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SOUTHWEST RESEARCH INSTITUTE
8500 Culebra Road, San Antonio, Texas 78206

STUDIES OF INTERNAL DISPLACEMENTS IN SOLID PROPELLANT GRAINS

(Elastomeric Strain Transducer)

J. D. Michie
L. U. Rastrelli
R. C. DeHart

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Robert C DeHart

Robert C. DeHart Director
Department of Structural Research

FOREWORD

The work described in this report was performed under Contract Nr. Nonr-3363(00)(FBM) Nr. 064-451/1-31-64 for the Office of Naval Research, Structural Mechanics Branch. The program's overall objective is to develop procedures for measuring internal strains in solid propellant grains. The information presented describes an elastomeric strain transducer development for utilization on high elongation materials.

The authors gratefully acknowledge the contribution of Mr. E. Anderson and Mr. R. Guerra for their assistance in the design, fabrication and testing of the prototype gages.

ABSTRACT

The transducer discussed in this report is a device that measures strain (up to 50 per cent) on viscoelastic materials such as the binder used in solid-propellant motors. The transducer is designed for surface mounting although the basic gage concept is also applicable to a device which can be embedded within a material. The active element is a mercury base fluid column of 6-mil diameter and 0. 5-inch lengths. Complete information is presented regarding the transducer construction, calibration and evaluation testing.

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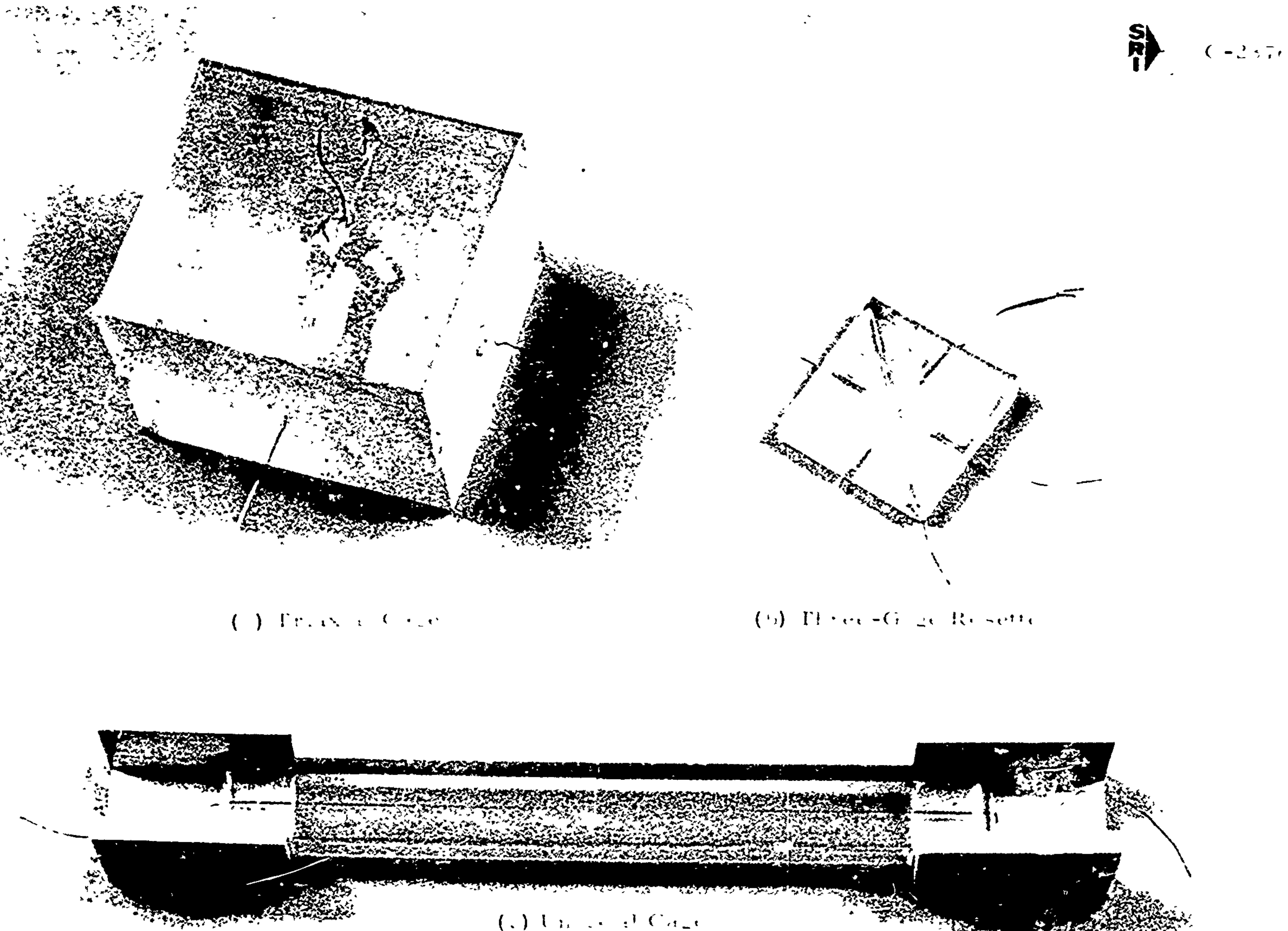
I. INTRODUCTION

In recent years the need for a device that could measure high elongation strains present in viscoelastic materials (such as solid propellant grains) has become apparent. Conventional methods for measuring surface strains on elastic, metallic materials have proved ineffective when applied to the high elongations prevalent in viscoelastic bodies. This can be attributed to two basic limitations: (1) the present strain measuring devices (such as wire or foil electrical resistant gages) have a low useful strain range (less than ten per cent); and (2) the reinforcing effect of a relatively rigid metallic gage mounted on the flexible viscoelastic member distorts the strain field under investigation. For these reasons it became evident that new techniques or innovations were required to satisfactorily retrieve structural and mechanical response intelligence from members in the rapidly expanding field of viscoelasticity.

Several new strain measuring concepts which indicated the potential for measuring strains of large magnitude were formulated. After a brief analytical evaluation, the most promising concept was selected for further study. In order to demonstrate the concept's validity, a conceptual prototype gage was designed and fabricated. This initial configuration consisted of a small inside diameter, thick-wall elastomeric tube filled with an electrical conducting fluid. As expected, the electrical resistance of the conducting fluid column changed as the elastomeric tube was axially deformed. this change in gage resistance was determined to be proportional (and nearly linear) to extensional deformations. Also, the prototype exhibited clearly discernible and measurable phenomenon for elongations up to forty percent.

Three exploratory models are pictured in Figure 1; the triaxial module (a) consists of three orthogonal gages, the rosette (b) consists of three coplaner (non-intersecting) gages and the uniaxial module (c) consists of the single active column (the aluminum channel at the ends of the uniaxial gage were bonded to the module to facilitate gripping during testing). Typical results of module testing are indicated in Figures 2 and 3. In Figure 2, the linear relationship between strain and resistance change is depicted for the uniaxial module in tension. In Figure 3, a similar relationship is shown for the triaxial module (Figure 1a) in compression; gages 2 and 3 reflect the Poisson effect.

Due to these promising indications, further effort was devoted to exploring the concept's potential and developing a practical high elongation strain transducer. A general review of the progress which has been made is presented in the following discussion.



( ) Triaxial Gage

(b) Three-Gage Rosette

( ) Uniaxial Gage

FIGURE 1 CONCEPTUAL ELASTOMERIC STRAIN GAGE PROTOTYPES

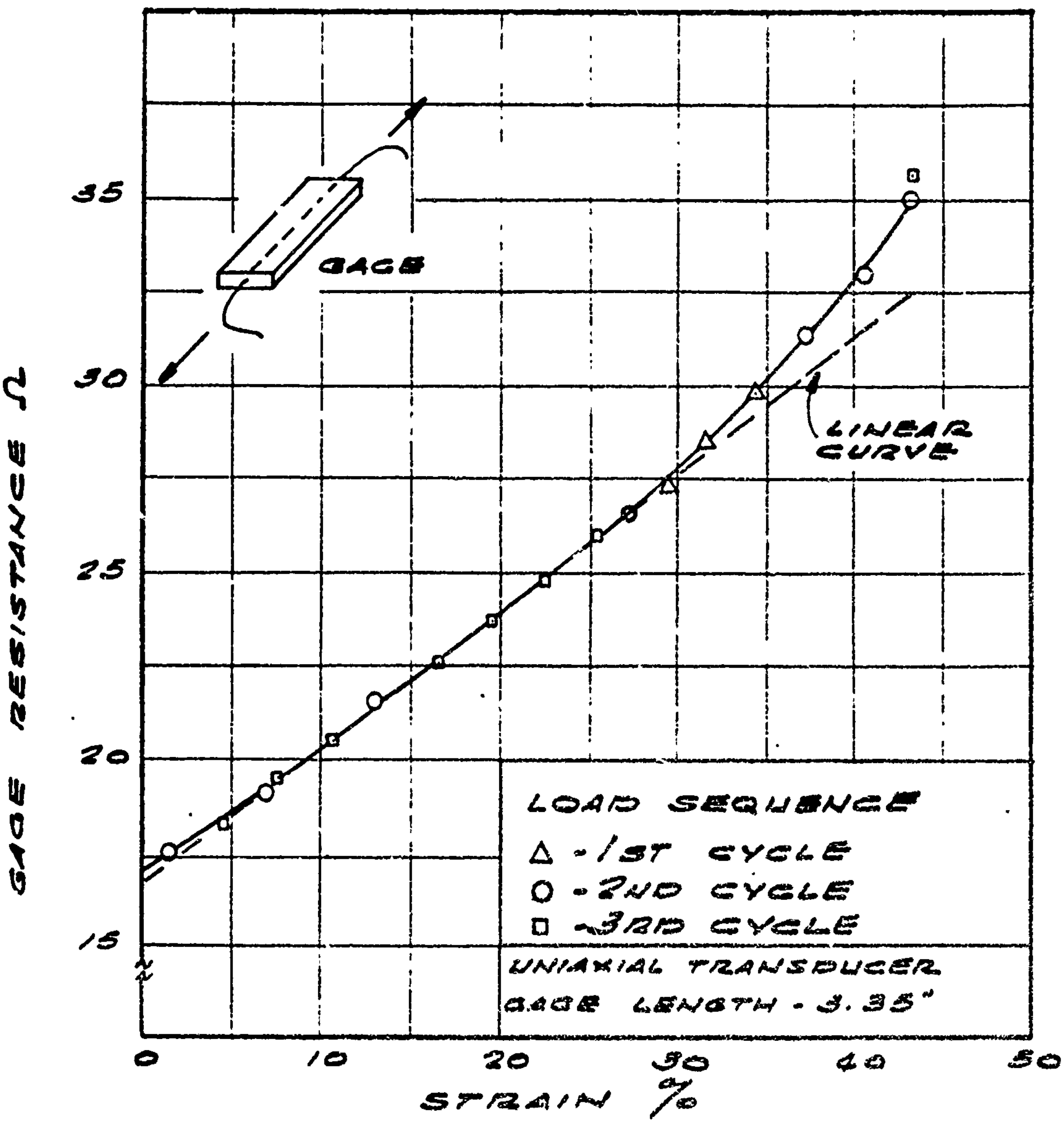


FIGURE 2 GAGE RESISTANCE VERSUS STRAIN FOR UNIAXIAL ELASTOMERIC TRANSDUCER IN TENSION.

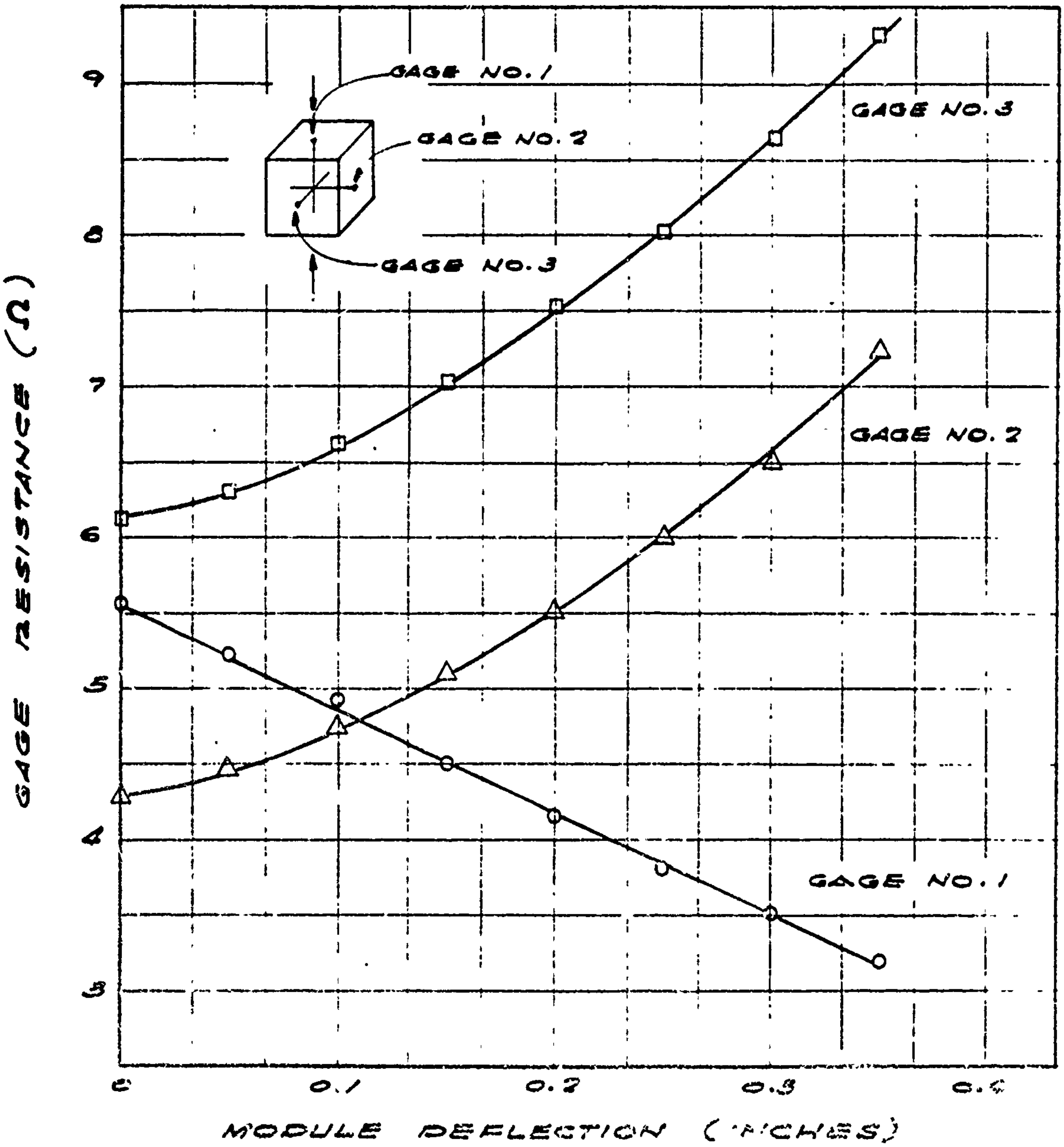


FIGURE 3 GAGE RESISTANCE VERSUS MODULE DEFLECTION FOR TRIAXIAL TRANSDUCER.

II. GAGE DESIGN AND FABRICATION

A gage configuration (shown in Figure 4) was selected early in the program to serve as a standard of comparison for the evaluation testing. Although the elastomeric strain transducer concept is applicable to both a surface mounted and an embedded gage, in the initial development studies the surface mounted configuration was chosen because of (a) its more sturdy construction, (b) the ease with which the gages could be attached and removed from test articles used in the intermittant elongation-calibration procedures and (c) its accessability which greatly facilitates visual and mechanical evaluation. A nominal gage length of 0.5 inch* was used for the initial prototype.

The elastomeric strain transducer is presently fabricated in three primary steps. The body of the transducer containing the gage length and the conducting fluid reservoirs is cast from Adiprine L-100**. The reservoirs are formed by 15 mil outside diameter hypodermic needles and the gage length by a 6 mil steel wire***. As shown in Figure 5, the steel wire is inserted through the hypodermic needles and held taut during the polyurethane casting and curing stages. The needles and wire are removed and the cured gage body is stripped from the mold, all needle, wire and mold surfaces which come in contact with the uncured polyurethane are

*Feasibility studies indicate that the gage length can be varied from 0.25 to 4 inches without a major modification to the basic design concept.

**Polyurethane compound by DuPont.

***Gages have been fabricated employing a 3 mil and a 1 mil gage length wire.

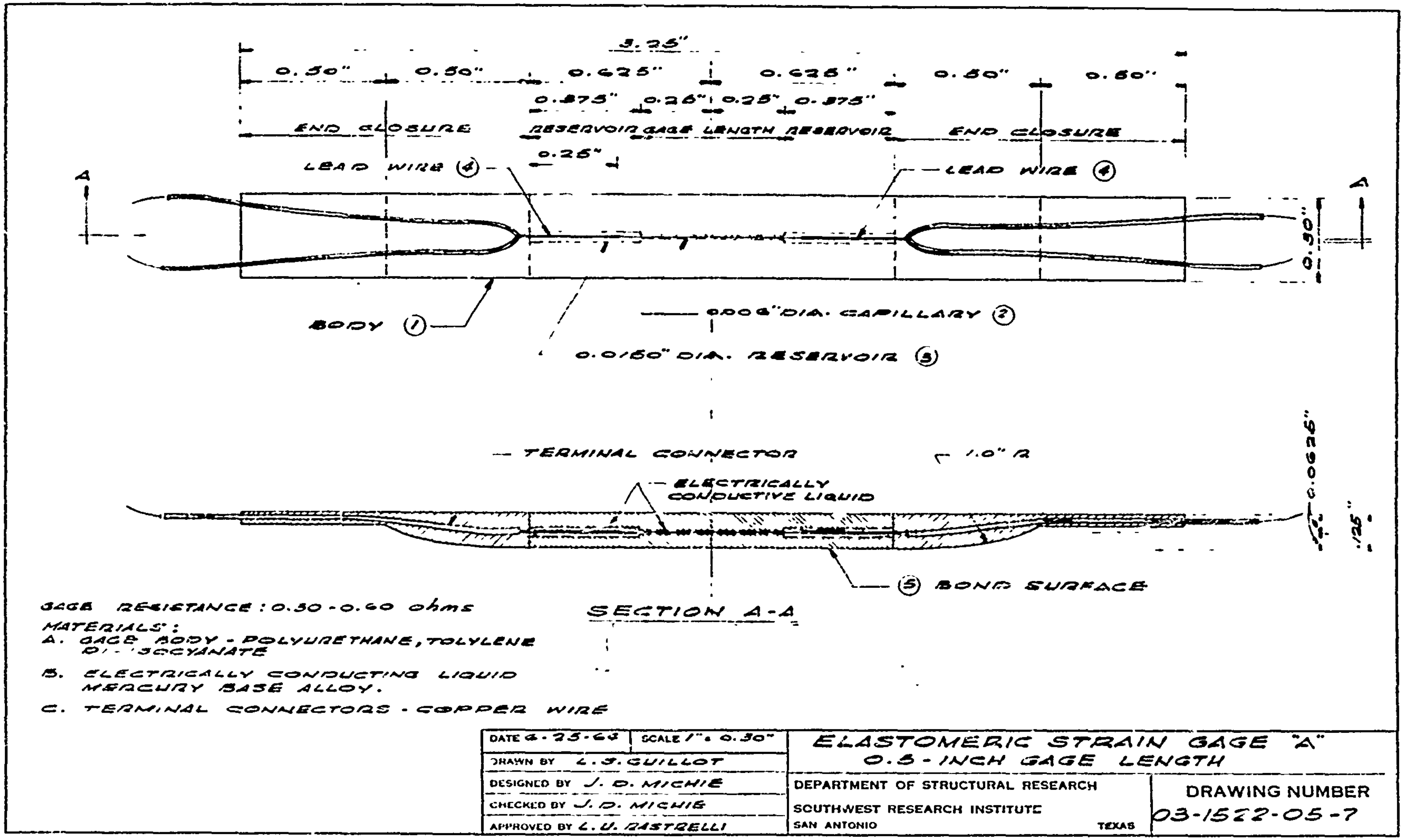


FIGURE 4 ELASTOMERIC STRAIN GAGE "A". DESIGN DRAWING.

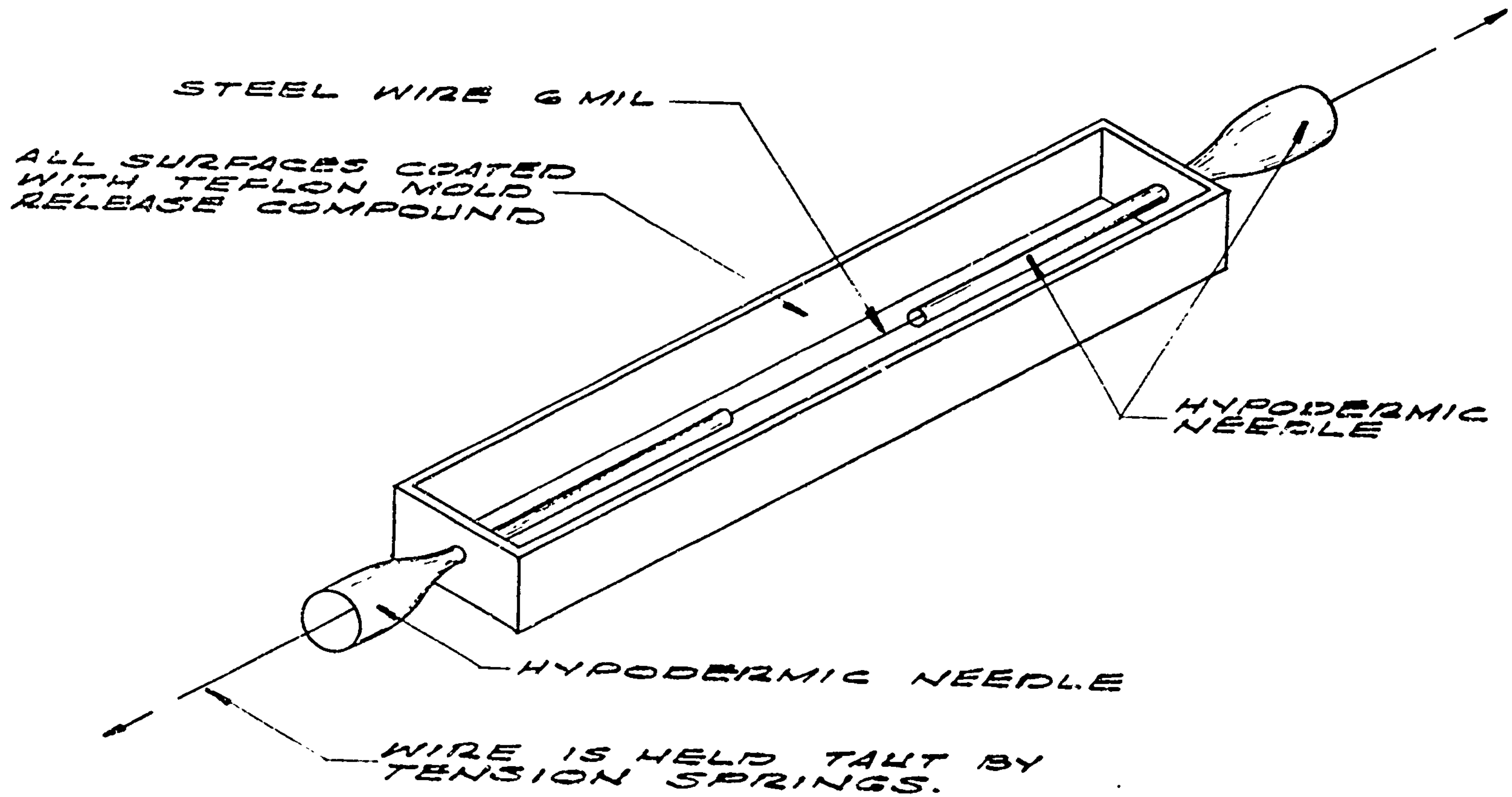
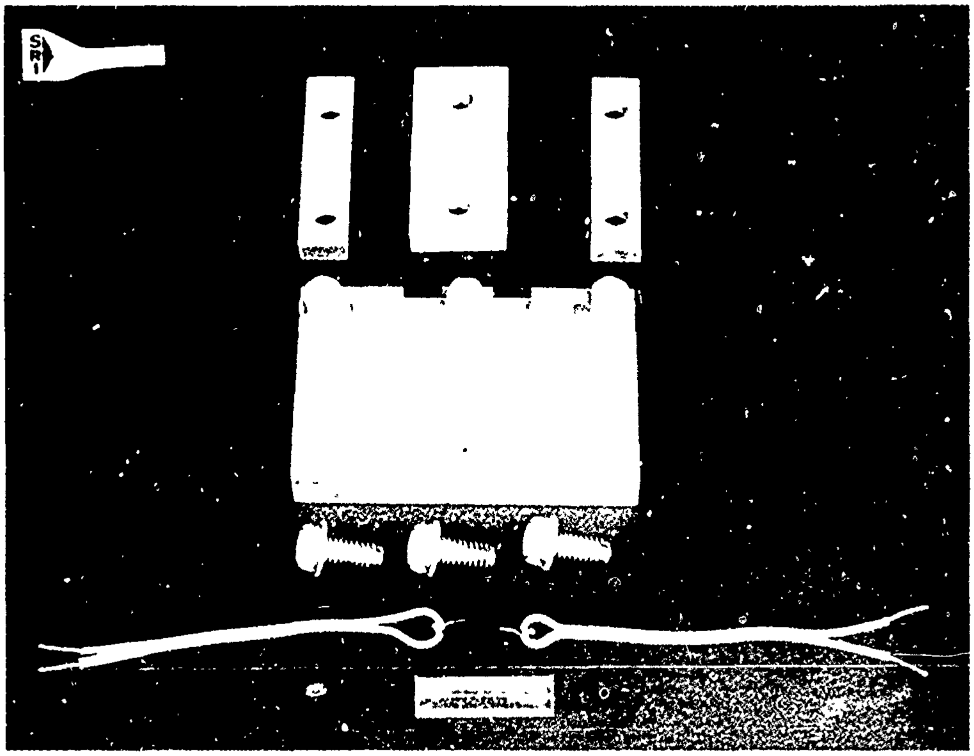
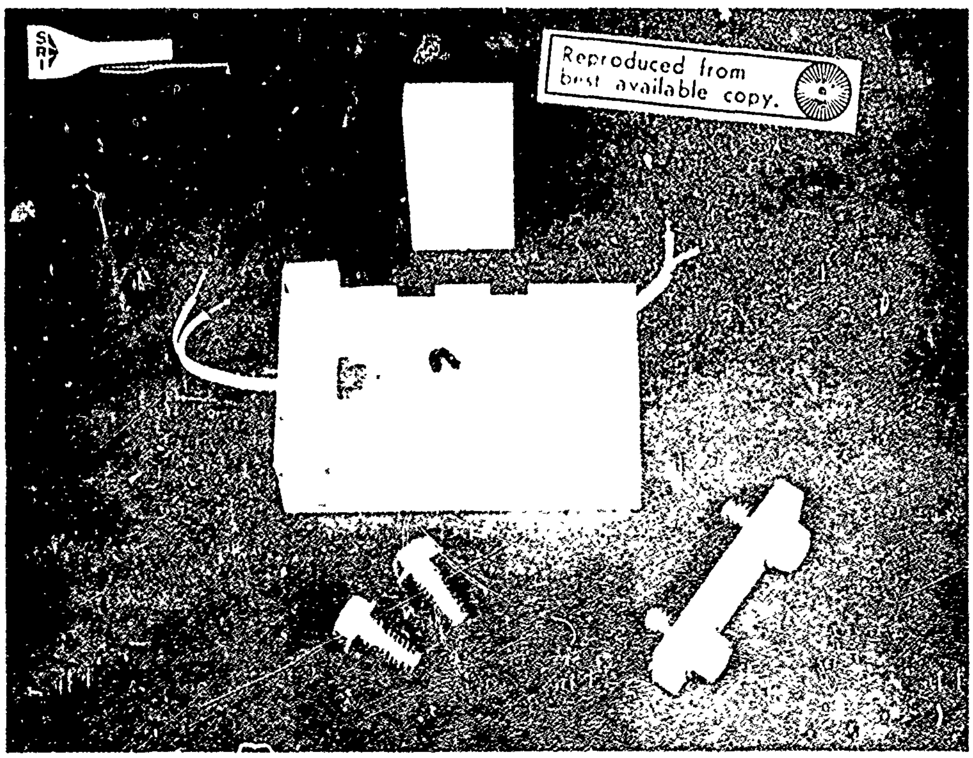


FIGURE 5 ELASTOMERIC GAGE MOLD PRIOR TO CASTING

coated with a teflon mold releasing agent prior to the casting operation. A mercury base alloy is injected into the reservoirs and gage length cavity with the necessary precautions to prevent entrapping of air or foreign particles. A two-wire terminal is inserted a precise distance into each reservoir to establish a low resistant wire-to-conductive fluid contact and to insure a consistent, nominal electrical resistance across the gage length. The gage body-lead wires composite is clamped into a mold fixture (Figure 6a) which restrains any relative motion within the composite. A second casting of polyurethane provides the seal for the conductive fluid and anchors the leads to the gage body (Figure 6b). The completed gage is a sturdy device capable of sustaining normal laboratory handling without damage.



(a)



(b)

FIGURE [illegible] TRANSDUCER ASSEMBLING MOLD FIXTURE

III. READOUT INSTRUMENTATION

An important aspect of the elastomeric transducer concept is the readout equipment and circuitry required to detect and measure resistance change in the gage. The strain transducer's relative low resistance (0 40 ohms for the 0. 5 inch gage length) is particularly applicable to a Kelvin bridge circuit (see Figure 7).

The principal feature of the Kelvin bridge is the cancellation of lead wire resistance from the gage circuit by a balancing procedure Since the nominal gage resistance is quite low, any error introduced into the measuring circuit by resistance change in the lead wires would be critical.

A Kelvin bridge (Figure 8) was specially designed to accommodate strain gages resistance measurement in the range of 0 to 20 ohms, the bridge has proved to be stable and have a repeatable accuracy of 1/4 percent for a 1 ohm reading. It is due to the peculiar Kelvin bridge circuit requirement that the elastomeric strain transducer configuration has the 2-two wire connection detail. Nevertheless, the gage configuration is applicable (without modification) to the less preferred Wheatstone bridge circuit.

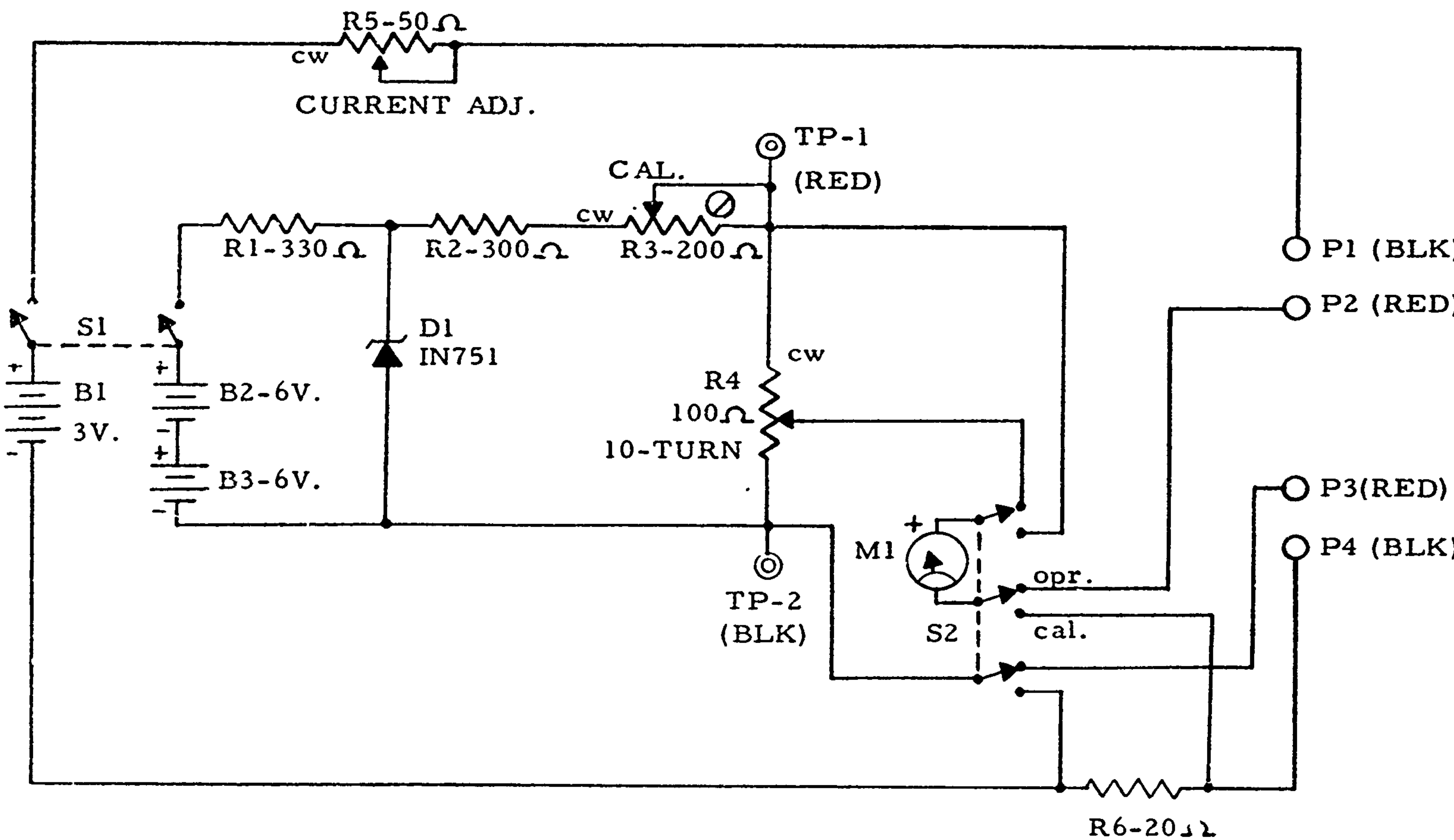


FIGURE 7 KELVIN BRIDGE CIRCUIT DIAGRAM

FIGURE 8 KELVIN BRIDGE

IV. CALIBRATION PROCEDURE

The establishment of the elongation-resistance change relationship for each prototype gage is performed with the aid of a micrometer dial extensiometer (Figure 9) The gages are positioned in the device. secured by bar clamps and then elongated in precise incremental distances At each increment. the electrical resistance across the strain transducer is noted. With these data a calibration curve (Figure 10) is plotted which indicates the elongation-resistance change characteristic of the particular gage tested.

Newly manufactured gages are immediately calibrated as a first proof test After each strain transducer evaluation (such as hydrostatic and elevated temperature tests) the gage is checked in the extensiometer to determine if any basic changes have occurred in the gage characteristics.

In positioning a gage in the extensiometer. it was determined the clamping affected the electrical resistance To eliminate this factor the gage's configuration was modified to include four lugs and is shown in Figure 11. The normal force of the extensiometer clamping action bears on the lugs. the gage is elongated by shear force between the lugs and the strain transducer body. Subsequent tests performed on the modified gage indicated that the adverse effect of the extensiometer clamping action had been eliminated The original and modified strain transducer prototypes are shown in Figure 12. The lugs (on the modified gage) can be easily removed after the gage is calibrated if their presence create an obstruction

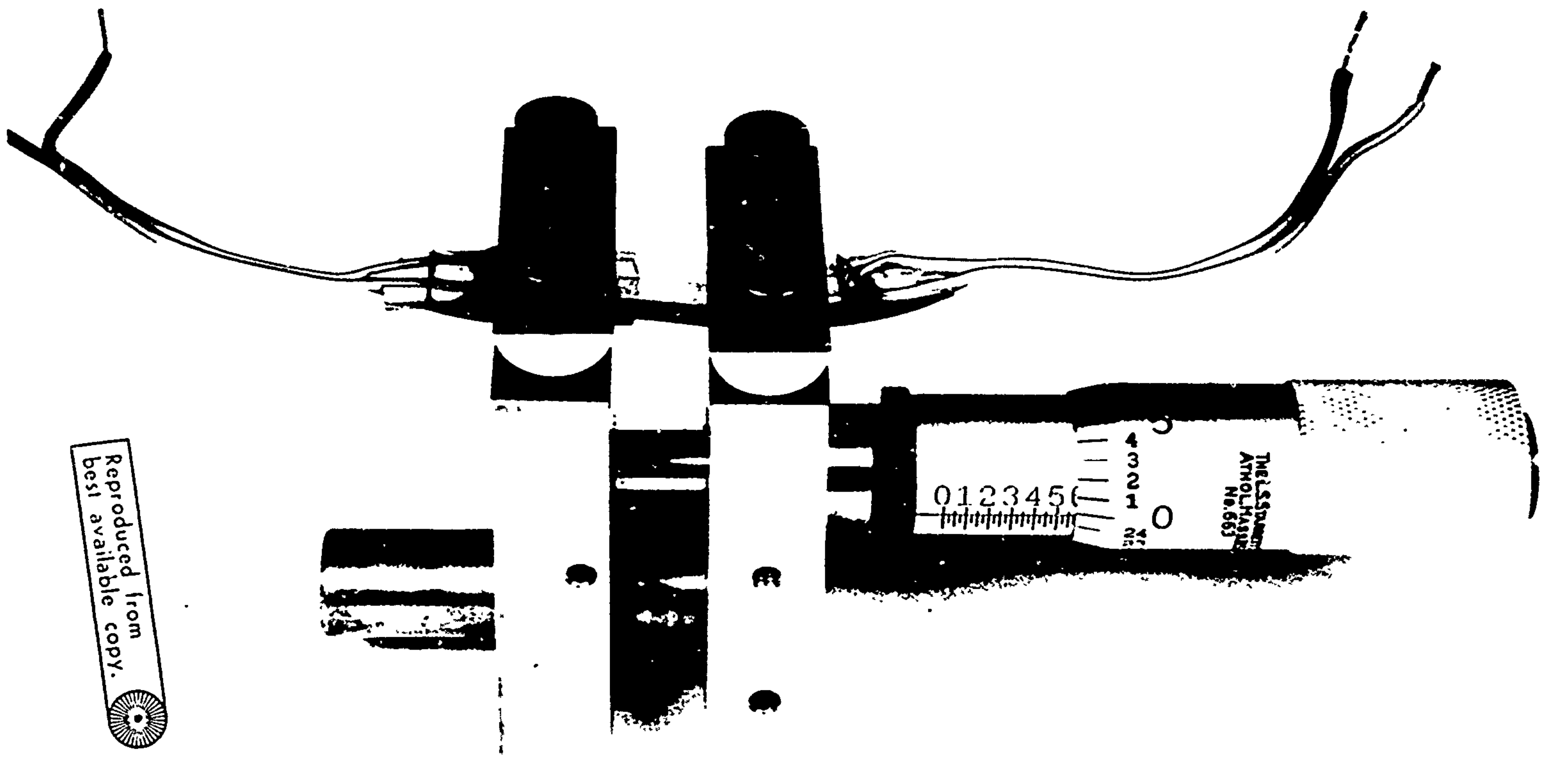


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FIGURE 9 ELASTOMERIC GAGE CALIBRATION EXTENSIOMETER

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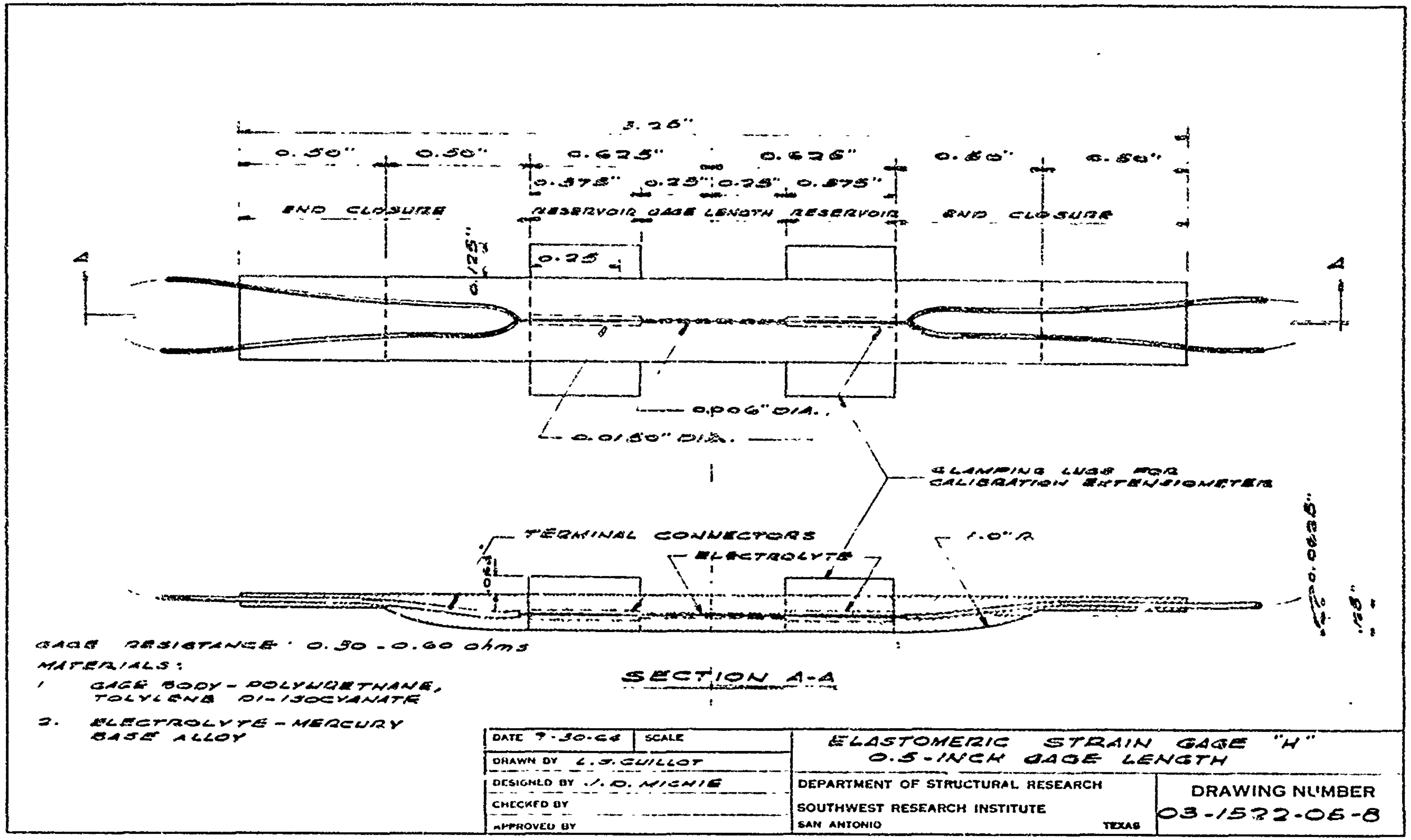

FIGURE 11 ELASTOMERIC STRAIN GAGE "H", DESIGN DRAWING

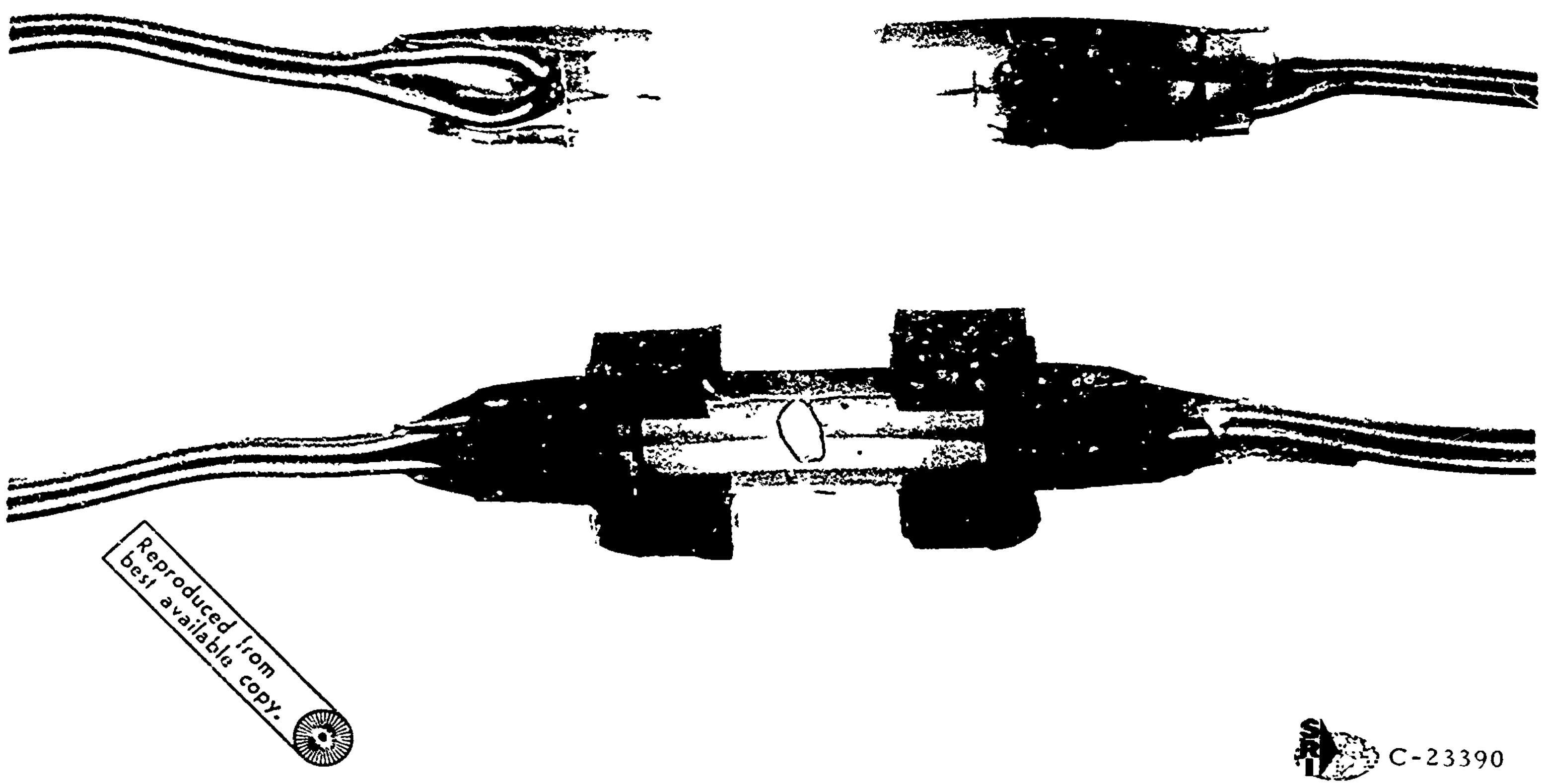

FIGURE 12 STRAIN TRANSDUCER PROTOTYPES: ORIGINAL (UPPER) AND MODIFIED (LOWER) DESIGNS

V. PRELIMINARY EVALUATIONS

In order to establish the elastomeric strain transducer's performance capability, a series of evaluation tests were devised and the prototype gages appraised according to their response

Nominal Resistance The nominal (non-strained) electrical resistance within the first prototype gage group (the gages were manufactured in groups of six) was found to vary from 0.30 to 1 10 ohms. The desirability of fabricating gages with uniform mechanical properties was deemed of utmost importance as a standard gage would provide a higher degree of confidence and would greatly simplify the readout equipment and circuitry

The initial gage group was examined radiographically The examination clearly indicated the nominal resistance variations could be attributed to two basic factors: (1) the lead wire penetration distance differed from gage to gage and (2) the gage capillary contained air bubbles within the mercury base alloy which were detectable only by radiographic examination. As mercury is more resistive than copper by a factor of 55 it is readily seen that a small error in the distance between the copper wire leads (across the gage length) would effect a large nominal electrical resistance change Likewise, the presence of foreign (dielectric) particles and air bubbles severely reduce the effective cross-sectional area of the capillary and, thus, alters the strain transducer's nominal resistance

Both of these deficiencies have been corrected by improved fabrication techniques. As illustrated in Figure 13, the nominal resistance range of 27 gages is 0.32 ohm (0.57-0.25); however, 85 percent of the gages are within a 0.16 ohm range. Additional refinements in the design and fabrication of the strain transducer will yield a more uniform gage.

Elongation. Upon the completion of fabrication, each gage is clamped in the extensiometer and elongated This procedure has two purposes: (1) to serve as a proof test to insure the gages function over the expected strain range, and (2) to establish the relationship of resistance change versus gage elongation.

All new gages have shown a need for several "shakedown" elongation cycles before the elongation-resistance change has stabilized and a repeatable curve is determined. These-cycles are performed in rapid succession with the gage never remaining in the extended configuration in excess of one minute to minimize the plastic deformation of the gage body. However, the polyurethane gage body exhibits a near total creep recovery when deformed for long time intervals and then released A typical elongation-resistance change curve is shown in Figure 10. The relationship is nearly linear over the 50 per cent strain range with a slight divergence from a constant slope within the initial 5 per cent strain and the 45 to 50 per cent strain segments The slopes of 14 transducers calibration curves are compared in the frequency distribution graph (Figure 14); the values vary from 0 70 to 1 10 ohms per inch of elongation

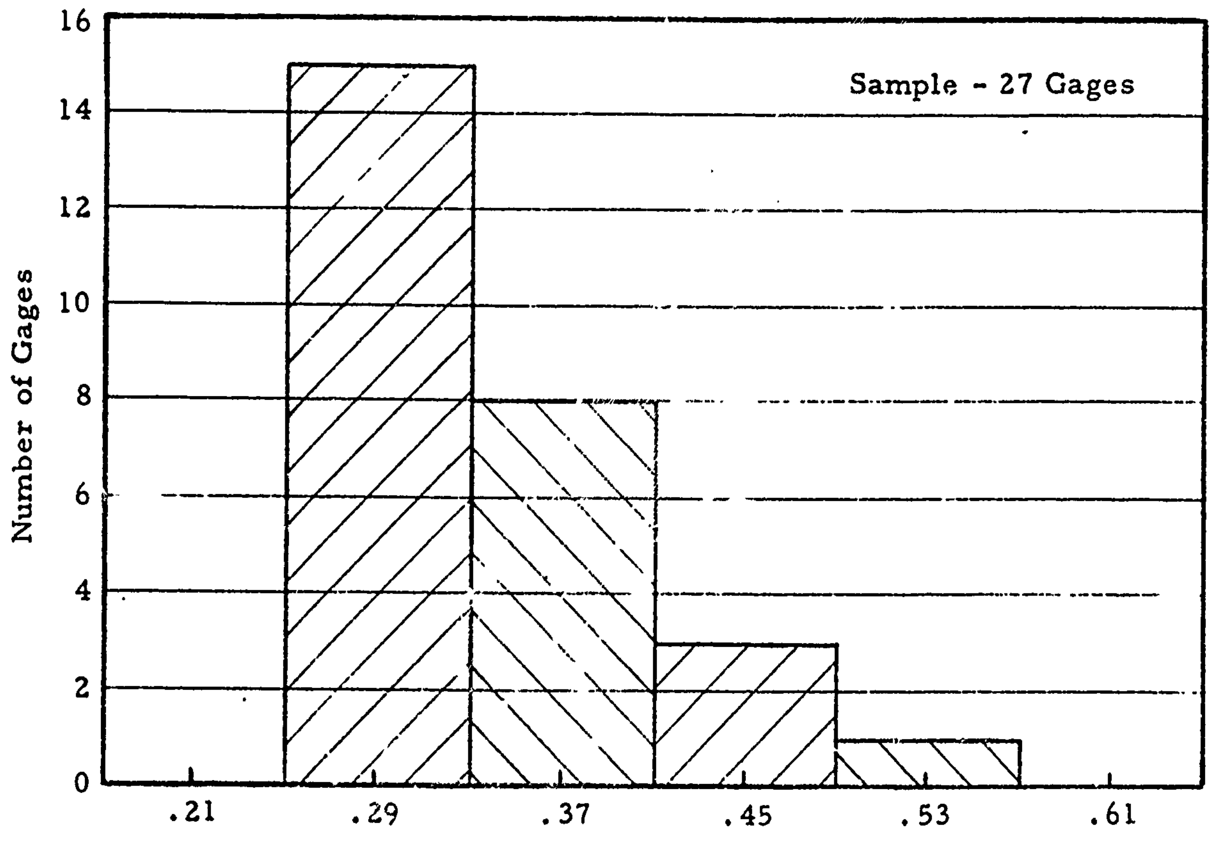

FIGURE 13 FREQUENCY DISTRIBUTION OF GAGE RESISTANCE (0.5 INCH GAGE LENGTH)

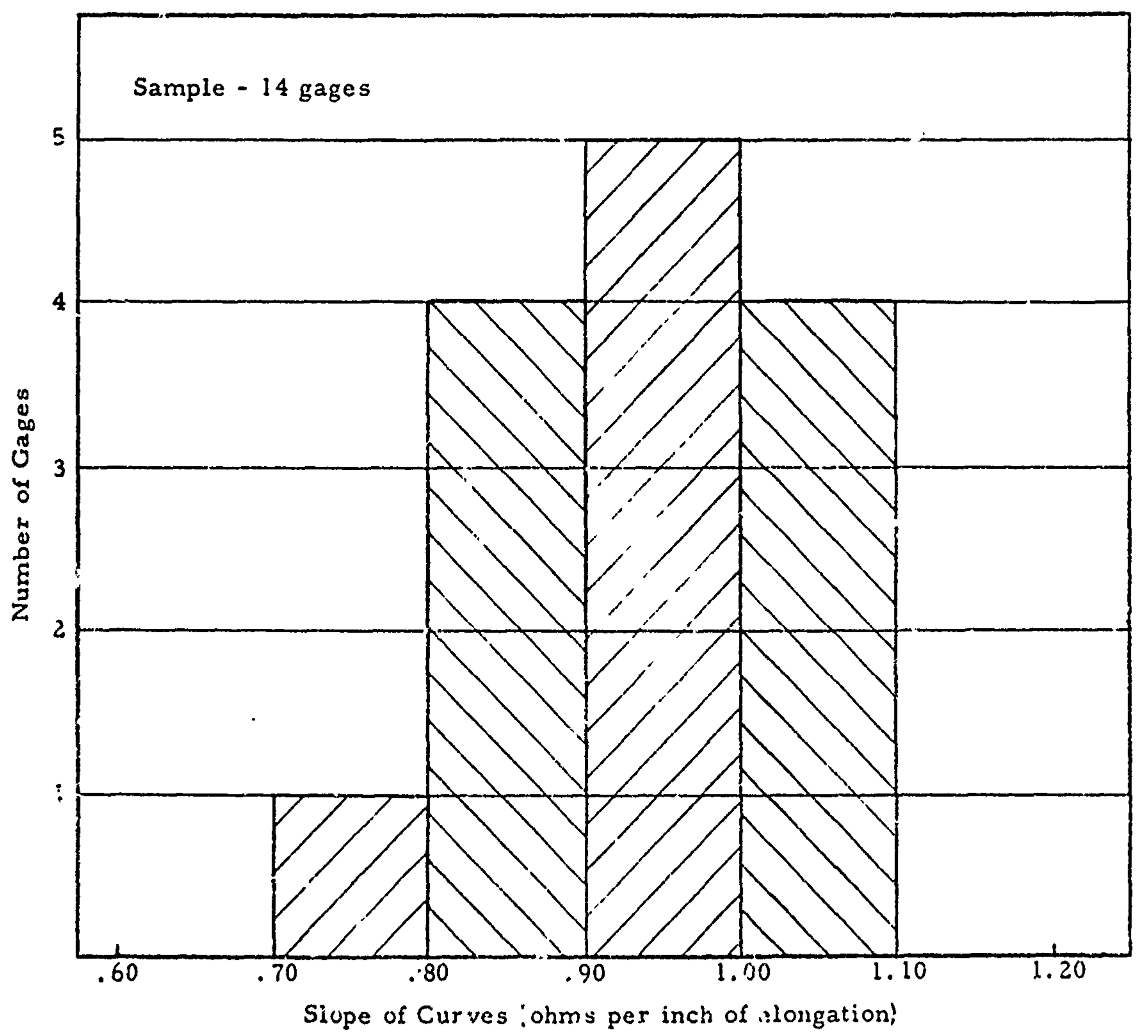

FIGURE 14 FREQUENCY DISTRIBUTION OF SLOPES FOR RESISTANCE VERSUS GAGE ELONGATION CURVES.

There appears to be no relationship between nominal resistance and the gages' calibration curve slopes.

In the calibration procedure, a gage is strained to a certain level of elongation; this is maintained constant until the next incremental deformation is applied. Being a viscoelastic material, the gage undergoes a stress-relaxing process at each stage of loading. Nevertheless, the resistance readings taken at several time intervals at each stage of elongation are consistent and, therefore, there is apparently no change in the gage length capillary geometry during stress relaxation. Conversely, upon release of the elongated gage, the strain transducer does not immediately return to its initial (no-load) configuration because of residual stresses. As the gage length capillary is responsive to most all body strains, it is not surprising that a variation of gage resistance exists while the body creeps to its initial geometrical configuration.

In an actual gage application, where the elastomeric strain transducer is bonded to a specimen's surface, a most important characteristic is its suppleness in relation to the specimen; that is, the gage's body should be a negligible reinforcing element when applied to the specimen's surface thereby allowing the surface to displace in an unhindered fashion. Accordingly, the gage will be forced to deform with the specimen surface on which it is mounted; this type of deformation is nearly independent of the gage's internal stresses. Consequently, the phase of the extensiometer calibration tests in which the gage is permitted to return to its initial (no-load) configuration has no counterpart in an actual gage application.

Temperature Environment. To ascertain the effects of temperature on the transducer, three gages were subjected to four cycles of elevated temperatures; the results of these tests are indicated by the plot of a typical gage in Figure 15. The gage was heat-soaked at each temperature increment for a period of 30 minutes to insure a stable reading. A maximum test temperature of 285°F was selected to correspond to the curing temperature of the transducer's body As indicated, there is an increase in gage resistance with an increase in temperature. This can be attributed to an accumulative effect of (1) a change in capillary goemetry due to the coefficient of thermal expansion and (2) a change due to the coefficient of thermal resistivity. The thermal effect appears to be reversible in general, however, the scatter of the data points indicate the lack of control of one or more gage parameters during the experimental evaluation. The possibility may exist that the gages may require "thermal shakedown" of 20 or 30 cycles before stabilizing into a predictable (and repeatable) thermal performance.

Pneumatic Environments. A potential application for the strain transducer would be on surfaces within a pressure environment. Accordingly, one of the preliminary tests consisted of subjecting three gages (un-mounted) to a pressure environment In Figure 16, the response characteristics of gage H-39, (which is typical of the gages tested) is shown. There is a reduction of gage resistance with an increased pressure

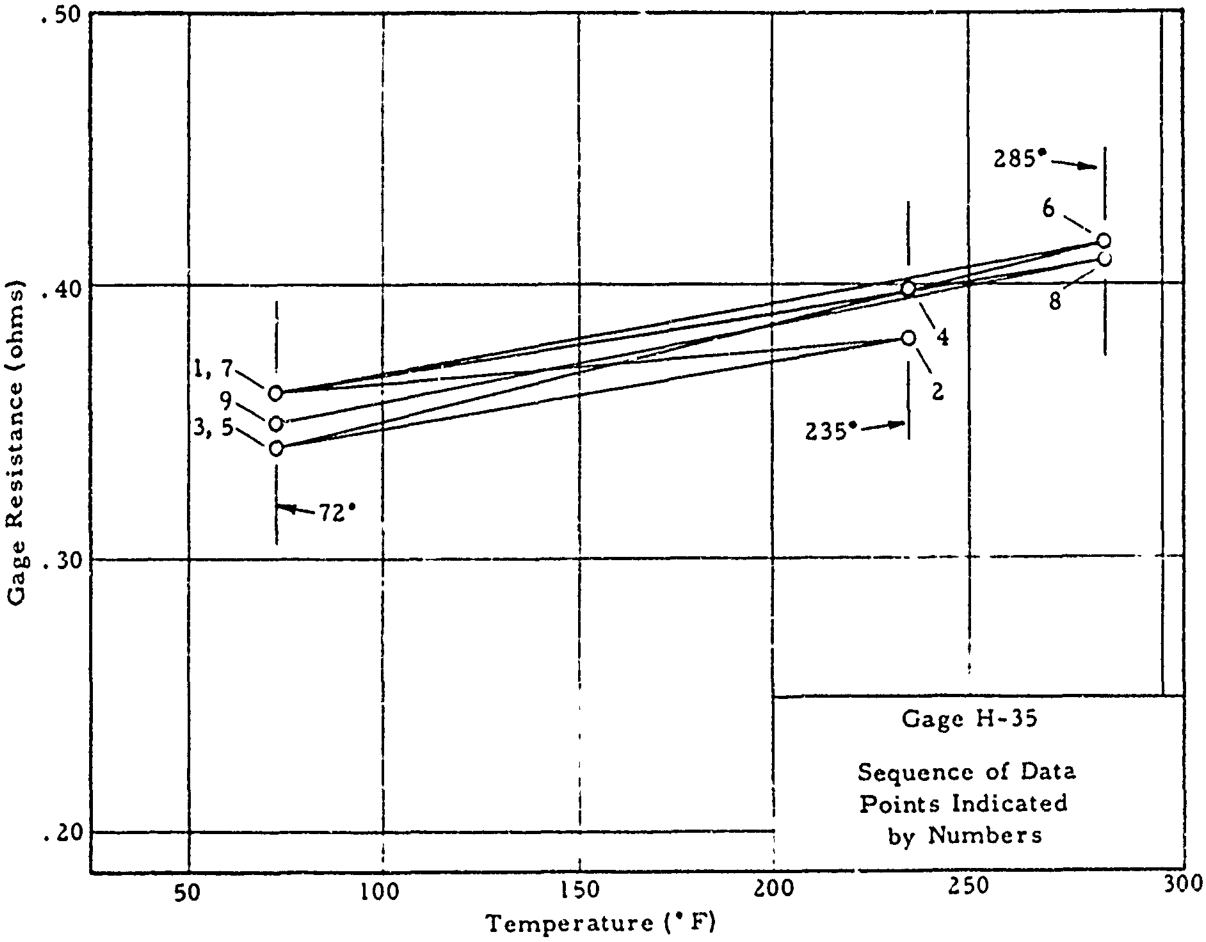

FIGURE 15 TYPICAL PLOT OF GAGE RESISTANCE VERSUS TEMPERATURE (FOUR CYCLES).

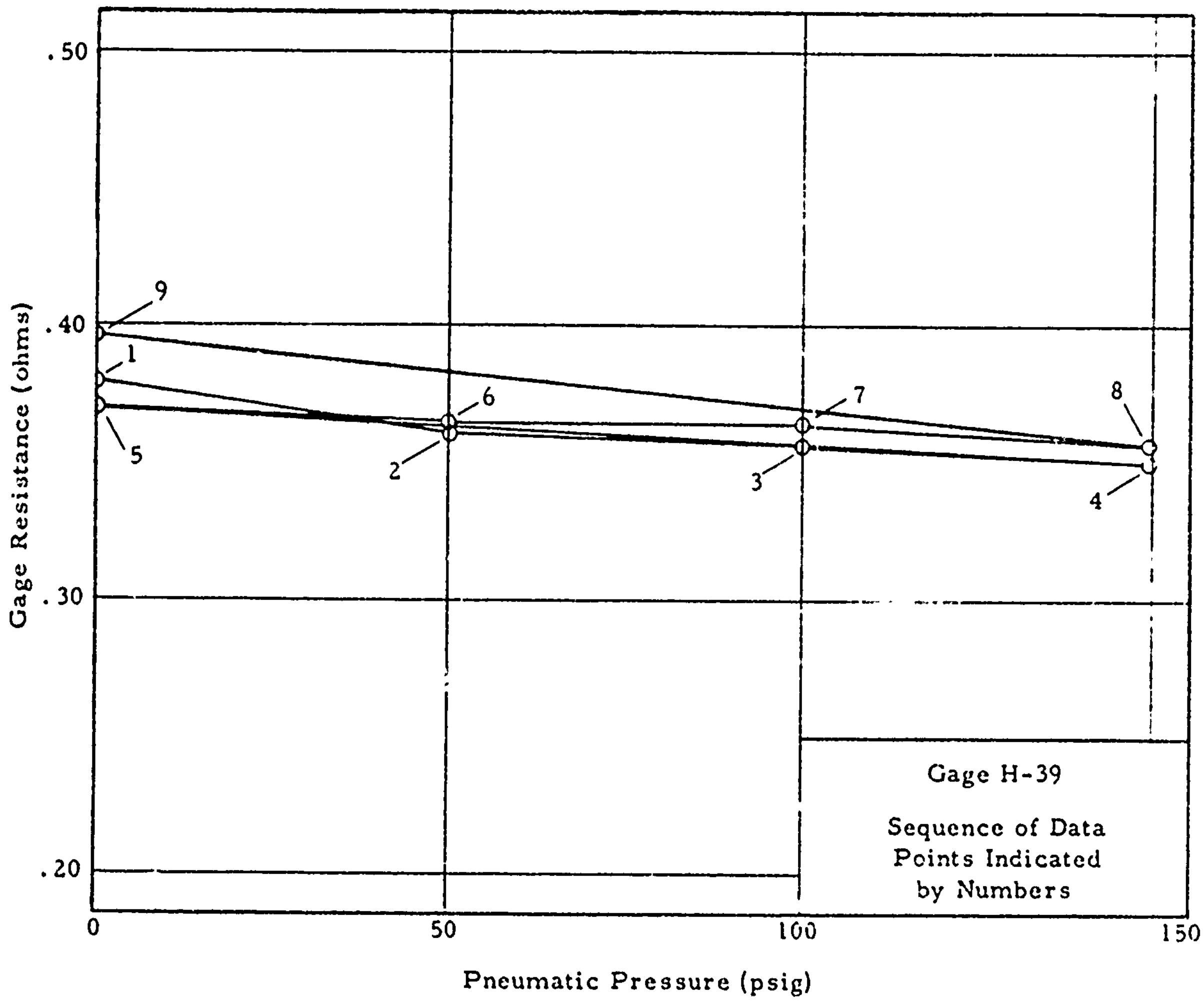

FIGURE 16 TYPICAL PLOT OF GAGE RESISTANCE VERSUS PNEUMATIC PRESSURE (TWO CYCLES).

environment. As with the thermal evaluation, the pneumatic environment tests are not conclusive. It was determined that pressurization duration was a critical factor as the gage body relaxed under the applied loading. Readings were taken at each load increment until the gage resistance stabilized. The data points shown in Figure 16 are terminal values generally measured after the pressure increment had been applied for a period of ten minutes.

VI. FUTURE WORK

The preliminary evaluation of the elastomeric strain transducers has demonstrated the concept's feasibility and has indicated possible scope of application. The gage was observed for performance characteristics under environmental parameters of temperature and pressure. Certain fabrication techniques were examined in relations to the gage performance and improved procedures incorporated where possible. However, several aspects of the strain transducer design require further study and improvement.

<u>Gage Resistance.</u> The nominal gage resistance (less than 1 ohm for 0.5 inch base length gage) is low in comparison to conventional electrical resistant gages. In addition to requiring special readout equipment and circuitry, the low resistance also adversely affects the strain transducer sensitivity. For transducer applications involving retrieval of intelligence through a slip-ring circuit, the strain prototype's signal would be obscured in the background noise.

Two readily apparent and immediate approaches to increase the gage resistance would be to (1) reduce the capillary cross-sectional area and/or (2) to utilize a conducting fluid with a greater electrical resistance Both 1 and 3 mil diameter capillaries* have been explored and appear to

*The prototype transducer "A" and "H" contain 6 mil diameter capillaries.

be feasible from a fabrication standpoint. Preliminary gage designs employing the 3 mil diameter capillary indicated a nonlinear relationship between elongation and resistance change; the 1 mil gage was erratic in performance. Nevertheless, a greater nominal resistance was achieved in both cases.

The selection of the conducting fluid is limited to those materials which are compatible with the polyurethane gage body. Water and oil base fluids react with polyurethane causing swelling in and around the capillary. The presently used mercury base fluid is an inert compound and provides a stable gage with a shelf life of several months. Although polyurethane exhibits desirable elastic and creep recovery properties, there are other material candidates which may suffice in these areas and be receptive to a broader range of conductive fluids. These candidates are being investigated.

Gage Rigidity. For elastomeric strain transducers, an important characteristic is gage rigidity. Special care is required in matching boundary conditions between the gage body and the surrounding medium. especially for the embedded gage. The surface mounted gage rigidity requirement is different from the embedded gage, in order to minimize a local stress field distortion caused by the reinforcing effect of the gage, the gage body (and bond cement) must have a maximum flexibility. The flexibility is a function of both gage dimensions (cross-sectional area of gage body) and the body material modulus. The initial prototype gage

(Figures 4 and 1̇) represent a relatively rigid device which will be modified to a more supple instrument. The modification will take the form of a reduced cross-sectional area for the gage body and the utilization of gage materials with lower moduli. The effectiveness of these modifications will be determined as a function of force required to elongate (or compress) a gage body through a specified displacement.

Temperature and Pressure Influence. The preliminary evaluations indicate that both temperature and pressure excursions effect a resistance change in the gages. The initial data was inconclusive as to exact empirical relationships, however, certain trends were noted. It is important that the study of these environmental parameters be continued in order that methods of controls may be developed. It is expected that calibration procedures (similar to those in use with conventional foil gages) will be feasible.

Range of Application. One of the basic attributes of the elastomeric gage concept is its application for high elongation strains (up to 50 per cent). The confidence limits of the initial prototypes is $\pm$ 2 per cent strain which immediately restrict its scope of application to strain ranges of 10 per cent or more. A refinement in this sensitivity is believed obtainable by increasing the gage resistance and improving the fabrication techniques.

Other Parameters. The influence of several other parameters on gage performance is presently unknown. The more important of these are (a) the effects of acceleration, (b) the limitation to frequency response and (c) the stability of a transducer during tests of extended duration and during a period of prolonged shelf life.