quality of Railway Passenger Cars" (Synopsis), Vol. 52, 1951, page 130.
- American Railway Engineering Assoc. Proceedings. "Impact and Bridge Stresses — Tests of Steel Girder Spans on The Chicago and North Western Railway," Vol. 52, 1951, page 1 (Advance Report of Committee 30).
- American Railway Engineering Assoc. Proceedings. "Service Tests of Various Types of (Rail) Joint Bars," Vol. 51, 1950, page 570 (Report of Committee 4).
- American Railway Engineering Assoc. Proceedings. "Iron and Steel Structures — Stress Distribution in Bridge Frames — Floor Hangers," Vol. 51, 1950, page 470 (Report of Committee 15).
- American Railway Engineering Assoc. Proceedings. "Roadway and Ballast Report on Physical Properties of Earth Materials," Vol. 51, 1950, page 710 (Report of Committee 1).
- American Railway Engineering Assoc. Proceedings. "Steel and Timber Pile Tests," Vol. 52, 1951, page 149 (Advance Report of Committee 8).
- Anderson, A. R. and Nevitt, C. R. "Application of Electric Strain Gages to Shipbuilding Problems," *Proc. Exp. Stress Analysis*, Vol. 1, No. 1, Addison-Wesley Press, Cambridge, 1944, pages 1-9.
- Aughtie, F. "Electrical Resistance Wire Strain Gages," *Inst. Mech. Eng. J. & Proc.* 152, Proc. 213-214, September, 1945.
- Ball, L. M. "Strain Gage Technique," *Exp. Stress Analysis*, V. 3, N. 1, Addison-Wesley Press, Cambridge, 1945, pages 1-22.
- Bassett, W. V.; Cromwell, H.; Wooster, W. E. "Improved Techniques and Devices for Stress Analysis with Resistance Wire Gages," *Exp. Stress Analysis*, V. 3, N. 2, Addison-Wesley Press, Cambridge, pages 76-88, 1945.
- Baumberger, R. and Hines, F. "Practical Reduction Formulas for Use on Bonded Wire Strain Gages in Two-Dimensional Stress Fields," *Exp. Stress Analysis*, V. 2, N. 1, Addison-Wesley Press, Cambridge, 1944, pages 113-127.
- Boodberg, A. "Stability of SR-4 Electric Strain Gages and Methods for Their Waterproofing and Protection in Field Service," *A.S.M.E. Trans.* November, 1948, pages 915-920.
- Boodberg, A. and Howe, E. D. "Method of Obtaining the Stress at the Mid-Thickness by Measurements from Only One Surface of a Plate," *Experimental Stress Analysis*, Vol. V, N. 1, Addison-Wesley Press, Cambridge, Mass., 1947, pages 56-58.
- Boodberg, Howe and York. "Stability of SR-4 Electric Strain Gages and Methods for Waterproofing and Protection in Field Service," A.S.M.E. Paper No. 47-A-120.
- Bossart, K. J. and Brewer, Given. "A Graphical Method of Rosette Analysis," *Exp. Stress Analysis*, V. 4, N. 1, Addison-Wesley Press, Cambridge, 1946, pages 1-8.
- Buckely, W. H. and Anderson, R. G. "Resistance Wire Strain Gages in Product Development," *Exp. Stress Analysis*, V. 9, N. 1, Addison-Wesley Press, Cambridge, 1951, pages 177-190.
- Carpenter, J. E. and Morris, L. D. "A Wire Resistance Strain Gage for the Measurement of Static Strains at Temperatures up to 1600°F," *Exp. Stress Analysis*, V. 9, N. 1, Addison-Wesley Press, Cambridge, 1951, pages 191-200.
- Clark, D. S. and Datwyler, G. "Stress-Strain Relations under Tension Impact Loadings," *Proc. ASM*, V. 38, 1938, pages 98-111.
- Cook, George W. "Electronic Instrumentation for Scientific Measurements," Paper presented at November 20, 1946 meeting of AIEE.
- Day, E. E. "Characteristics of Electric Strain Gages at Elevated Temperatures," *Exp. Stress Analysis*, V. 9, N. 1, Addison-Wesley Press, Cambridge, 1951, pages 141-150.
- DeForest, A. V. and Stern, F. B. Jr. "Stresscoat and Wire Strain Gage Indications of Residual Stresses," *Exp. Stress Analysis*, V. 11, N. 1, Addison-Wesley Press, Cambridge, 1944, pages 161-169.
- Dietz, A. G. H. and Campbell, W. H. "Bonded Wire Strain Gage Techniques for Polymethyl Methacrylate Plastics," *Exp. Stress Analysis*, Vol. V, No. 1, Addison-Wesley Press, Cambridge, pages 59-62, 1947.
- Eney, W. J. "Discussion of Paper Entitled Bonded Wire Strain Gage Techniques for Polymethyl Methacrylate Plastics," *Exp. Stress Analysis*, Vol. V, N. 1, Addison-Wesley Press, Cambridge, 1947, pages 63-66.
- Fehr, R. O. and Parker, E. R. "Measurement of Dynamic Stress and Strain in Tensile Test Specimen," *Proc. Exp. Stress Analysis*, Vol. 1, No. 1, Addison-Wesley Press, Cambridge, 1944, pages 76-82.
- Flax, A. H. and Wardle, M. C. "Application of Electric Strain Gages to Aircraft Design Problems," *Exp. Stress Analysis*, V. 2, N. 1, Addison-Wesley Press, Cambridge, 1944, pages 50-66.
- Gibbons, C. H. "The Use of the Resistance Wire Strain Gage in Stress Determination," *Proc. Exp. Stress Analysis*, Vol. 1, No. 1, Addison-Wesley Press, Cambridge, 1944, pages 41-45.
- Gorton, R. E. "Development and Use of High-Temperature Strain Gages," *Exp. Stress Analysis*, V. 9, N. 1, Addison-Wesley Press, Cambridge, 1951, pages 163-176.
- Grossman, N. "A Nomographic Rosette Computer," *Exp. Stress Analysis*, V. 4, N. 1, Addison-Wesley Press, Cambridge, 1946, pages 27-35.
- Grover, H. J. "The Use of Electric Strain Gages to Measure Repeated Stresses," *Proc. Exp. Stress Analysis*, V. 1, N. 1, Addison-Wesley Press, Cambridge, 1944, pages 110-115.
- Hartman, E. C.; Moore, R. L. M.; and Rebbun, F. E. "Impact and Bridge Stresses — Tests of Aluminum and Steel Railway Bridge Girders," *Proc. Am. Ry. Engr. Assoc.*, V. 51 (1950), page 287 (Report of Committee 30. Work done by Aluminum Co. of America Research Laboratories Engineering Design Division).
- Hathaway, Claude M. "Electrical Instruments for Strain Analysis," *Proc. Exp. Stress Analysis*, V. 1, N. 1, Addison-Wesley Press, Cambridge, 1944, pages 83-93.
- Hewson, T. A. "A Nomograph Solution to the Strain Rosette Equations," *Exp. Stress Analysis*, V. 4, N. 1, Addison-Wesley Press, Cambridge, 1946, pages 9-26.
- Hoovgaard, Wm. "Determination of Stresses in Plating from Strain Measurement," *Trans. Soc. Naval Architects and Marine Engrs.*, V. 39, 1931, Pages 25-33.
- Hoskins, E. E. and Olesen, R. C. "An Electrical Computer for the Evaluation of Strain Rosette Data," *Exp. Stress Analysis*, V. 2, N. 1, Addison-Wesley Press, Cambridge, 1944, pages 67-77.
- Jasper, Norman H. "The TMB (Taylor Model Basin) Strain Cycle Gage and Counter; An Instrument for the Statistical Determination of the Strain History of Structures," *Proceedings — Soc. for Exp. Stress Analysis*, V. 9, N. 2, 1952.
- Kammer, E. W. and Pardue, T. E. "Electric Resistance Changes of Fine Wires During Elastic and Plastic Changes," *Proc. Soc. for Exp. Stress Analysis*, V. 7, N. 1, Addison-Wesley Press.
- Kimble, E. L. "A Method of Effecting SR-4 Strain Gage Operation Under Water," *Exp. Stress Analysis*, V. 3, N. 2, Addison-Wesley Press, Cambridge, 1945, pages 53-54.
- Mahlmann, C. V. and Sigoda, M. "SR-4 Gages at Low Tempera-

- tures," Report to Prof. W. M. Murray, M.I.T. for work in Research in *Exp. Stress Analysis*, Spring Term of 1949.
- Majors, H., Jr. "Characteristics of Wire Gages Under Various Conditions," *Exp. Stress Analysis*, V. 9, N. 1, Addison-Wesley Press, Cambridge, 1951, pages 123-140.
- Manson, S. S.; Kemp, R. H.; and Morgan, W. C. "High-Temperature Strain Gages and Their Application to Measurement of Vibratory Stresses in Turbosupercharger Buckets," *Exp. Stress Analysis*, V. 5, N. 1, Addison-Wesley Press, Cambridge, 1947, pages 90-100.
- Mehaffey, W. R.; Van Scoyoc, T. N.; and Schouer, D. S. "A Direct-Coupled Amplifier for Recording Dynamic Strain," *Proc. Soc. Exp. Stress Analysis*, V. 6, N. 1.
- Meier, J. H. "Improvements in Rosette Computer," *Exp. Stress Analysis*, V. 3, N. 2, Addison-Wesley Press, Cambridge, 1945, pages 1-3.
- Meier, J. H. and Mehaffey, W. R. "Electronic Computing Apparatus for Rectangular and Equiangular Strain Rosettes," *Exp. Stress Analysis*, V. 2, N. 1, Addison-Wesley Press, Cambridge, 1944, pages 78-101.
- Milbradt, K. P. "Ring Method Determination of Residual Stresses," *Exp. Stress Analysis*, V. 9, N. 1, Addison-Wesley Press, Cambridge, 1951, pages 63-74.
- Murray, W. M. "An Adjunct to the Strain Rosette," *Proc. Exp. Stress Analysis*, Vol. 1, N. 1, Addison-Wesley Press, Cambridge, 1944, pages 128-133.
- Murray, W. M. "Machine Solution of Strain Rosette Equations," *Exp. Stress Analysis*, V. 2, No. 1, Addison-Wesley Press, Cambridge, 1944, pages 106-112.
- Rauch, L. L. "Electronic Commutation of Strain Gages for Telemetering," *Exp. Stress Analysis*, V. 5, N. 1, Addison-Wesley Press, Cambridge, 1947, pages 111-118.
- Reno, H. "Instruments for Aircraft Strain Analysis," *Exp. Stress Analysis*, V. 2, N. 2, Addison-Wesley Press, Cambridge, 1944, pages 106-117.
- Roberts, H. C. "Electric Gaging Methods: Their Selection and Application," *Exp. Stress Analysis*, V. 2, N. 2, Addison-Wesley Press, Cambridge, 1944, pages 89-94.
- Ruge, Arthur C. "The Bonded Wire Gage Torquemeter," *Proc. Exp. Stress Analysis*, V. 1, N. 2, Addison-Wesley Press, Cambridge, 1944, pages 68-72.
- Sibila, K. F. "Use of Strain Gages on Wind Tunnel Models," *Exp. Stress Analysis*, V. 3, N. 1, Addison-Wesley Press, Cambridge, 1945, pages 23-31.
- Thurston, A. L. and Curhman, R. W. "Precision Determination of Weight by Means of Bonded Strain Gages," *Exp. Stress Analysis*, V. 3, N. 1, Addison-Wesley Press, Cambridge, 1945, pages 62-70.
- Tschebotarioff, G. P. "Use of Electric Resistivity Strain Gages over Long Periods of Time," *Exp. Stress Analysis*, V. 3, N. 2, Addison-Wesley Press, Cambridge, 1945, pages 47-52.
- Wenk, Edward, Jr. Letter to Editor describing a technique for protecting wire resistance strain gages located under water at high pressures. *Soc. Exp. Stress Analysis Proceedings*, V. 8, N. 1, 1950, pages 14-16.
- Williams, S. B. "The Dyadic Gage," *Exp. Stress Analysis*, V. 1, N. 2, Addison-Wesley Press, Cambridge, 1944, pages 43-55.
- Wyly, L. T.; Scott, M. B.; McCammon, L. B.; and Lindner, C. W. "A Study of the Behavior of Floorbeam Hangers," *Proc. American Railway Eng. Assoc.*, V. 51 (1950), page 51.
- Campbell, W. R. and Medbery, A. F. "Performance Tests of Wire Strain Gages V-Error in Indicated Bending Strains in Thin Sheet Metal Due to Thickness and Rigidity of Gage," Tech. Note No. 1318, National Bureau of Stds., Washington, D. C., July, 1947.
- Campbell, W. R. "Preliminary Investigation of the Strain Sensitivity of Conducting Films," (to be published by Nat. Bureau of Stds. about December, 1952.)
- Campbell, W. R. "Performance Tests of Wire Strain Gages—III. Calibration at High Tensile Strains," NACA, Tech. Note 997, December, 1945.
- Campbell, W. R. "Performance Tests of Wire Strain Gages—VI. Effect of Temperature on Calibration Factor and Gage Resistance," NACA Tech. Note 1456, Washington, D. C., January, 1948.
- Campbell, W. S. "The T.M.B. (Taylor Model Basin) Type 5A Strain Indicator," Report No. 645, David Taylor Model Basin, Navy Dept., Washington, D. C.
- Campbell, W. S. "Operating and Service Manual for the TMB Type 1A Strain Indicator," Navy Dept., David Taylor Model Basin, Washington, D. C., Report R-351, July, 1947.
- Cook, G. W. "A Carrier-Type Strain Indicator," Report No. 565, Navy Dept., David Taylor Model Basin, Washington, D. C., November, 1946.
- Darnell, R. C. "The T.M.B. (Taylor Model Basin) Strain Gage," Report No. 292, David Taylor Model Basin, Navy Dept., Washington, D. C.
- Darnell, R. G. "Service Strain Tests—Technique and Procedure," Report No. 468, David Taylor Model Basin, Navy Dept., Washington, D. C.
- De Forest, A. V. and Fanning, R. "A Preliminary Investigation of Strain Sensitive Materials: A Report from M.I.T. to NACA, Contract No. NAW464, March 28, 1938.
- De Forest A. V. and Leaderman, H. "The Development of Electrical Strain Gages," NACA Tech. Note 744, January, 1940.
- De Shazer, G. A. "An Improved Portable Strain Gage," Report No. 272, David Taylor Model Basin, Navy Dept., Washington, D. C.
- De Shazer, G. A. "Instructions for Setting Up and Operating Electrically Recording Extensometers Fitted with Bellevue Gages—Serial Nos. 1 to 5 Inclusive," Report No. 278, David Taylor Model Basin, Navy Dept., Washington, D. C.
- Dow, N. F. "The Analysis of Strains Indicated by Multiple-Strand Resistance—Type Wire Strain Gages Used as Rosettes," Nat. Advisory Comm. for Aeronautics, January, 1943.
- Duke, Margaret E. and Wenk, Edward, Jr. "The Graphical Solution of 45-Degree Strain Rosette Data and Determination of Error in the Calculated Stresses Due to Errors in Measured Strains," Report No. 600, David Taylor Model Basin, Navy Dept., Washington, D. C.
- Eisenberg, P.; Macovsky, M. S.; and Stracke, W. "A Six-Component Dynamometer for the Measurement of Forces and Movements on Models of Ship Appendages," Report No. 692, David Taylor Model Basin, Navy Dept., Washington, D. C.
- Greenfield, M. A. and Shapiro, M. M. "Instrumentation for Measurement of Underwater Explosion Pressures," Report No. 523, David Taylor Model Basin, Navy Dept., Washington, D. C.
- Gustafsson, Gotthard, V. A. "How to Use GH-Gages," (to be published by Nat. Bureau of Stds. about December, 1952).
- Hill, H. N. "A Semi-Graphical Method for Analyzing Strains Measured on Three and Four Gage Lines Intersecting at 45°," NACA, Tech. Note 709, May, 1939.
- Huggenberger, A. U. "A New Strain Gage without Transverse Sensitivity and the Wheatstone Bridge as a Basic Strain Measuring Method" (Consult. Engr., Zurich of Switzerland). To be published by Nat. Bureau of Stds. about December, 1952.
- Kemp, R. H.; Morgan, W. C.; and Manson, S. S. "The Application of High-Temperature Strain Gages to the Measurement of Vibratory Stresses in Gas-Turbine Buckets," NACA, Tech. Note No. 1174, April, 1947.
- Klemperer, W. B. "A Rosette Strain Computer," NACA, Tech. Note 875, December, 1942.
- Manson, S. S. "An Automatic Electrical Analyzer for 45° Strain Rosette Data," NACA, Tech. Note 941, May, 1944.
- Manson, S. S. "Charts for Rapid Analysis of 45° Strain Rosette Data," NACA, Tech. Note 940, May, 1944.
- Manson, S. S. and Morgan, W. C. "Effect of Misalignment of Strain Gage Components of Strain Rosettes," NACA, Tech. Note 1133, September, 1946.
- Miller, B. L.; Anderson, L. D.; and Shoub, H. "The Performance of Wire-Resistance Strain Gages as Influenced by the Drying

Time of Three Mounting Cements," TMB Report R-213, January, 1946.

Nettles, J. C. and Tucker, M. "Construction of Wire Strain Gages for Engine Application," NACA Advance Restricted Report 3L03, or NACA Wartime Report No. E122, December, 1943, Washington, D. C.

Osgood, W. R. "Determination of Principal Stresses from Strains on Four Intersecting Gage Lines 45° Apart," U. S. Bureau of Stds. Jr. Research, Paper 851, V. 15, Pages 579-581, December, 1935.

Pardue, T. E.; Kammer, E.; and Vigness, I. "Electrical Resistance Changes in Fine Wires Subject to Plastic and Elastic Elongation," Naval Research Lab Report 0-2377, September 28, 1944.

Roberts, H. C. "Notes on the Application of SR-4 Strain Gages," Tech. Report to Office of Naval Research, July 20, 1949 (Revised Feb. 10, 1951).

Sette, W. J.; Anderson, L. D.; and McGinley, J. G. "Resistance-Strain Characteristics of Stretched Fine Wires," Report R-212 Navy Dept. — David Taylor Model Basin, September 1945, Washington, D. C.

Sette, W. J. "Resistance-Strain Characteristics of Stretched Fine Wires," Report No. 254 (Pt. 17), David Taylor Model Basin, Navy Dept., Washington 7, D. C.

Shoub, H. "Wire-Resistance Gages for the Measurement of Large Strains," Report No. 570, David Taylor Model Basin, Navy Dept. Washington, 7, D. C.

Stang, H. and Greenspan, M. "Graphical Computation of Stresses from Strain Data," U. S. Bureau of Stds. Jr. Research, Paper 1034, V. 19, pages 437-441, October, 1937.

Statham, Louis. "The Unbonded Resistance Wire Strain Gage," (to be published by Nat. Bureau of Stds. about December, 1952).

Suppiger, E. W. and Jordan, R. L. "The Determination of Stresses from Strains Measured on Three Intersecting Gage Lines," Army Air Forces Tech. Report 4822, October, 1942.

Thurston, A. L. "Commercial Weighing with Resistance Strain Gages," (to be published by Nat. Bureau of Stds. about December, 1952.)

Trilling, C. "Tests of Hand Strain Gages," Report No. 285, David Taylor Model Basin, Navy Dept., Washington 7, D. C.

Valore, R. C. Jr., "The Application of Bonded-Wire Resistance Strain Gages to the Measurement of Internal Strain in Concrete," (to be published by Nat. Bureau of Stds. about December, 1952).

Vigness, I. and Pardue, T. E. "Poisson Ratio Determinations for Elastic and Plastic Strains of Tensile Specimens," (to be published by Nat. Bureau of Stds. about December, 1952).

Watstein, David. "Effect of Rate of Straining on the Compressive Strength and Modulus of Elasticity of Concrete," (to be published by Nat. Bureau of Stds. about December, 1952).

Wenk, Edward Jr. "A Frame for Testing Structural Models," Report No. 599, David Taylor Model Basin, Navy Dept., Washington, D. C.

Wenk, Edward Jr. "An Elastic-Tube Gage for Measuring Static and Dynamic Pressures," Report No. 627, David Taylor Model Basin, Navy Dept., Washington 7, D. C.

Wenk, Edward Jr. "A Diaphragm-Type Gage for Measuring Low Pressures in Fluids," Report No. 665, David Taylor Model Basin, Navy Dept., Washington 7, D. C.

Miscellaneous

Boiten, R. G. "The Cementing and Waterproofing of Resistance Strain Gages," (to be published by Nat. Bureau of Stds. about Dec., 1952).

Czerlinsky, E. "Investigation of the Change of Resistance in Wires Produced by Tension" (Untersuchungen Über Die Widerstandsänderung Von Drahten Durch Zug), (Jahrbuch 1938 Der Deutschen Luftfahrtforschung II, pages 377-380). Translated by Dr. F. A. Raven, Navy Dept., David Taylor Model Basin, Translation 183, Washington, D. C., October, 1943.

Hewson, T. A. "Strain Rosette Analyzer," B.S. Thesis in Mech. Engr., Mass. Inst. of Tech., June, 1945.

Hewson, T. A. "Rosette Strain Calculator," Tech. Eng. News, V. 26, N. 2, Mass. Inst. of Tech., pages 38, 39, 54, 55, October, 1944.

McGoldrick, R. T. "Shock and Vibration Instrumentation for Ships," Paper presented at June, 1952, Applied Mechanics Div. Conf. of ASME, Penn State College.

Meier, J. H. "The Development of an Electrical Strain Gage and its Application to the Stress Problem in Elevated Water Tanks," M.I.T., Sc. D. Thesis, Dept. of Civil Engr., 1939.

Ruge, A. C. "The Bonded Wire Strain Gage in the Field of Instrumentation," (to be published by Nat. Bureau of Stds. about Dec., 1952.)

Sevand, A. H. and Day, E. E. "Characteristics of Electric Strain Gages at Low Temperature," M.I.T. Master of Science Thesis, Dept. of Mech. Engr., 1946.

Soete, W. "The Strain Gage," (In Dutch) Tech. Wet. Tijdschr. 20, 4, 71-75, April, 1951.

Tomlinson, Herbert. "On the Increase in Resistance to the Passage of an Electric Current Produced on Certain Wires by Stretching," Proc. Royal Soc. of London, V. 26. Mar. 1, 1877 to Dec. 20, 1877, pages 401-410.

Urwin, C. R. and Swainger, K. H. "Minimizing Zero Drift in Electrical Strain Gage Bridges," Jour. Roy. Aero. Soc., V. 51, Nov., 1947.

Widdis, F. C. "Electrical Wire Resistance Strain Gauge and its Applications," *Machinery* (London), Aug. 31, 1950 pages 259-264.

Wilkie, M. J. "Strain Measurements," *Electrical Times* (London), Sept. 1, 1949, pages 275-280.

"The Performance of Resistance-Type Strain Gauges," Engineering Laboratory, Royal Naval College, Greenwich, February, 1943.

"SR-4 Portable Strain Indicator," Bulletin 169, Baldwin Loco. Works, Southwark Division, Philadelphia, 1943.