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AD 748628

STUDIES OF INTERNAL DISPLACEMENTS IN SOLID PROPELLANT GRAINS

(Development of an Elastomer Strain Gage)

J. D. Michie
E. L. Anderson

INTERIM REPORT
SwRI Project 03-1043
Contract Nr. NOnr-3363(00)(FBM)
Nr. 064-451/11-30-65

Prepared for
Structural Mechanics Branch
Office of Naval Research
Washington, D. C.

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Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY *(Corporate author)* Southwest Research Institute 8500 Culebra Road San Antonio, Texas 78206	2a REPORT SECURITY CLASSIFICATION Unclassified 2b GROUP

3 REPORT TITLE

Development of an Elastomer Strain Gage

4 DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Interim, March 1965 - February 1967

5 AUTHOR(S) *(Last name first name, initial)*

Michie, J. D., Anderson, E. L.

6 REPORT DATE March 15, 1967	7a TOTAL NO. OF PAGES 78	7b NO. OF REFS None

8a CONTRACT OR GRANT NO. NOnr 3363(00) FBM b PROJECT NO 064-451/11-30-65 c d	9a. ORIGINATOR'S REPORT NUMBER(S) SwRI Project Nr. 03-1043 9b OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10 AVAILABILITY/LIMITATION NOTICES

[redacted]

11 SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Structural Mechanics Branch Office of Naval Research Washington 25, D.C.

13 ABSTRACT

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Presented in this report is a brief history of the elastomer gage history along with development trends. Also delineated are the gage's fabrication and application procedure and the required readout equipment.

[illegible]

1a

DD FORM 1473

Unclassified

Security Classification

Unclassified

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14 KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Strain gage						
Elastomer						
Electrically resistance						
Liquid metal element						
High elongation						

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I. INTRODUCTION

In recent years, the need has become apparent for a device that can detect and indicate strain variations in viscoelastic materials. Conventional methods used for measuring surface strains on stiff materials such as metals and concrete have proved ineffective when applied to viscoelastic bodies which experience high elongations. This ineffectiveness can be attributed to two basic gage limitations: (1) the available strain measuring devices, such as wire or foil electrical resistant gages, have a low useful strain range, generally less than 2 percent; 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 is evident that a new experimental technique or innovation is needed in the rapidly expanding field of viscoelasticity to enable the satisfactory retrieval of meaningful structural and mechanical response intelligence.

Although the conventional SR-4 wire and foil gages in their present configuration are incapable of accurately indicating strain in structures composed of soft materials, the gages difficiencies can be attributed to their construction (i.e., stiffness) and not to the phenomenon of relating the device's calibrated resistance change to elongation. Since the electrical resistant strain gage has proved so versatile in the laboratory from aspects such as speed and accuracy of data acquisition and the capability of being

monitored remotely and automatically, the gage elongation-resistance change phenomenon has been retained as a desirable principle of the elastomer gage. Therefore, the development effort has been directed to making the electrical resistant strain gage more supple and able to sustain a larger elongation range. Consequently, the wire and foil grid systems, as well as the paper and phenolic carriers, were discarded in the elastomer gage's initial concept. Instead of a rigid wire (or foil), an active element composite of metallic powder and a polymer matrix was cast and tested. Later, the metallic powder composite was replaced by mercury and then by a liquid metal alloy. It was clearly demonstrated in the early experimental evaluations that the electrical resistance response of the liquid metal element was similar to the relatively rigid wire gage; in fact, the resistance change was determined to be a near linear function of gage elongation over a majority of the strain range.

As with most developments, the evolution of the elastomer gage has been characterized by erratic progress. Generally, a breakthrough in the gage configuration design or manufacturing technique would greatly enlarge the device's potential. A brief history of this development is presented in Section II, with current gage technology described in Section III; the development trends and gage potential are projected in Section IV. Appended to the report are some theoretical gage aspects (Appendix A) and the design drawings of the elastomer gages (Appendix B). A chronology of important elastomer gage development milestones is delineated in Appendix C.

II. DEVELOPMENT HISTORY

A. Background

In the elastomer gage development program, the fundamental use of the gage response phenomenon of relating elongation (or strain) to a resistance level remains unchanged. The primary research effort has been devoted to developing a gage configuration that is practical and reliable. Accordingly, there are several elastomer gage characteristics which have received special consideration:

(1) The gage should possess an optimum balance between strain sensitivity and useful range.

(2) The device should be supple for a surface-mounted application; for an embedded use, the gage body modulus should match the specimen's modulus.

(3) For a more universal application and for use on structures with high strain gradients, the gage's geometry should be of a miniaturized size.

(4) The gage configuration should permit its attachment to specimens to be performed in a compatible and precise manner.

(5) To sustain normal handling and application stresses, the gage should be compact and sturdy.

(6) Simplicity should be emphasized in design and fabrication details to effect gages with reproducible characteristics.

It is apparent that some of these characteristics such as gage sturdiness and suppleness are in direct conflict, and hence certain trade-offs have been necessary in the gage development. Also, it has become clear that no one gage configuration possesses the desired elastomer gage

properties for all applications, and hence several devices have evolved, each with a somewhat limited application.

B. Initial Concept

To circumvent the relative stiffness of the wire or foil gage, the initial elastomer gage concept was based on a scheme which replaced the integral wire element with a metallic powder conductor, the thought being that the powder conductor would exhibit the typical strain gage electrical resistance change but with a much lower modulus. In order to impart an elastic characteristic to the conductor, the metallic powder was dispersed in an elastomeric matrix.

The powder conductor, approximately 1/16 in. in diameter and 2 in. long, was prepared by adding aluminum powder to an uncured polyurethane elastomer at a ratio of 80 percent powder and 20 percent elastomer (by weight). After being cured, the cylindrical composite strand of elastomer and aluminum particles was evaluated but was found to be nonconductive. It is surmised that, with the utilization of a conductive pigment of silver in lieu of the aluminum particles, a successful model would have resulted. Nevertheless, the metallic powder concept was discontinued in favor of a more promising liquid metal element approach.

C. Liquid Metal Element Gage

The liquid metal element strain gage concept is based, at least partially, on the same principle as the conventional SR-4 wire strain

gage. That is, as the gage body elongates or shortens, the small capillary containing the conductive liquid deforms in length and cross-sectional area. This deformation of capillary geometry results in a predictable variation in the liquid element resistance; furthermore, the resistance change is a direct function of the gage's axial deformation.

In order to demonstrate the validity of this concept, a prototype model was designed, fabricated and tested. The initial gage configurations* consisted of a small inside diameter, thick-walled elastomer tube filled with mercury. The prototype gage capillary was formed by casting a small diameter wire in the elastomer body. After stripping the wire from the body, the capillary was filled with mercury. Terminal wires (approximately equal to the capillary diameter) were inserted a short distance into the fluid element filled capillary from each gage end; the connections were sealed and the wires securely attached to the gage body by a polyurethane potting application. As expected, the electrical resistance of the mercury column changed as the elastomer device was axially deformed. The model exhibited clearly discernable and measurable resistance change values for elongations up to 100 percent. Three of the early prototypes are shown in Figure 1; the metal channels attached to the uniaxial gage are to provide a positive means to grip the device during testing.

*See Appendix B, Gage P-1.

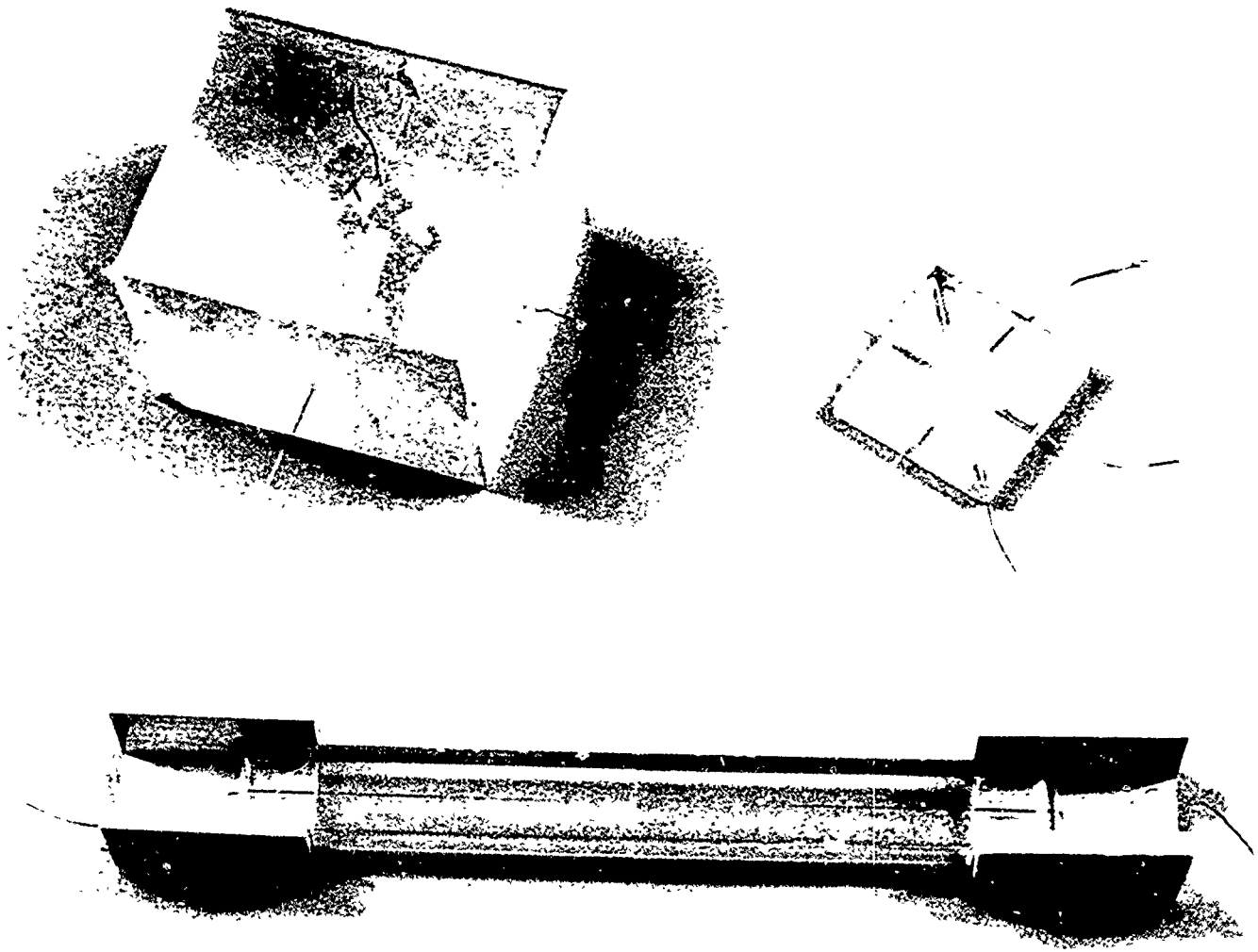

FIGURE 1. ELASTOMER GAGE PROTOTYPES

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D. Gage Evolution

The first working model of the elastomer gage revealed three features that required refinement in order to make the device useful as a research tool: (1) the contact between the terminal wire and the fluid element was erratic and deteriorated with time; (2) the conceptual prototype was large, cumbersome and impractical for most applications; and (3) the device was insensitive to small strain increments. Consequently, the primary effort in the elastomer strain gage development program has been directed to these problem areas.

1. Terminal Contact

The electrical contact between the conducting fluid and the terminal wires was erratic in the initial prototype gage due to the wire-mercury junction detail. Since the wires were approximately the same diameter as the capillary, the wire-fluid contact surface was limited to the small area at the wires' ends, particularly when the capillary diameter decreased as a result of gage elongation. To circumvent this deficiency, enlargements or reservoirs were formed at the capillary extremities to house the connection. With this arrangement, the wire to fluid contact surface is larger as it extends along the wire for a short length and is less influenced by the gage's elongation. The effective gage length is determined by the distance between reservoirs.

The deterioration of the terminal connection was attributed to the chemical reaction between the mercury or mercury base alloy and

the copper terminal wire. After exploring several terminal wire materials, platinum was substituted for copper in the gage construction since platinum, in the presence of mercury, is essentially chemically inert. With these modifications, the terminal contacts have hence exhibited positive and stable characteristics.

2. Miniaturization

A "macaroni" or thick-walled tubular configuration was utilized as the gage body of the initial prototype device. Although this device demonstrated the validity of the elastomer strain gage concept, it was crude and possessed limited capabilities for immediate use in the laboratory. A more practical gage configuration was needed from the aspects of both fabrication and application. In place of the tubular design, a gage body with a flat, rectangular cross section and with a small circular capillary formed along its major axis was developed. This particular shape was easily fabricated (thus decreasing the fabrication attrition rate and improving the gage reliability) and easily bonded to a test surface.

In Figure 2, one of the earlier gage body molds is shown just prior to the casting of the polyurethane elastomer. The small diameter wire, strung through the hypodermic needles and through the center of the mold, formed the gage element capillary; the hypodermic needles formed the housing for the terminal wires--element fluid contact.

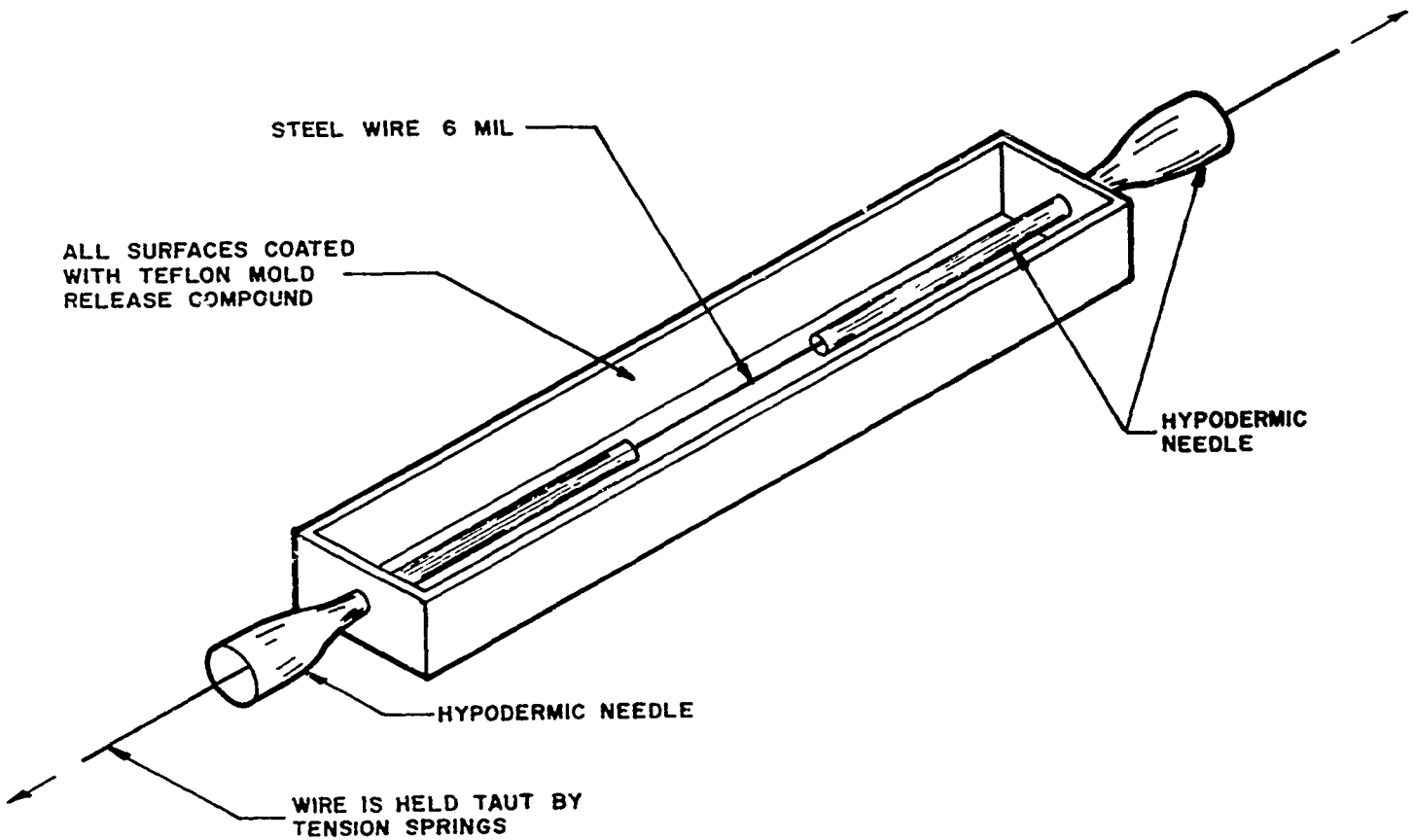

FIGURE 2. ELASTOMER GAGE MOLD PRIOR TO CASTING

Prior to casting the elastomer, the model surfaces were coated with a releasing agent to facilitate the post-cure stripping operation. After the elastomer had been cast and cured in a vacuum-heat environment, the wire and hypodermic needles were withdrawn from the gage body leaving a thin capillary and two contact housings.

In the miniaturization process, certain changes have been made in the overall design and in the casting procedures. The thickness of the basic gage body was reduced from 0.125 to 0.018 in. and the width from 0.250 to 0.125 inch. For standarization, a gage length was arbitrarily set at a nominal 0.50 inch. Another innovation was the change in reservoir geometry. In the preminiaturized gage, the reservoirs were cylindrical (15-mil diameter) and extended from each end into the gage body 0.25 inch. In the gage evolution, these reservoirs were changed to spherical cavities approximately 10 mils in diameter. After filling the capillary and spherical cavities with the fluid metal and the terminal wires are inserted into these cavities, the entire gage assembly is encapsulated in polyurethane and then cured. The finished gage has overall dimensions of 0.1875 in. × 0.030 in. × 1.00 inch.

A most important objective of the miniaturization process has been to improve the suppleness* of the surface-mounted elastomer gage. As any integral device bonded to a test surface reinforces and, hence, restricts the test article deformation, it is desirable to employ

*As defined in this report, suppleness is measured by the force required to elongate a gage to a unit displacement (i.e., grams per 1-percent strain).

a device with a minimum structural stiffness in order to limit this "distortion" effect to an acceptable level. Although the stiffness of the elastomer gage is a function of both the polymer modulus and the gage cross-sectional area, only the gage area has been adjusted; nevertheless, this adjustment has been quite effective. As an example, in changing the gage's area dimensions from 0.125 in. × 0.30 in. to 0.185 in. × 0.030 in., the section area (and hence the stiffness) was reduced by a factor of 6.45, and the suppleness of the small device was determined to be 3.52 gm per 1-percent strain.

Another aspect of the strain gage which is directly related to miniaturization is the separation between the gage element and the test surface. As illustrated in Figure 3, two different types of gage indication errors are introduced by this separation distance. In the first type, the gage element does not elongate to the same dimension as the specimen surface due to shear lag in the elastomer gage body. For the flexure case, the gage element elongates more or less than the test surface depending on its radius of curvature. In both cases, the error is directly proportional to the separation distance. It has, therefore, been a development objective to arrange the gage element as near as possible to the attachment surface.

3. Sensitivity

To increase the resistance change per unit strain (ohms per 1-percent strain), it is apparent from theoretical

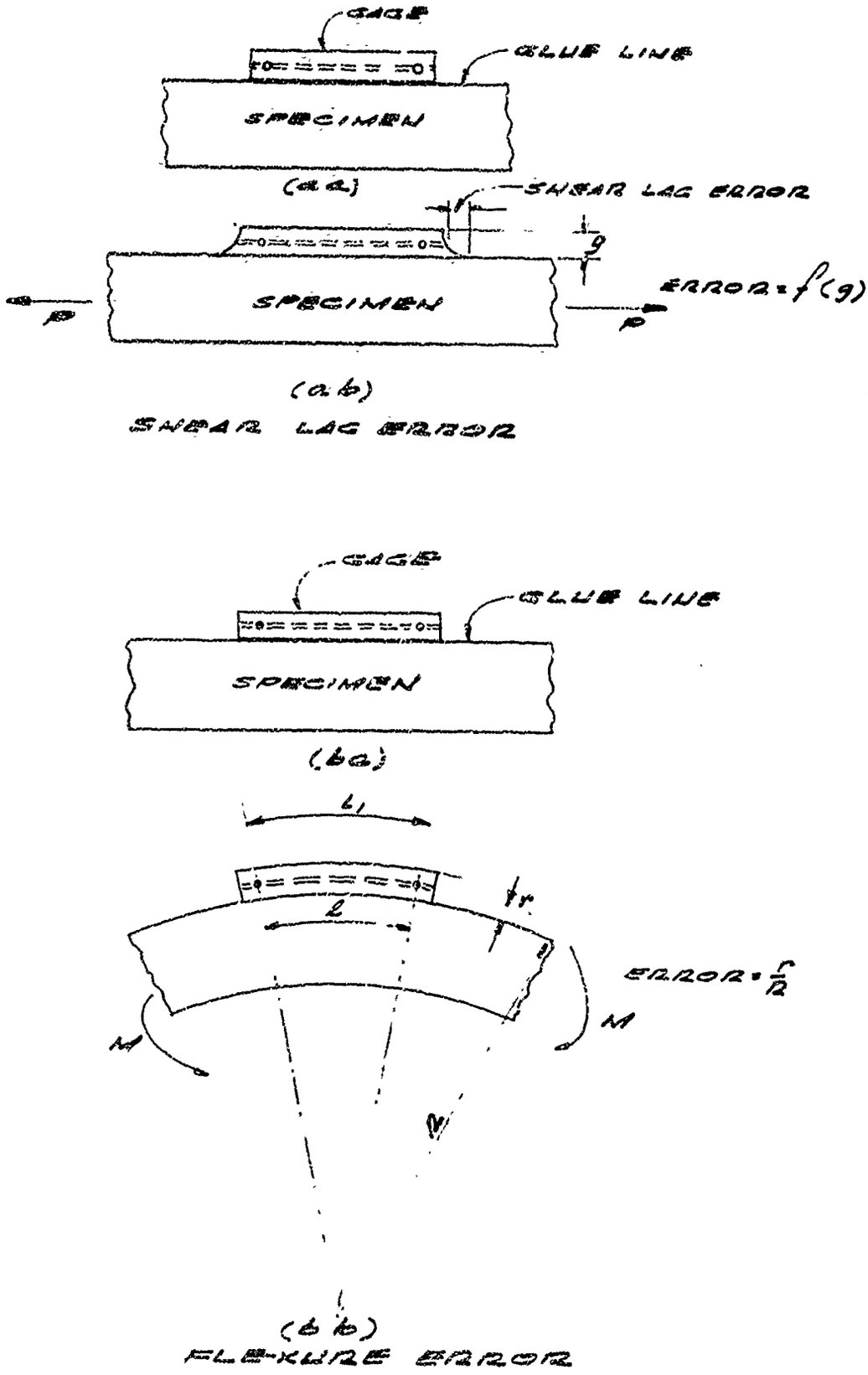

FIGURE 3. TWO INHERENT SURFACE GAGE ERRORS

considerations* that the nominal gage resistance must be increased. Three approaches have been explored as methods to increase the gage resistance; these are: (1) employing an element fluid with high resistivity, (2) reducing the capillary's sectional area, and (3) increasing the active element length.

To date, the selection of an element fluid has been limited to those materials which are compatible with the polyurethane gage body. Water and oil base fluids have been found to cause swelling and deterioration of the elastomer in the vicinity of the capillary. Mercury and mercury base alloy fluids, on the other hand, have resulted in stable gages with shelf life exceeding several months. Although polyurethane exhibits desirable elastic properties and has been extensively utilized in the gage development program, other elastomers are available and may be receptive to a broader range of conductive fluids.

The early attempts at fabricating transducers with small diameter capillaries failed because the capillaries could not be properly filled with the mercury fluid. Mercury, possessing a high surface tension, was limited to capillaries of about 6-mil diameter or larger. However, a mercury base alloy† was found to have a low surface tension and overcame the capillary filling operation difficulties. (This mercury alloy, due to its wetting action, also provides a better electrical contact with

*See Appendix A.
†Mercury-indium-thallium.

the terminal wires.) Capillaries as small as 1-mil diameter have been successfully cast and filled. As expected, the smaller diameter capillaries have resulted in higher resistance gages (from 0.4 to 10 ohms or more).

The third method employed in improving the elastomer gage sensitivity has been to increase the active element length. In order to maintain a compact gage (and the 0.5-in. gage length), a multielement configuration has been devised in which several parallel (and coplanar) elements are connected in series. The total gage resistance is, of course, a summation of the individual element's resistance. Essentially, the same procedures are used in making the single and multielement gages.

4. Large Strain Capabilities

Examination of the dimensional changes of the miniature elastomer transducer undergoing strain shows that under small or moderate axial movements the terminal wire position in the liquid metal reservoir changes insignificantly. However, under high levels of strain, the rigid wire has the tendency to move out of the reservoir as it is pulled axially through the straining elastomer gage body. This "withdrawal" of the terminal wire at high orders of strains results in erratic resistance indications and/or loss of contact with the conducting liquid. To obviate this tendency, the terminal wires are presently inserted through the walls of the reservoir from the side and perpendicular to the gage axis. This slight alteration has extended the range of strain measurement up to the point of gage body rupture.

III. CURRENT ELASTOMER GAGE TECHNOLOGY

The current elastomer strain gage technology represents the fruition of at least two generations of gage development. Until recently, the gage concept was only a promising experimental technique with the initial prototype gage no more than a laboratory curiosity. However, innovations in the fabrication techniques have provided the experimenter with a useful and important laboratory tool. The contents of this section are devoted to presenting a brief summary of the elastomer gage and its more important properties.

A. Fabrication Procedure

Various techniques have been employed in the gage manufacturing process. An ever present objective in the fabrication procedures has been to develop an effective but simple method to build consistent, reliable and accurate devices. The procedure presented in this section has been utilized for the past year and has produced a high quality and effective item.

In the initial elastomer gage fabrication step, a filament, which forms the gage capillary, is suspended in a fixture and held in a tension condition by springs (Fig. 4). Small deposits of uncured epoxy are applied along the filament at precise intervals; due to the epoxy's high surface energy, the deposits develop into near-perfect spheres of approximately 10 mils diameter. These spheres form the conductive fluid reservoirs, and the distance between two spheres establishes the device gage length.

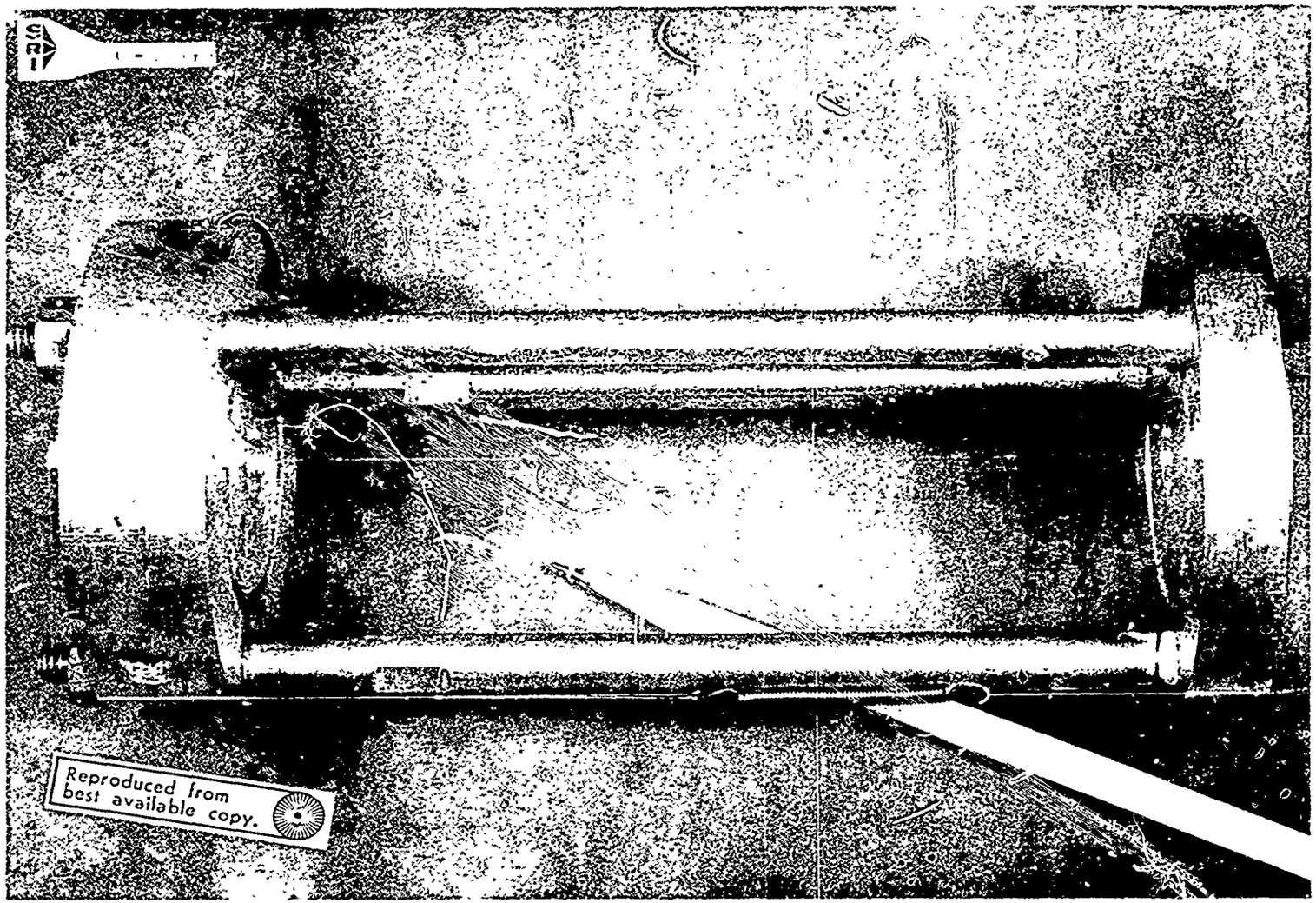

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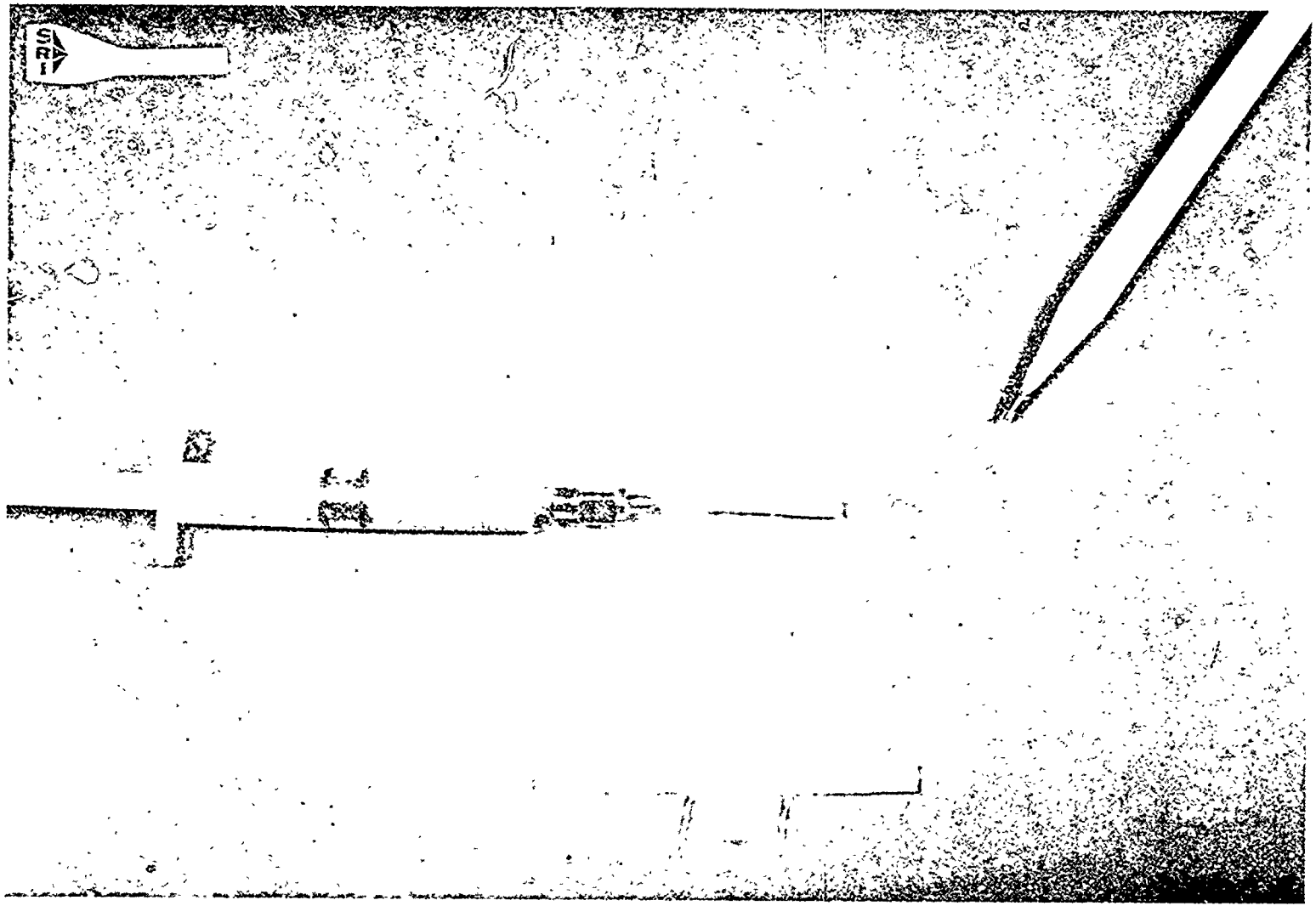
FIGURE 4. FIXTURE FOR APPLYING EPOXY SPHERES TO CAPILLARY FILAMENT

After the epoxy spheres have cured, the filament is positioned in the gage body mold and held taut by tension springs. All surfaces which will contact the polyurethane are then coated with a thin Teflon film. After being filled with the polyurethane, the mold is placed in a vacuum oven (235°F) for 2 hours for curing.

The gage body is shown in Figure 5a immediately after it has been stripped from the mold. The filament and epoxy spheres are removed from the gage body in two steps: (1) the filament is pulled at one end until a sphere is exposed and severed, and (2) the remaining epoxy sphere and filament are then pulled free of the gage body from the opposite end. Excess material is trimmed from the body (Fig. 5b), and the capillary and reservoirs are filled with the metallic fluid (Fig. 5c). Platinum terminal wires are inserted into the reservoirs and metallic fluid (Fig. 5d). To provide a sturdy device, the gage body and terminal wire assembly is encapsulated in polyurethane and once again cured in an evacuated oven. This encapsulation provides a seal for the element fluid and anchors the terminal wires to the gage body.

B. Configurations

All elastomer strain gages presently be produced employ the same basic metallic fluid element; only the diameter, gage length and arrangement of the capillary elements vary. However, elastomer gages are classified according to end-use into surface-mountable and embedable devices.



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1. Surface-Mountable

This type of gage is designed to be attached to the surface of a specimen with a suitable adhesive. In cases where the direction of strain is known, the uniaxial gage (either a single or multielement device) can be employed with the axis of the element(s)being aligned with the direction of strain. For the biaxial strain problem, either three uniaxial gages can be arranged at 45° increments and bonded separately to the specimen or the three gages can be combined within a module (at 45° increments) and the module attached at the location, this latter approach is preferred from standpoints of accuracy and convenience of installation (Fig. 1).

In Figure 6, two single element gages are shown. The top device has a 2-mil diameter, 0.50-in. long element, while the lower gage has a 1-mil diameter, 0.10-in. long element. To be noted is the different methods of introducing the terminal wires into the reservoirs. A ten-cent coin is shown in the figure to provide a size reference.

Four stages of the multielement gage are depicted in Figures 7 and 8. Gage Model BM-1 uses an external bus arrangement to connect the elements in series. For BM-2, internal platinum buses join the appropriate elements; also, the terminal wires are inserted through the gage wall into the reservoir instead of along the extended capillary. The need for buses is eliminated in the BM-3a and BM-3b models as the appropriate reservoirs' spheres intersect (Fig. 8). Again, note the different methods of inserting the terminal wires into the reservoirs.

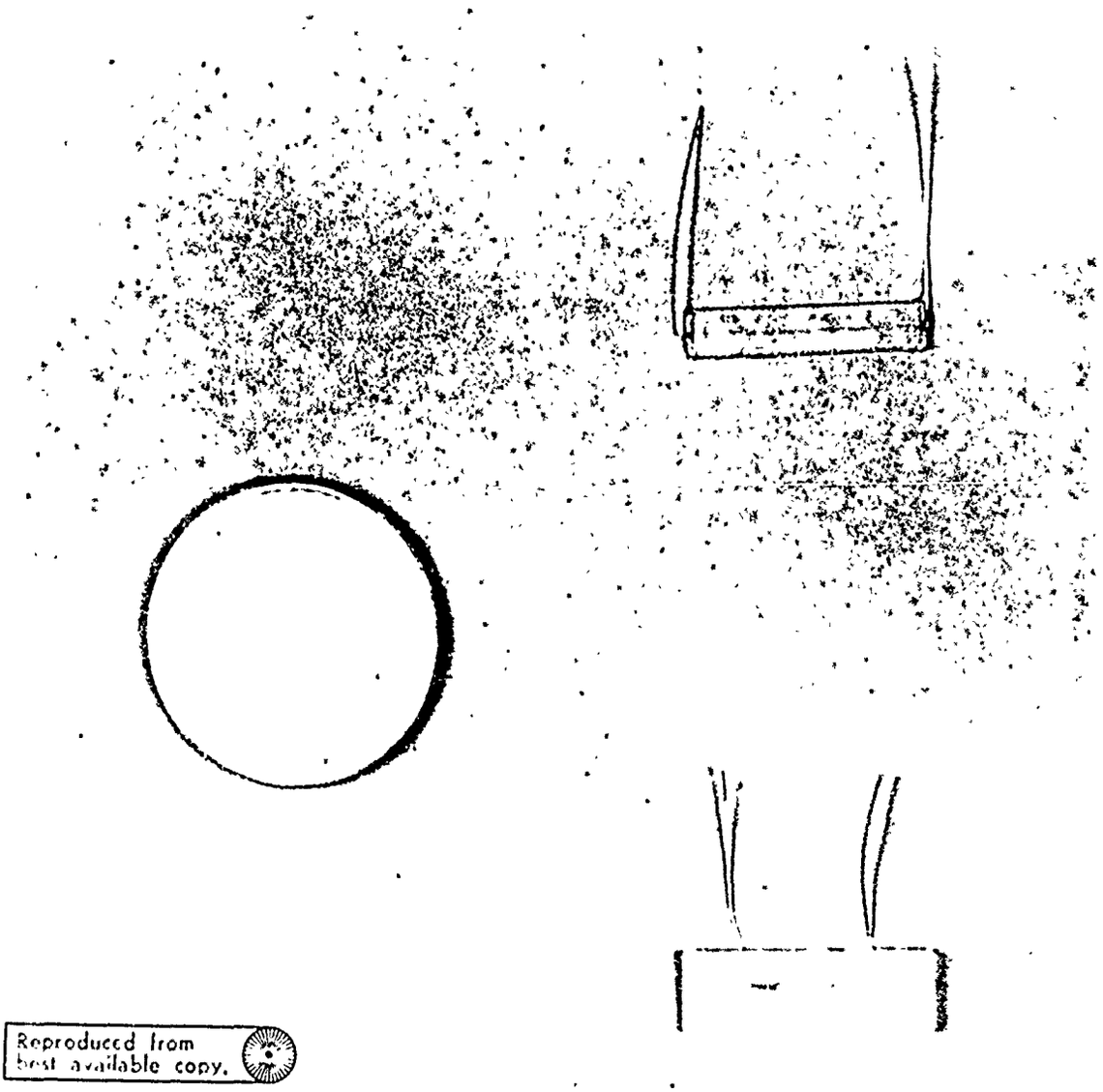

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FIGURE 6. SINGLE ELEMENT ELASTOMER GAGES

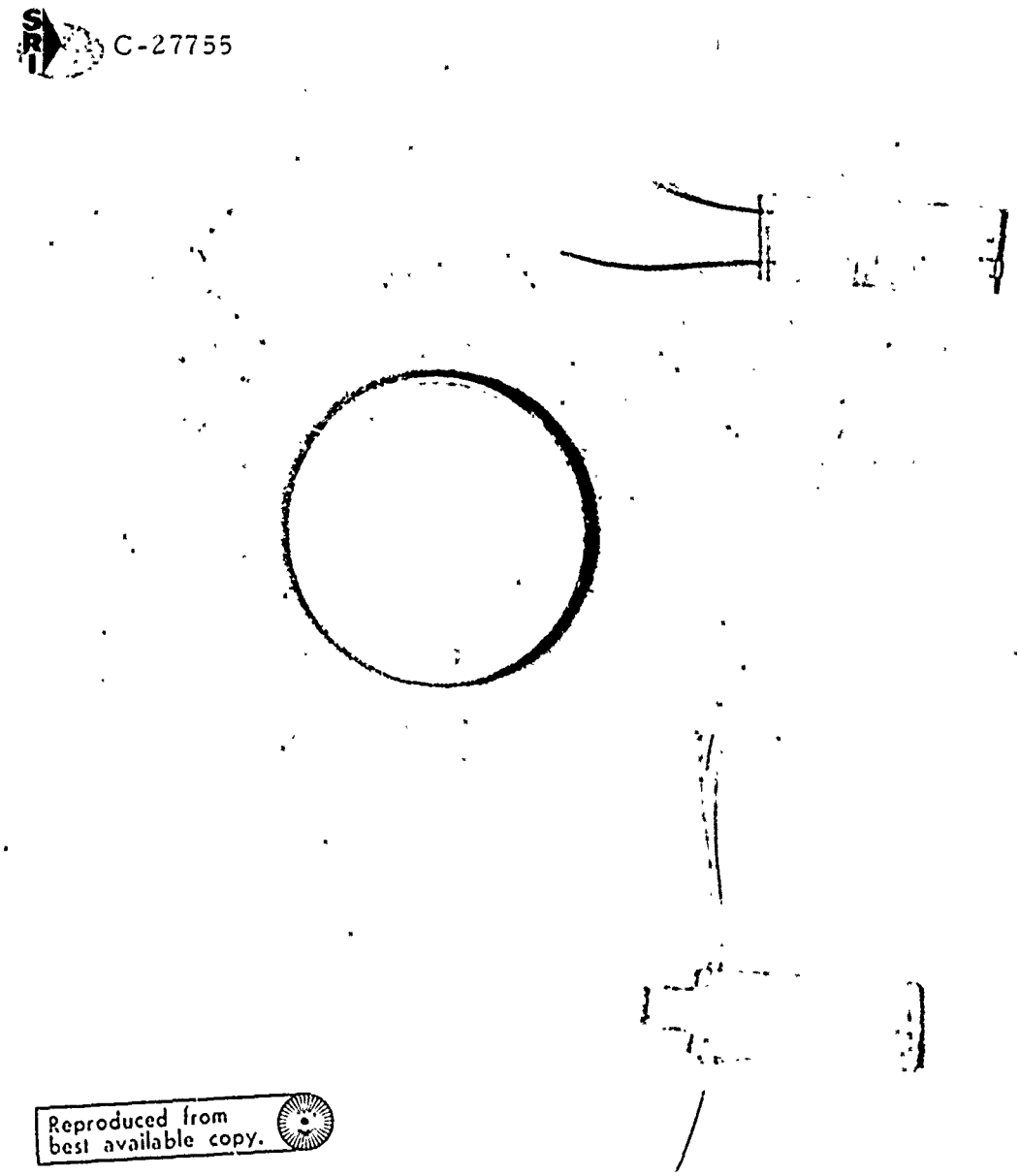

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FIGURE 7. MULTIELEMENT ELASTOMER GAGES

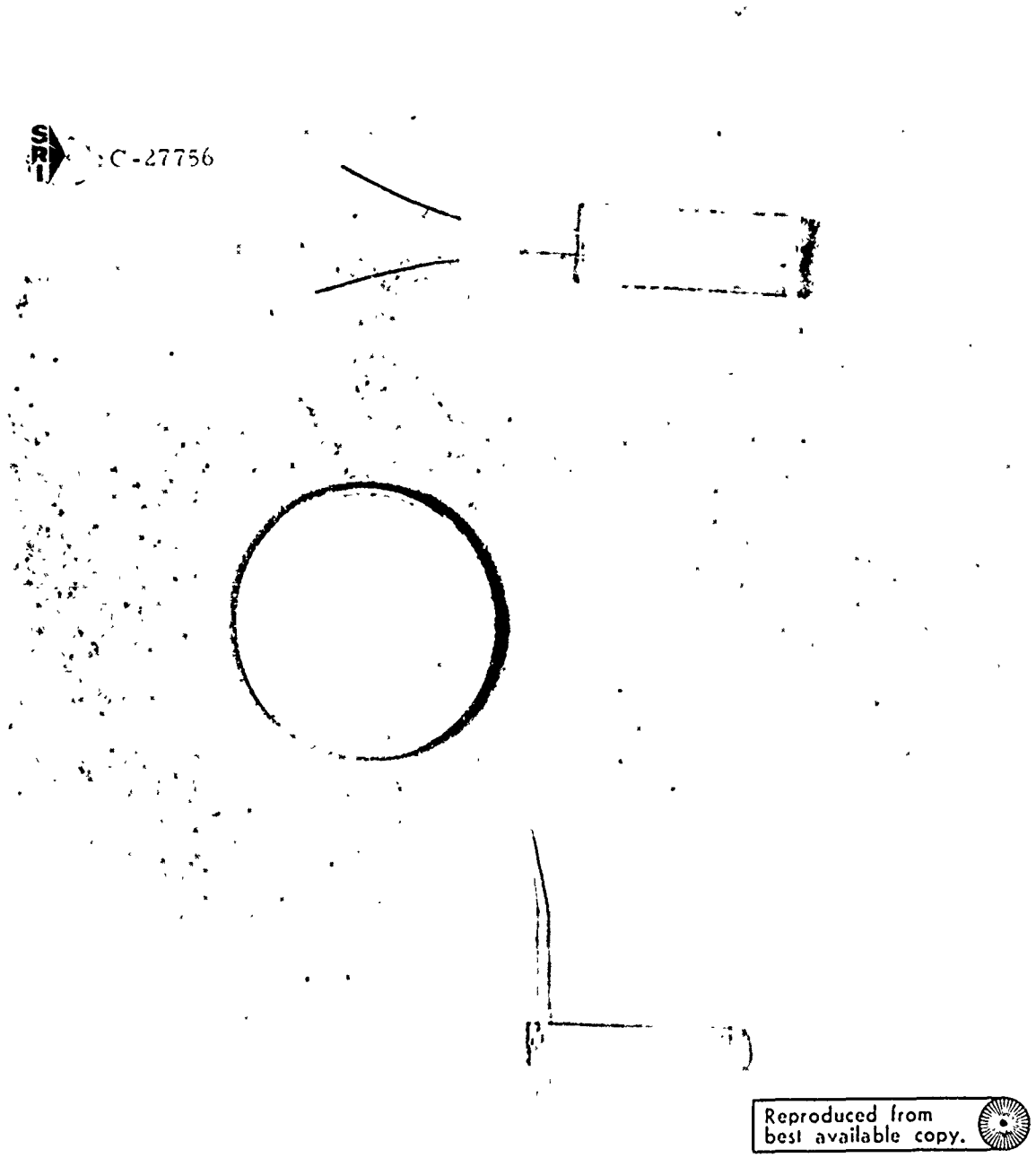

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FIGURE 8. MULTIELEMENT ELASTOMER GAGES

2. Embedable Device

The surface-mounted gage is a sufficient instrument for retrieving data from thin structure in which the strain variation between surfaces is negligible. However, new breeds of structures are coming into existence which are composed of relatively soft material (compared to metals). In many of these structures, the thickness of the walls is significant, an example of such structures is the solid propellant grain. In these cases where the strain variation between surfaces becomes less definative, an experimental tool such as the orthogonal strain module is needed to acquire the strain gradient An orthogonal strain module is designed to acquire the necessary strain intelligence to permit the computation of the three principal strains. Four elements (three orthogonal) are required if the directions of principal strain are unknown (Fig. 9).

Since the gage is embeded and occupies a finite volume of structural material, the gage modulus should match the structure material modulus to minimize the three-dimensional strain field distortion. Although this requirement entails the tailoring of a gage modulus to each application, this flexibility is available in polymer technology nevertheless, it is an added restriction.

C. Characteristics

The elastomer gages' more important characteristics are delineated in Table 1. All of the gage configurations from the earliest conceptual

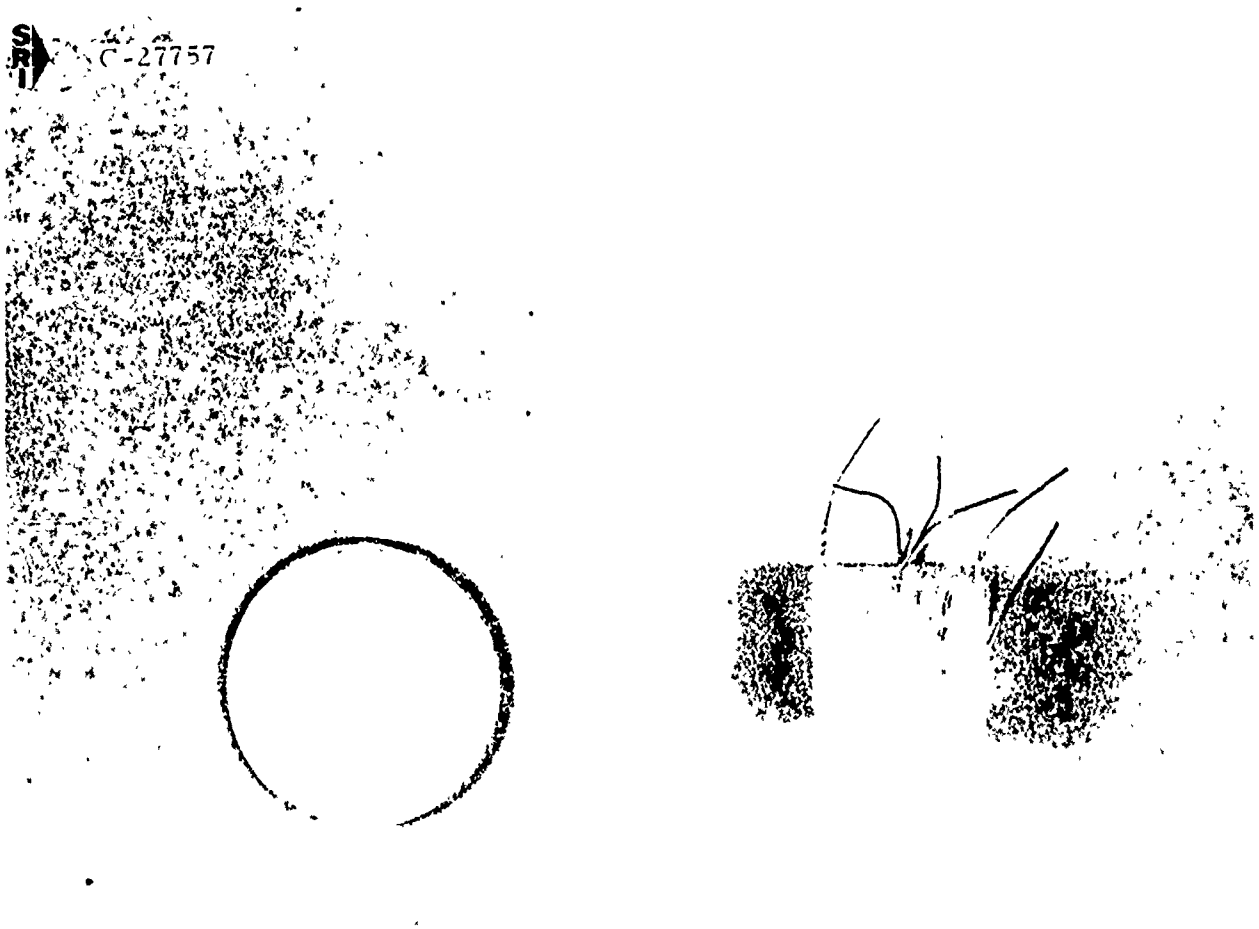

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FIGURE 9. TRIELEMENT, ELASTOMER STRAIN MODULE

TABLE 1. ELASTOMER STRAIN GAGES PROPERTIES

Gage Configuration*	Overall Dimensions (in.)			Number	Gage Elements		Nominal Resistance (ohms)		Strain Range (%)	Strain Sensitivity (ΔR/1% Strain)		Gage Suppleness‡ (gm/1% Strain)	Remarks
	Length	Width	Thickness		Length (in.)	Diameter (mils)	Actual	Theoretical		Actual	Theoretical†		
P-1	6.0	0.063		1	6	15	1.135	1.28	100	0.008	0.02		
P-2	3.5	0.300	0.125	1	3.35	6	17.0	4.50	42	0.266	0.340		
P-3	1.45	1.70	1.85	3	1.70	6	5.65	2.27	21	0.117	0.113		Data presented for element one
A, H	3.25	0.30	0.125	1	0.50	6	0.29-0.53	0.391	50	0.005	0.008	22.7	
BS-1	1.00	0.187	0.030	1	0.50	2	2.7-4.8	3.52	60				
	1.25	0.187	0.030	1	0.75	1.7	5.4-9.9	8.00	60	0.359	0.160	3.52	
	1.00	0.187	0.030	1	0.50	1.45	5.0-9.0	6.70	60				
BS-2	1.00	0.187	0.030	1	0.50	2	2.7-4.8	3.52	100	0.029	0.032		
BM-1	0.70	0.187	0.030	4	0.50	2	2.7-4.8	3.52	100		0.032	3.50	
BM-2	0.70	0.187	0.030	4	0.50	2	2.7-4.8	3.52	100		0.032		
BM-3	0.70	0.187	0.030	4	0.50	2	2.7-4.8	3.52	100		0.032		
T-1	0.50	0.50	0.50	4	0.375	1.45	3.6-6.1	4.80					

*See appendix B for design drawings.
†$\Delta R = 2R_o(1 + \epsilon)\Delta\epsilon$
‡Suppleness is defined as the force required to elongate gage body 1 percent.

prototype (P-1) to the more recent BM-3 models are compared. Besides the gages' geometry and fundamental features such as element length and diameter, the table presents data on nominal resistance, strain range, strain sensitivity and gage body suppleness.

1. Nominal Resistance

Nominal resistance is important in strain gage selection as it establishes the gage strain sensitivity and, consequently, the precision requirement for the readout instrumentation, the smaller the nominal resistance, the more precise and sensitive the resistance meters must be.

The actual nominal resistances have varied in a random pattern about the theoretical value[1]. This variation can be attributed to the relatively unsophisticated gage fabrication process. As the element diameter has been reduced (the conductor resistance increases as the element diameter decreases), shorter gage lengths have become possible without sacrificing the magnitude of nominal resistance. Figure 10 shows the advantage of the smaller diameter elements.

2. Current Capacity

In the test of four 2-mil diameter element, 3-ohm gages, the maximum current capacity was determined to be in excess of 300 ma. Continuity was broken at 400 ma for three gages and 500 ma for the last device. After a 30-minute recovery period, all four gages were checked

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See Equation A.8, Appendix A.

[1]Equation A.1, Appendix A for the Hg-In-Th alloy, ρ is 328 ohms-mil-foot.

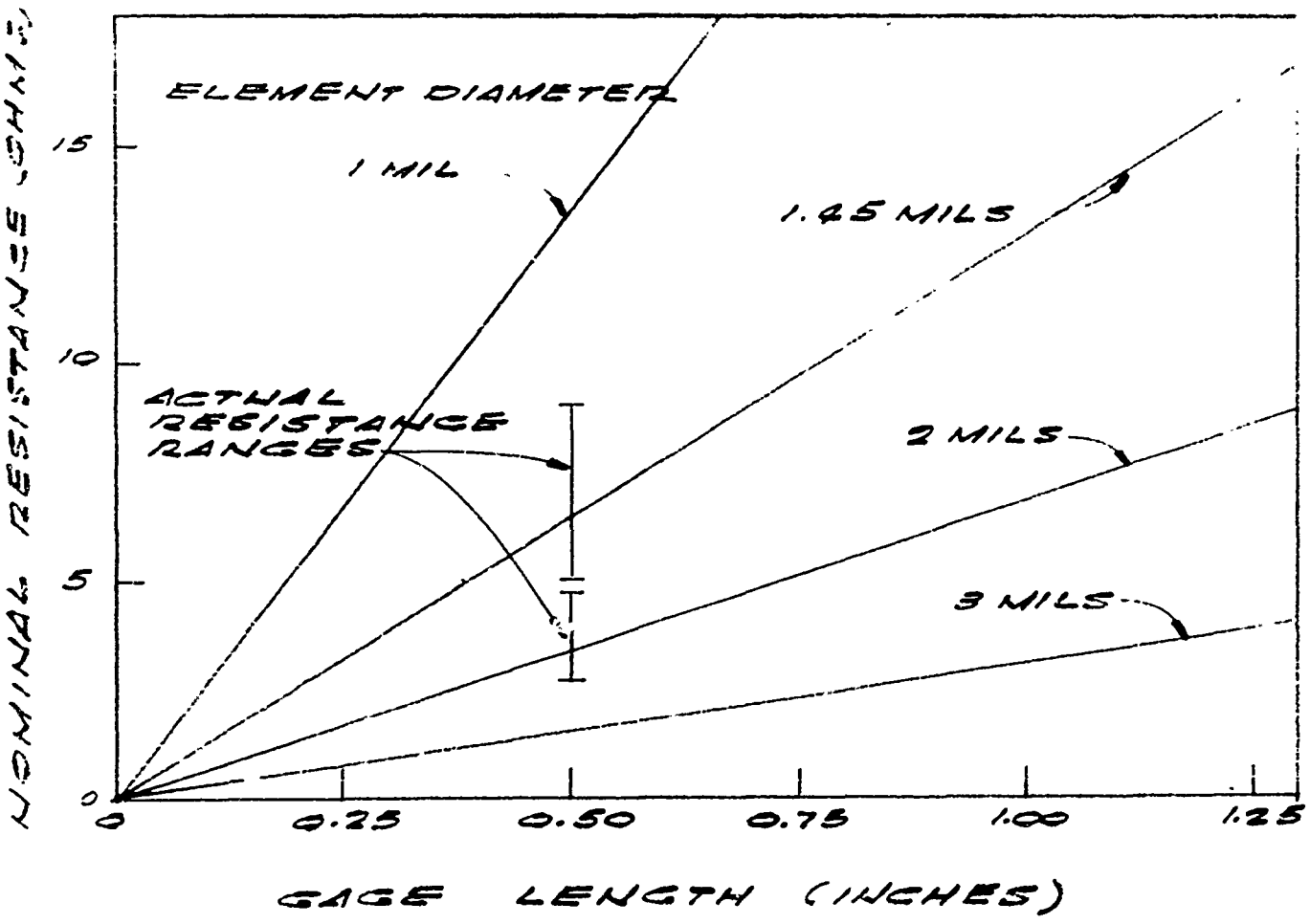

FIGURE 10. NOMINAL GAGE RESISTANCE AS A FUNCTION OF ELEMENT LENGTH AND DIAMETER

and were found to have reestablished continuity with resistances equal to the pretest values. This temporary loss of gage element continuity was probably caused by degassing of the polymer gage body due to high localized heating of the element, it is suspected that gas pockets formed across the element area and interrupted the circuit. When the excess temperature was dissipated, the gas was absorbed into the gage body, and the element circuit was restored.

The 400-ma current capacity has posed no restriction on the elastomer gage. Generally, a current of 20 to 50 ma has been determined to be adequate and sufficient to activate the device and to acquire the desired response signal.

3. Suppleness

For the gage configurations currently being fabricated, the suppleness of the gages with zero shelf life ranges from 3 to 15 gm per 1 percent strain. As the gage body ages, the material modulus (and thus the suppleness value) increases. The rate and magnitude of this aging process is unknown, however, it is believed little if any gage body degradation occurs in the first 30 or perhaps 60 days of shelf life.

With present gage designs, especially the single element devices, the suppleness value can be significantly improved (lowered) by reducing the gage width. However, the relatively wide gage (0.187 in.) is a sturdy device which has a tolerance for rough handling. As the need for more supple gages becomes known, the gage sectional area can be reduced.

4. Strain-Resistance Change

Due to unavoidable variation in gage fabrication procedures, each elastomer device has demonstrated distinct characteristics such as nominal resistance. Because of this fact, it has been necessary to establish the strain-resistance change relationship by subjecting each gage to a calibration procedure. (The calibration procedure is described in Section F.) Data from such a calibration process is plotted in Figures 11, 12 and 13 for three early model gages. With this information, the resistance of an applied elastomer gage can be converted directly to strain. Although the calibration procedure is effective, it requires a considerable effort.

An alternate to the calibration procedure has been under study. The method would utilize an analytical approach but maintain some reliance on experimental data. As presented in Appendix A, the theoretical strain can be computed by the following expression.

$$\epsilon = \sqrt{\frac{R}{R_o}} - 1$$

where

ϵ - strain

R_o and R - nominal and strained resistances, respectively

This formula takes into consideration the higher order strain terms.

A plot of the strain computed from the resistance variation of a 2-mil gage is compared to the 1.1 correlation curve in Figure 14.

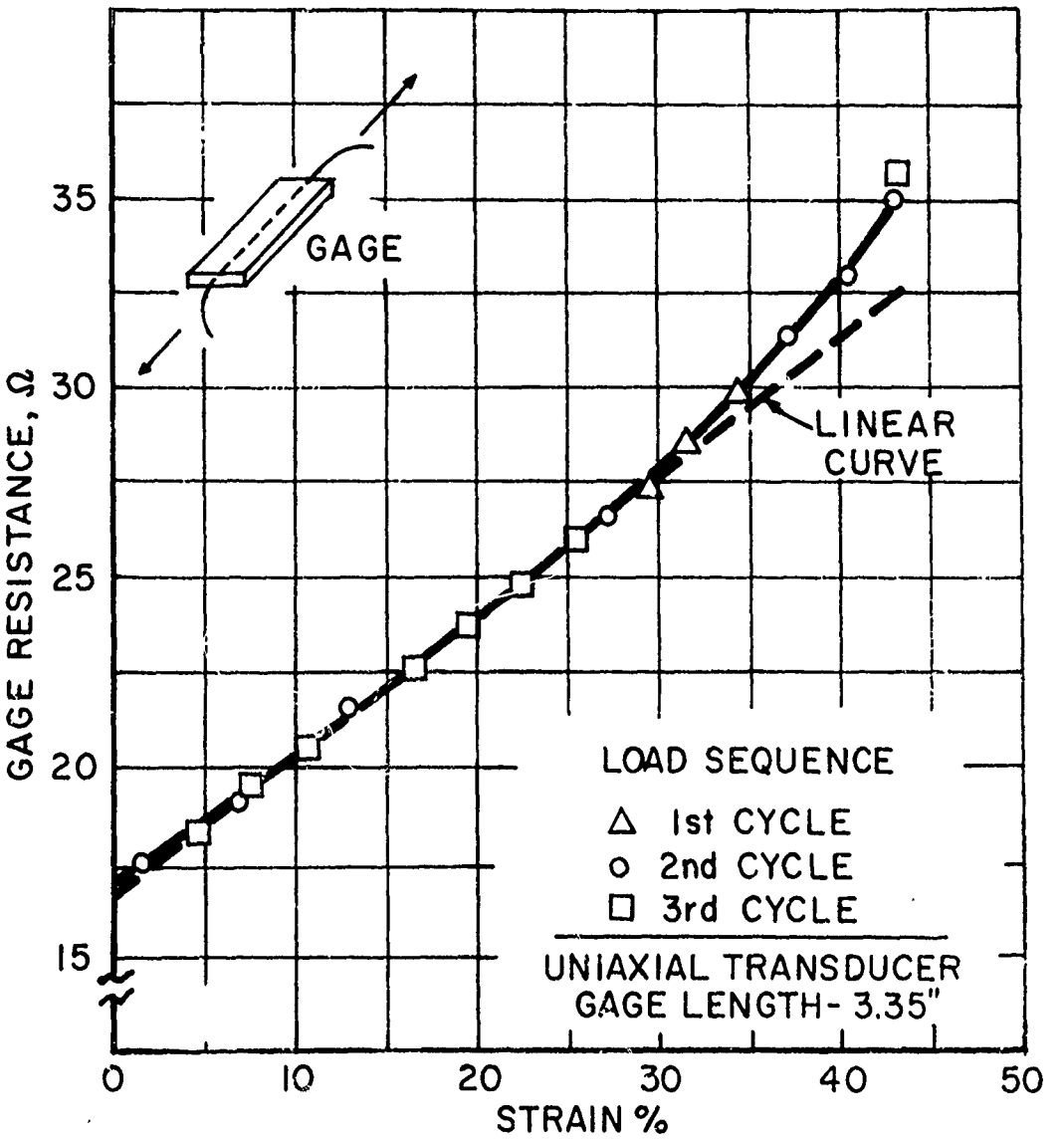

FIGURE 11. CALIBRATION CURVE FOR STRAIN MODULE P-2

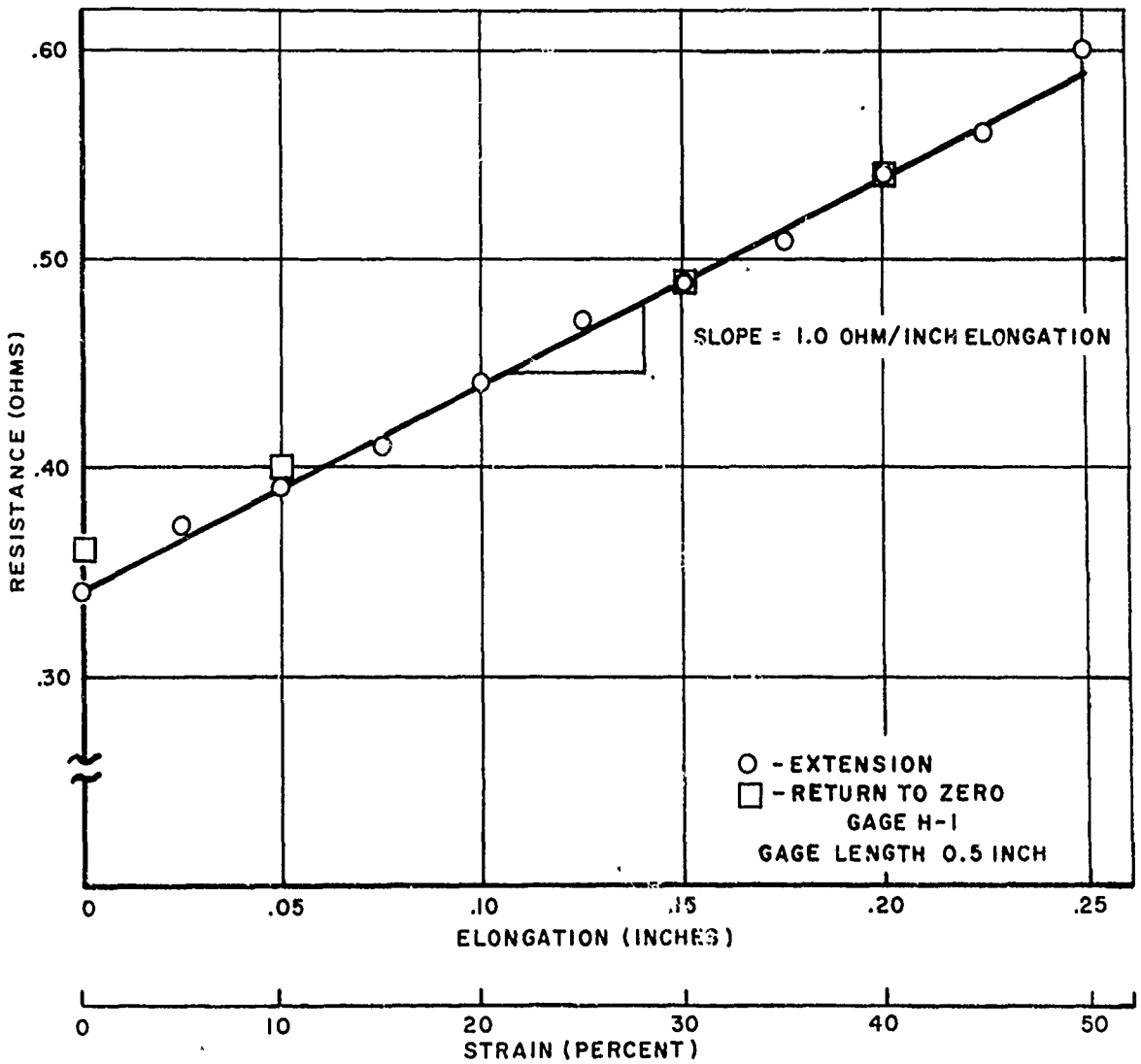

FIGURE 12. CALIBRATION CURVE FOR STRAIN GAGE H-1

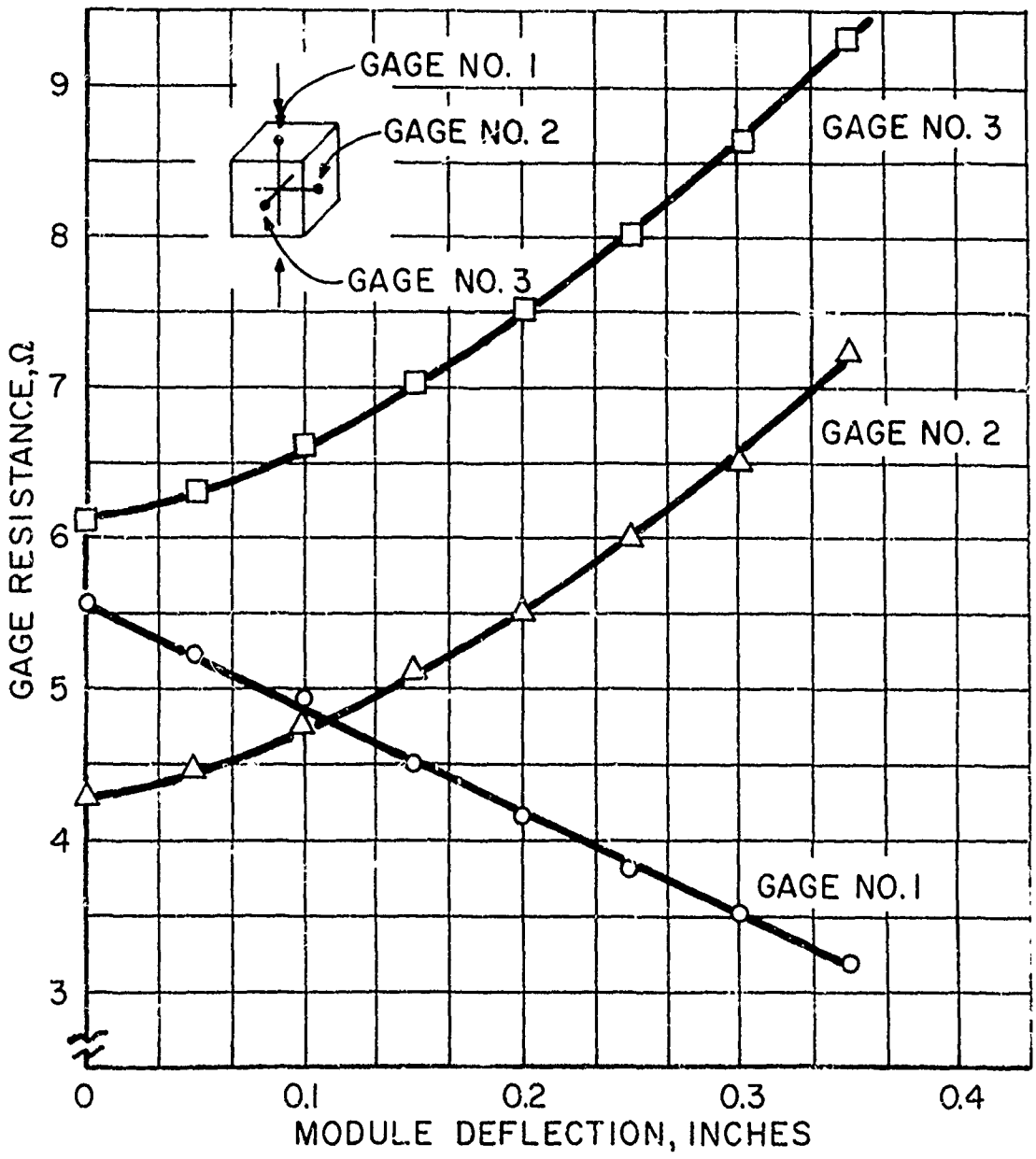

FIGURE 13. CALIBRATION CURVES FOR STRAIN MODULE P-3

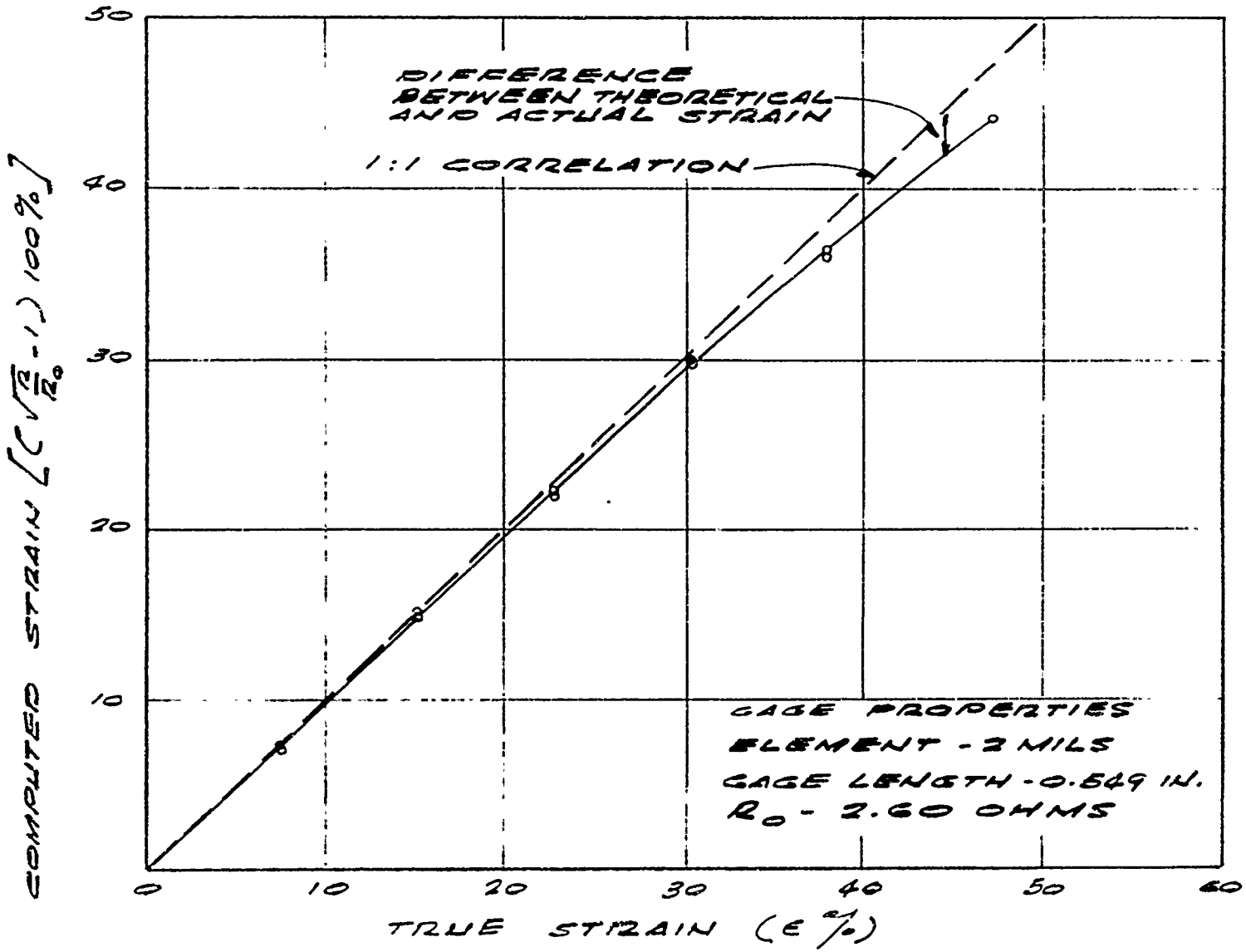

FIGURE 14. THEORETICAL VERSUS ACTUAL STRAIN

The error in the theoretical prediction is the vertical distance between the curves. As an example, for a ture strain (abscissa) of 40 percent, the strain value computed from experimentally derived resistance measurements (R_o and R) would be 38.3 percent or a strain error of 1.7 percent. The cause of this discrepancy is undefined. Nevertheless, the theoretical strain expression can be modified with a corrective constant to bring the two curves into agreement.

5. Pneumatic Pressure Effect

Possible applications of the elastomer gage would situate the device in a pressure environment. Experimental investigations performed on attached and unattached gages in pneumatic environments up to 500 psig indicate there is no change in gage resistance. However, one gage became inoperable upon release of the test pressure, for this case, it was conjectured that gas was entrapped in the element capillary during the pressurization stage, expanded at depressurization and forced a discontinuity in the gage element

6 Temperature Effects

Temperature variations in the elastomer gage and the gage circuit are critical as they produce changes in the measured resistance. This resistance variation is generally referred to as apparent strain and must be either corrected or compensated for in electrical strain gage applications. As described in Appendix A, a 4°F change in element temperature will produce a 0.1-percent apparent strain.

In Table 2, some typical electrical properties are presented for metals used in the gage construction. To be noted is that the coefficients of resistance for platinum and copper (terminal wires) are greater than three times the value for mercury. Hence, it is imperature to control not only the temperature of the gage element but also the lead and terminal wires.

A plot of the resistance change-temperature variation is shown in Figure 15 for Gage H-35 At least a portion of the variation in the data can be attributed to the degassing and gas absorption process occurring in the polymer gage body.

D. Application Procedure

Bonding an elastomer gage to a test article is a relatively simple task but must be performed correctly if the gage is to respond in an adequate manner The adhesive material must be capable of transmitting a sufficient shearing force across the test article-gage boundary to elongate or compress the elastomer strain sensor. At the same time, the glue line should exhibit a modulus approaching that of the gage or the test article in order to preclude a reinforcing ply. Further, the glue line should be a minimum thickness to minimize the errors of shear lag and flexure distortion.

One procedure that has been utilized with success is described in Table 3. The adhesive material presented in this method is a contact

TABLE 2. PROPERTIES OF GAGE METALS

Property	Conductors			
	Liquids		Solids	
	Mercury	Mercury Alloy*	Platinum	Copper
A. Electrical Resistivity				
1. (ohms-cm^2/cm) $\times 10^{-6}$	96.8	55	10.72	1.72
2. (ohms-mil-ft)	576	328	63.8	10.37
B. Coefficient of Resistance (o_c)	0.00089	---	0.003	0.00393

*Mercury-Thallium-Indium

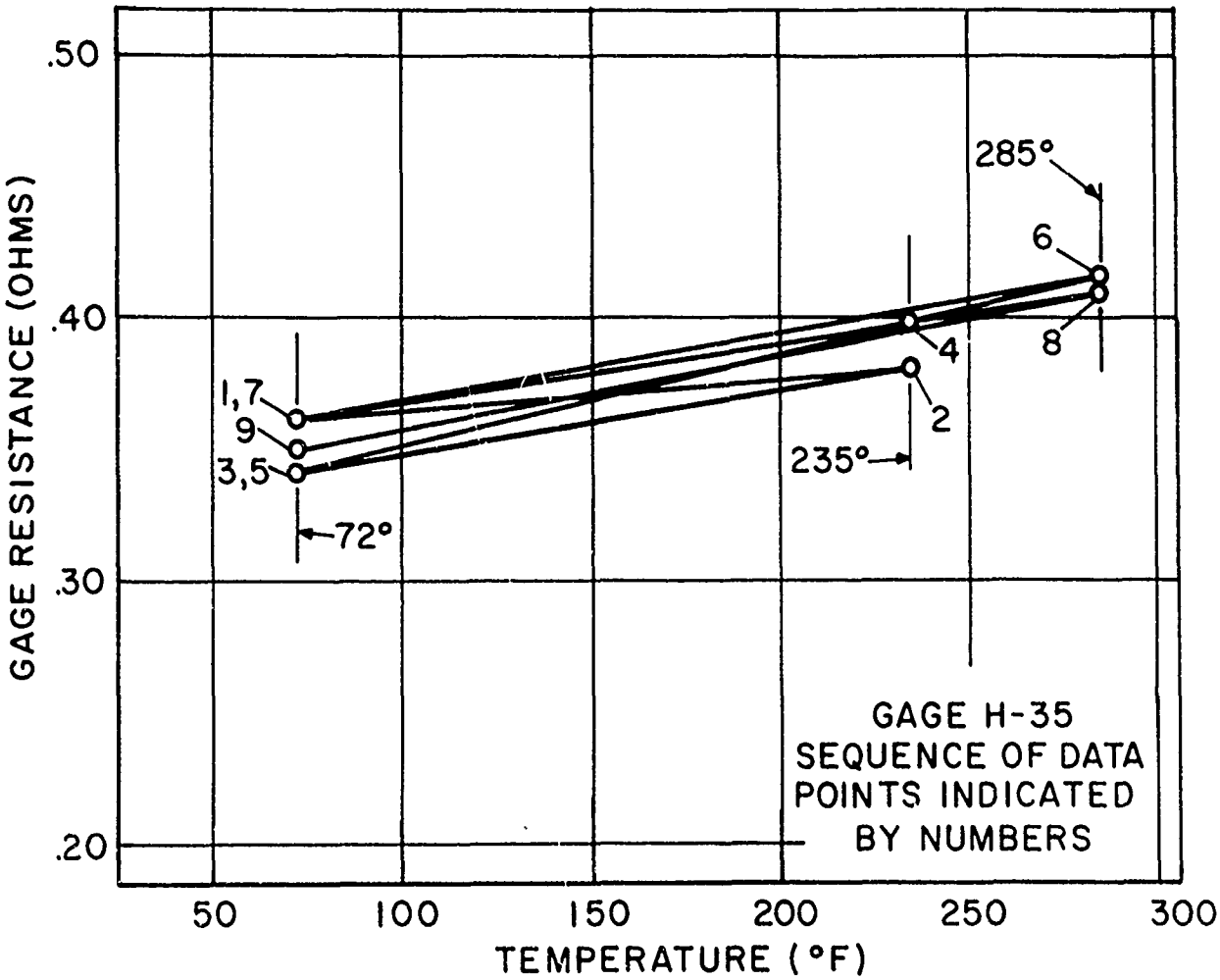

FIGURE 15. GAGE RESISTANCE CHANGE AS A FUNCTION OF TEMPERATURE

TABLE 3. SURFACE-MOUNTED GAGE APPLICATION PROCEDURE

1. Clean the attachment surfaces of the elastomer gage and the test article with an organic solvent (i.e., acetone) to remove surface debris and grease.

2. With a fine grit paper, roughen the attachment surfaces.

3. Position the elastomer gage on the test surface in correct alignment, and establish reference benchmarks in the near vicinity of the placement.

4 Clean the test surface again with the organic solvent taking precaution not to disturb the benchmarks.

5. Apply a thin film (approximately 1 mil) of contact cement* to the elastomer gage and the test article attachment surfaces, and allow films to dry for 15 minutes.

6 Carefully align the elastomer gage with the benchmarks, and bring the cement coated surfaces together. Apply a slight hand pressure to insure a positive bond with a minimum film thickness. The gage is immediately ready for service.

*Weldwood All Purpose Contact Cement.

cement. Although polyurethane has been used in some applications, contact cement has been found to be preferable for two reasons: (1) the contact cement application can be accomplished well with a 1-hour period while the polyurethane method requires more than 2 hours, and (2) the contact cement procedure results in a thinner film (usually less than 1-mil thickness).

The placement of an embedded elastomer module is usually performed by one of two schemes. In one, the finished module is supported in a precise position and orientation in the test specimen mold by the module elements terminal wires and/or auxiliary strands, polyurethane for the test specimen is then cast and cured. Segmental casting is employed as an alternate method. A portion of the test article is cast and at least partially cured to a state which will support the transducer placement, after positioning the gage on the first casting, a second casting of polyurethane (or test article material) is performed to complete the model. Both schemes are not entirely satisfactory. In the first, the terminal wires and strands remain in the model in a taut condition and thus provide some undesirable reinforcement. In the second scheme, segmental castings have been shown to contain residual shrinkage stresses at the interfaces. Nevertheless, models constructed and instrumented by either scheme can provide meaningful and important information.

E. Readout Equipment

The elastomer strain gage response phenomenon (electrical resistance change) is probably one of the more universally employed analogs. Nevertheless, a fundamental understanding of the interaction between the two basic components (strain gage and readout equipment) is required in the selection, application and utilization of the strain gage in order to avoid or at least minimize the system inherent errors.

Certain readout equipment characteristics are considered critical in the strain gage circuitry design. In addition to the requirement that the resistance meter must accommodate the gage nominal resistance and its expected variation (up to 400 percent), the readout equipment must possess the sensitivity and precision to detect and respond in a repeatable and predictable manner to a resistance increment which is equivalent to a desired strain sensitivity The excitation current must be limited in magnitude and application duration to minimize the temperature buildup in the gage. Another consideration is associated with the circuitry wiring connecting the strain gage with the readout equipment. This lead wire resistance adds ballast to the circuit thereby decreasing the readout sensitivity, and the lead wires are subjected to thermal variations which in turn produce erroneous apparent strain indications.

In the initial prototype gage evaluation, a Simpson ohm meter was used as the readout equipment due chiefly to its availability. However, it

was apparent that a more accurate device was needed. Subsequently, a Kelvin and a Wheatstone bridge were used with success.

Three variations of the Wheatstone bridge are shown in Figure 16. Basically, a variable resistor is adjusted to compensate for an increase or decrease in the active gage resistance, this adjustment maintains a zero current flow across the galvanometer. The Kelvin bridge, also schematically shown in Figure 16, overcomes an inherent fault of the Wheatstone bridge A two-step measuring procedure (Figs. 16d and 16c) automatically cancels the strain gage lead wire resistance from the circuit, and thereby increases the readout equipment s sensitivity, especially for low resistance gages However, it is to be noted that a double lead wire is required for the Kelvin bridge system.

In either system, the elastomer gage should be monitored at discrete intervals and with a minimum of circuitry current (i. e., less than 50 ma, possibly 5 ma) to prevent temperature buildup across the gage.

F. Calibration

Within the rather limited elastomer gage fabrication experience, the performance of each device has been found to deviate in a random pattern from the theoretical predicted behavior Is is surmised this variation can be attributed to an undefined fabrication detail inconsistency. Nevertheless, this deviation characteristic necessitates the calibration of each device in order to establish its unique resistance change-strain relationship.

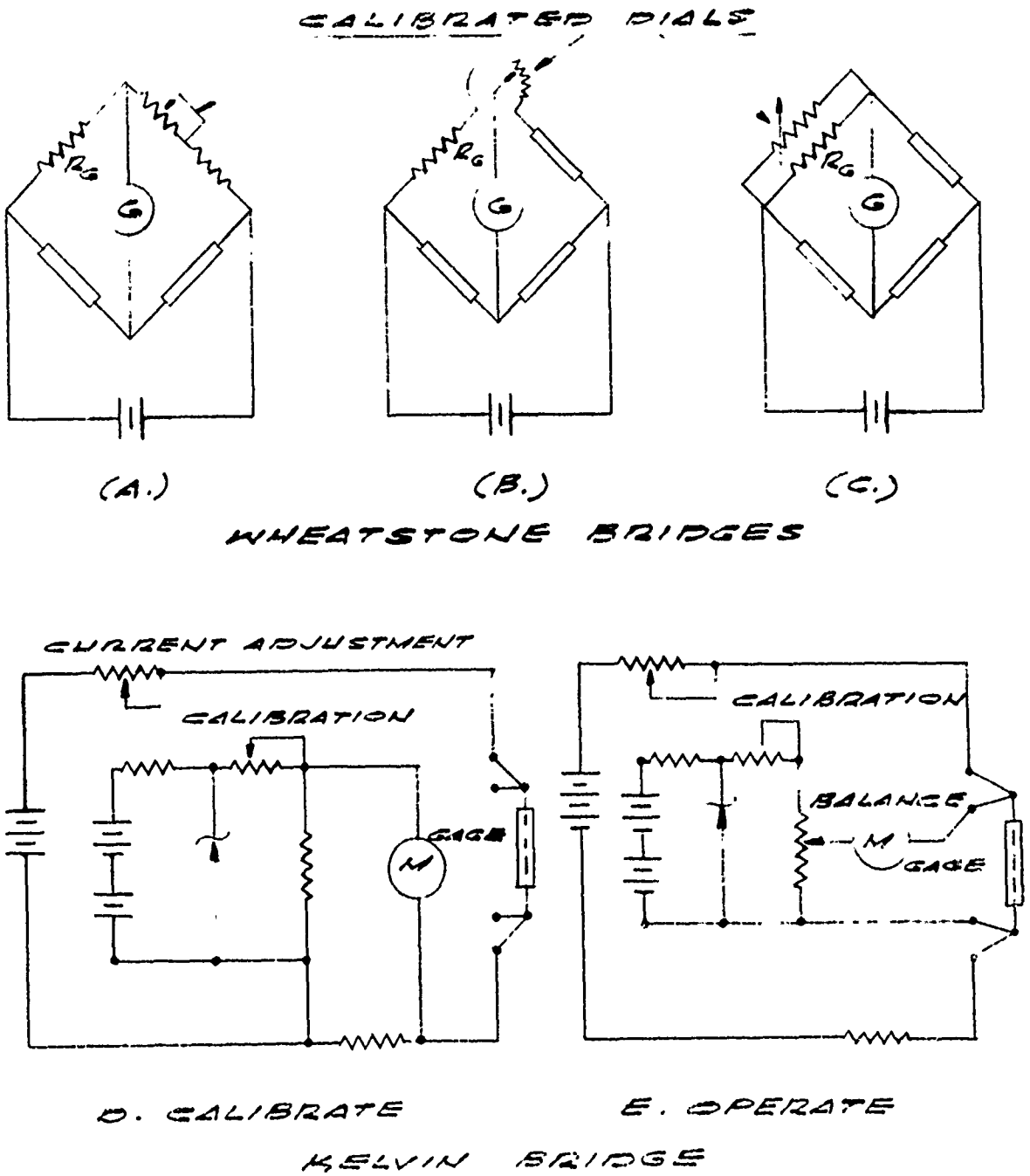

FIGURE 16. WHEATSTONE AND KELVIN BRIDGE CIRCUITS

Several calibration techniques have been employed with the same objective of elongating the device in precise displacement increments and measuring the gage resistance at each deformation stage. The main difference in these techniques has been in the methods of gripping the device or attaching the gage to a test band. One technique which was used with an early prototype gage is shown in Figure 17.

Recently, a different procedure has been employed with satisfactory results A gage is fabricated with extended ends or tabs (Fig. 18a), and the device is bonded to an elastomer strip only in the region of these tabs (Fig. 18b). After being monotonically elongated and the resistance change data are acquired, the gage is removed from the calibration configuration by cutting the device at the tabs. A calibrated gage, ready for application, is shown in Figure 18c. This procedure calibrates the device in tension only, the gage compression characteristics must be determined from analytical expressions.

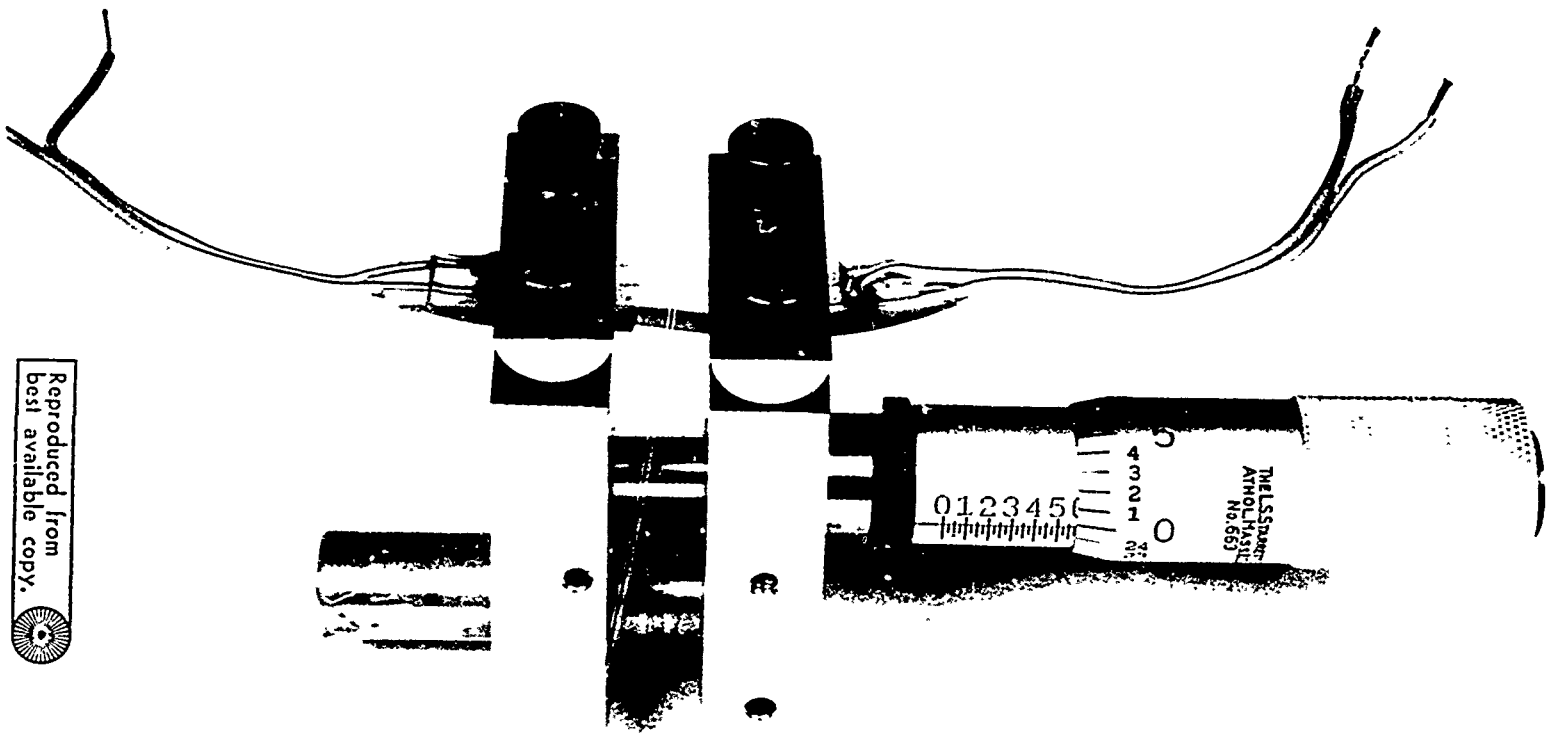

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FIGURE 17. CALIBRATION FIXTURE FOR "H" MODEL GAGES

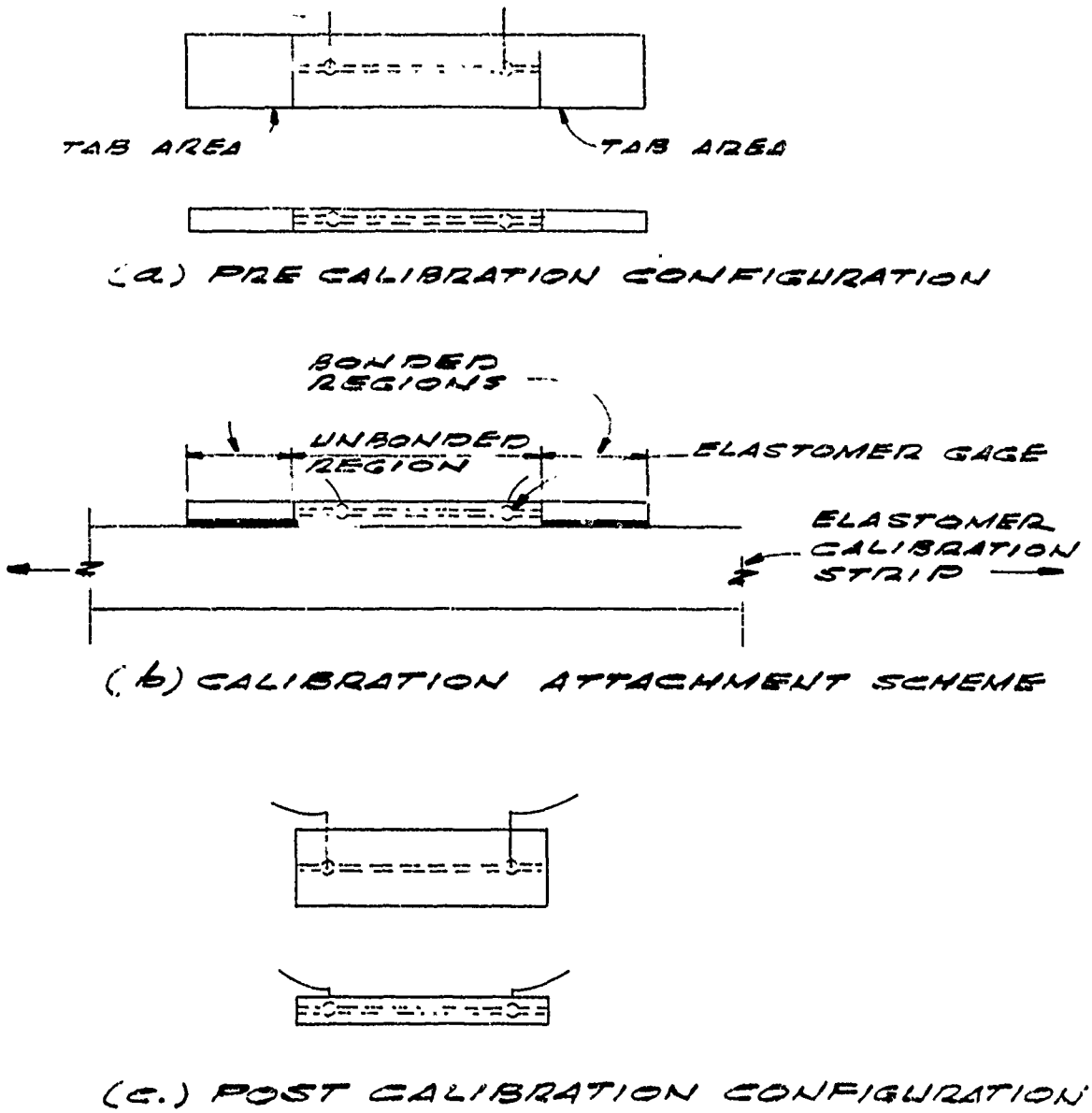


FIGURE 18. ELASTOMER GAGE CALIBRATION TECHNIQUE

IV. DEVELOPMENT TRENDS

In its present stage of development, the elastomer gage can acquire strain intelligence which is meaningful and useful in the viscoelastic structures field. On the other hand, there are gage characteristics that need additional exploration to further enhance the device's capabilities and performances. Several of these ideas are presented to indicate the possible direction of future elastomer gage development trends.

A. Materials

Only a limited number of materials have been employed in the gage construction to date. The objectives in the program have been to verify the gage concept and to produce a working model. Most research attention has been directed to finding one material system which results in an acceptable gage and then providing the necessary controls to produce a consistent product. Hence, relatively little effort has been devoted to selecting and experimentally evaluating the spectrum of materials that is available for the gage body.

The polymer which has been so extensively utilized, polyurethane, does exhibit a number of remarkable and desirable properties such as modulus and transparency. However, polyurethane is sensitive to oil and water base solutions which cause the material to swell and deteriorate. Hence, the elastomer gage made from polyurethane cannot possess active elements filled with these fluids or be exposed to their environment.

There are, undoubtedly, other polymers which possess the desired mechanical properties (modulus, etc.) and which are inert or resistent to a broader range of fluids and environments. One prospective material, fluorosilicone, is compared with polyurethane in Table 4. Likewise, there may be other element fluids which have a higher specific resistivity and can be substituted for the mercury base alloy.

B. Configurations

Within the purview of the elastomer gage composed essentially of a small diameter, liquid metal filled capillary, there are several indicated modifications which could improve one or more aspects of the gages performance.

1. Gage Length

The present elastomer gage generation, with the established 0.5-in. gage length, has a broad and general application. However, this 0.5-in. dimension was set when the gage maximum nominal resistance was less than 1.0 ohm as only 6-mil diameter capillary gages were being fabricated. With the evolution of the smaller diameter capillaries (1.0 mil) and the corresponding increase in gage resistance, the need to maintain a relatively long gage length (0.5 in.) has become less restrictive. It is presently within elastomer gage technology to fabricate sensors with a 1/8-in. gage length and having a nominal resistance exceeding 1 ohm. However, further improvement in this area is desirable.

TABLE 4. GAGE BODY POLYMERS

Properties	Materials	
	Polyurethane*	Fluorosilicone†
A. Hardness (Shore "A")	52	25
B. Tensile Strength (psi)	150	375
C. Elongation (%)	300	150
D. Fuel Resistance (% Swelling)		
ASTM Oil 1	4	Nil
ASTM Oil 3	39	4
E. Corrosive Resistance		
Sulfuric acid	Dissolved (4 days, 50% solution)	Excellent (10% solution)
Ammonia	4% Swelling (100% NH_4OH)	Excellent (50% solution)

*Adiprene L/Castor oil, E.I. duPont
†733 RTV, Dow Corning

2. Gage Thickness

The spherical reservoirs which are located at the gage length extremities (and determine the gage length) serve as housings for the lead wire--element fluid connections. Presently, the diameter of these spheres is approximately 10 mils and, hence, at least five times the capillary diameter. As the reservoirs are contained within the gage body, the sphere's diameter establishes a lower limit for the gage body thickness. In order to develop a gage with a further reduced "reinforcing effect" when applied to a supple surface, a direct approach is to reduce the gage's sectional area. Furthermore, to reduce or minimize "shear lag" and flexural distortion, the thickness of the gage should be reduced. It is apparent that a smaller diameter reservoir or one with a flatter geometry is necessary before a thinner gage is possible.

Two schemes are being investigated which would result in smaller, or at least thinner, reservoirs and yet preserve the positiveness of the terminal wire to element fluid contact. In the first, the reservoir would be formed by a material which would maintain its shape during the gage body curing process; after this curing process, the material would be dissolved leaving the reservoir cavity of desired geometry. The second idea would be to eliminate the need of the reservoir by casting the terminal wires in the gage body, these wires could be wrapped or intimately molded around the capillary forming filament. After the gage body had

cured, the filament would be removed and the element fluid inserted (as in the present fabrication procedure). The terminal wires would be in contact with the element fluid in place of the capillary forming filament.

3. Element Deposition

Presently, the element capillary is formed by a small diameter filament; after the gage body has cured and the filament has been stripped from the body, the capillary is filled by injection with the electrically conductive fluid. This technique is limited to simple patterns of elements with diameters of 1 mil or greater. An alternate to this procedure would be to surface-deposit the conductive fluid on a thin gage body ply. By use of a template, intricate gage patterns could be fabricated with relative ease. After this deposition, a second polymer casting would encapsulate the initial gage body ply and the thin fluid element grid.

C Applications

With the continued evolution of the elastomer strain gage, new applications are developing. Although its primary purpose has been to acquire deformational intelligence from solid propellant grain, there are many other uses for this unique device.

1. Structural Plastics

The number of important structures and machines which are composed, at least partly, by polymers is increasing. Some of these devices consist of complex geometries which defy theoretical analysis.

Consequently, experimental strain analysis is required to define the mechanical behavior of these structures. Although brittle coating, photostress and Moire techniques are available, the elastomer gage is most applicable.

2. Timber Structures

Even though timber is one of the oldest building materials, surprisingly little experimental strain analysis has been performed on wood structures. When considering that wood is an anisotropic material, it is quickly seen that interpretation of experimentally acquired data from any but the most simple structures would be a most formidable task. Nevertheless, new structural timber geometries such as folded plates, arches and orthotropic plates are being designed, but with an apparent degree of uncertainty. Again, the elastomer gage should have a significant application.

3. Tires

Already, the elastomer gage has been employed in the static and dynamic investigations of aircraft tires. This work has been of preliminary nature; yet, it has explicitly demonstrated the feasibility of this application.

APPENDIX A

THEORETICAL BEHAVIOR OF THE ELASTOMER STRAIN GAGE

APPENDIX A

THEORETICAL BEHAVIOR OF THE ELASTOMER STRAIN GAGE

A.1 Strain-Resistance Relationship

The active element of the elastomer strain gage is a relatively long, cylindrically shaped capillary filled with an electrically conductive fluid. As the gage is axially deformed, there are corresponding changes in the element dimensions. The capillary lengthens or shortens, and the diameter of the capillary cross section decreases or increases, respectively.

The gage element resistance can be expressed by the following expression:

$$R = \rho \frac{L}{A} \tag{A.1}$$

where

R - gage resistance in ohms

ρ - element resistivity in ohms per circular-mil-ft

L and A - capillary length and sectional area expressed in ft and circular mils, respectively

Generally, the resistivity ρ is not a constant but varies with the magnitude of pressure (or stress) being subjected to the material; however, for the elastomer strain gage, the pressure which can be transmitted from the gage body to the fluid is quite low (less than 500 psi) Therefore, the error introduced into the expression in assuming the resistivity as constant is negligible.

Fortunately, the volume of the capillary remains essentially constant even though the gage body undergoes considerable deformation. This constant volume characteristic is due to two material properties. First, the elastomer utilized in the gage body construction has a Poisson's ratio which approaches 0.5, and hence the gage body dimensions behave according to a constant volume law during gage deformation.* Second, the capillary is filled with an incompressible fluid which at least asserts that the volume of the element fluid remains constant while the volume of the capillary may change under some conditions (i.e., maybe high elongations). Thus,

$$V_o = L_o A_o$$

and (A.2)

$$V_o = LA$$

where

L_o and A_o - capillary's dimensions for the unstrained elastomer gage

L and A - dimensions for any specific gage strain state

Also,

$$\begin{aligned} L &= L_o + \Delta L \\ &= L_o\left(1 + \frac{\Delta L}{L}\right) \\ &= L_o(1 + \epsilon) \end{aligned} \qquad \text{(A.3)}$$

At least at low strain levels.

where

ΔL - element's elongation increment

ϵ - strain

Combining Equations (A. 1) and (A.2), the area parameter is eliminated

$$R_o = \frac{\rho}{V_o} L_o^2 \tag{A.4}$$

$$R = \frac{\rho}{V_o} L^2 \tag{A.5}$$

Dividing R by R_o and expressing L in terms of L_o and Equation (A. 3),

$$\frac{R}{R_o} = (1 + \epsilon)^2 = (1 + 2\epsilon + \epsilon^2) \tag{A.6}$$

For small strains, the high order term (ϵ^2) can be neglected without introducing appreciable error; however, for strains in excess of 20 percent, the ϵ^2 term should be considered.

Equation (A. 6) is solved for ϵ and plotted in Figure A. 1

$$\epsilon = \sqrt{\frac{R}{R_o}} - 1 \tag{A.6'}$$

Also, for comparison, the high order term (ϵ^2) is neglected in Equation (A. 6) and is plotted in Figure A. 1.

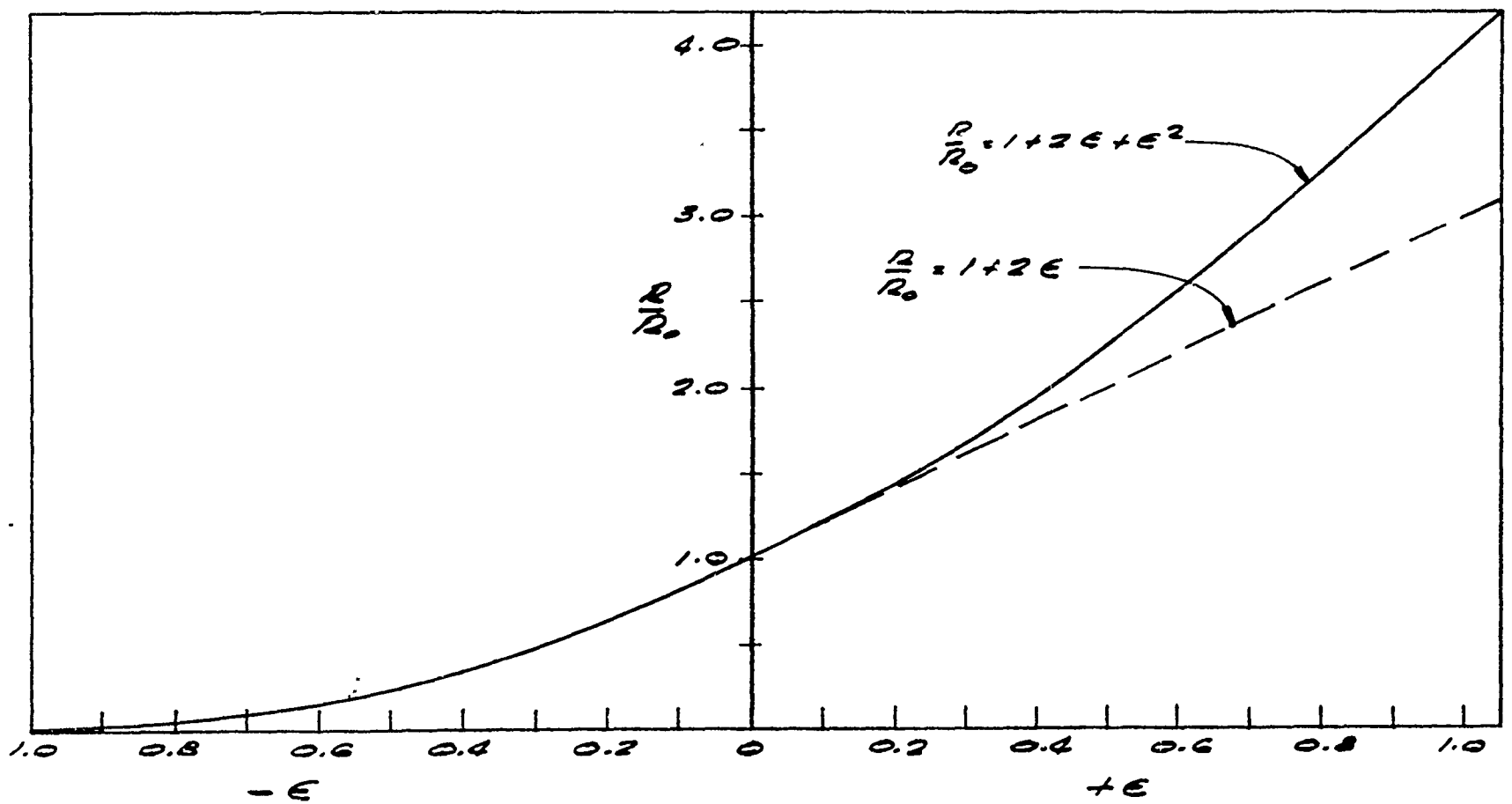


FIGURE A.1 THEORETICAL RESISTANCE RESPONSE
FOR ELASTOMER STRAIN GAGE

$$\epsilon = \frac{1}{2}\left(\frac{R}{R_o} - 1\right) \tag{A.7}$$

A.2 Strain Gage Sensitivity

Strain gage sensitivity could be defined as the smallest strain increment in a test article that can produce a repeatable resistance change in the gage element. However, this definition would encompass the quality of the gage application (thickness, modulus of glue line, etc.) and the resistance measuring instrumentation. Consequently, the authors have chosen to define strain sensitivity as the resistance change produced in an elastomer gage (unmounted or mounted) by a 1.0-percent uniaxial strain increment.

By differentiating Equation (A.6) with respect to ϵ, the sensitivity is defined

$$\frac{dR}{d\epsilon} = 2R_o(1 + \epsilon) \tag{A.8}$$

$$\Delta R = 2R_o(1 + \epsilon)\Delta\epsilon \tag{A.9}$$

It is evident that the gage resistance change rate is directly dependent on the element nominal resistance (R_o) and to a lesser extent by the strain level (ϵ).

A.3 Resistance Measuring Equipment

The elastomer strain gage works on the same principle as the conventional SR-4 strain gage. However, the nominal resistance and the

resistance change experienced by the elastomer gage are different from the SR-4 gage, and hence the resistance measuring equipment required by the two cases is quite distinct.

As depicted in Figure A.1, a 42-percent strain increment (tension) will increase the nominal resistance by 100 percent; for a 100-percent strain increment, the nominal resistance will be multiplied by a factor of 4. Consequently, the ohm meter (or ohm bridge) must have a wide range of operation. Also, the ohm meter must possess the required sensitivity. The curves shown in Figure A.2 were developed from Equation (A.9) and relate the precision requirement for the resistance measurement (K_R) to that of the strain (K_ϵ). As an illustration of the plot, assume that a strain precision of ±100 microstrain is required from a 10-ohm gage strained to 50 percent. Beginning at the 100-microstrain abscissa (10^{-4}) and proceeding vertically to the 10-ohm gage, 50-percent strain curve and then horizontally to the ordinate, it is found that the resistance must be measured to at least ±0.003 ohm. If a 100-ohm gage were used, the resistance precision could be relaxed to ±0.030 ohm.

A.4 Temperature Effects

A change in gage temperature will increase or decrease the element resistance and thus produce a false or apparent strain indication. The source of the heat can be external to the gage or generated by the measuring equipment excitation current. In either case, the magnitude of

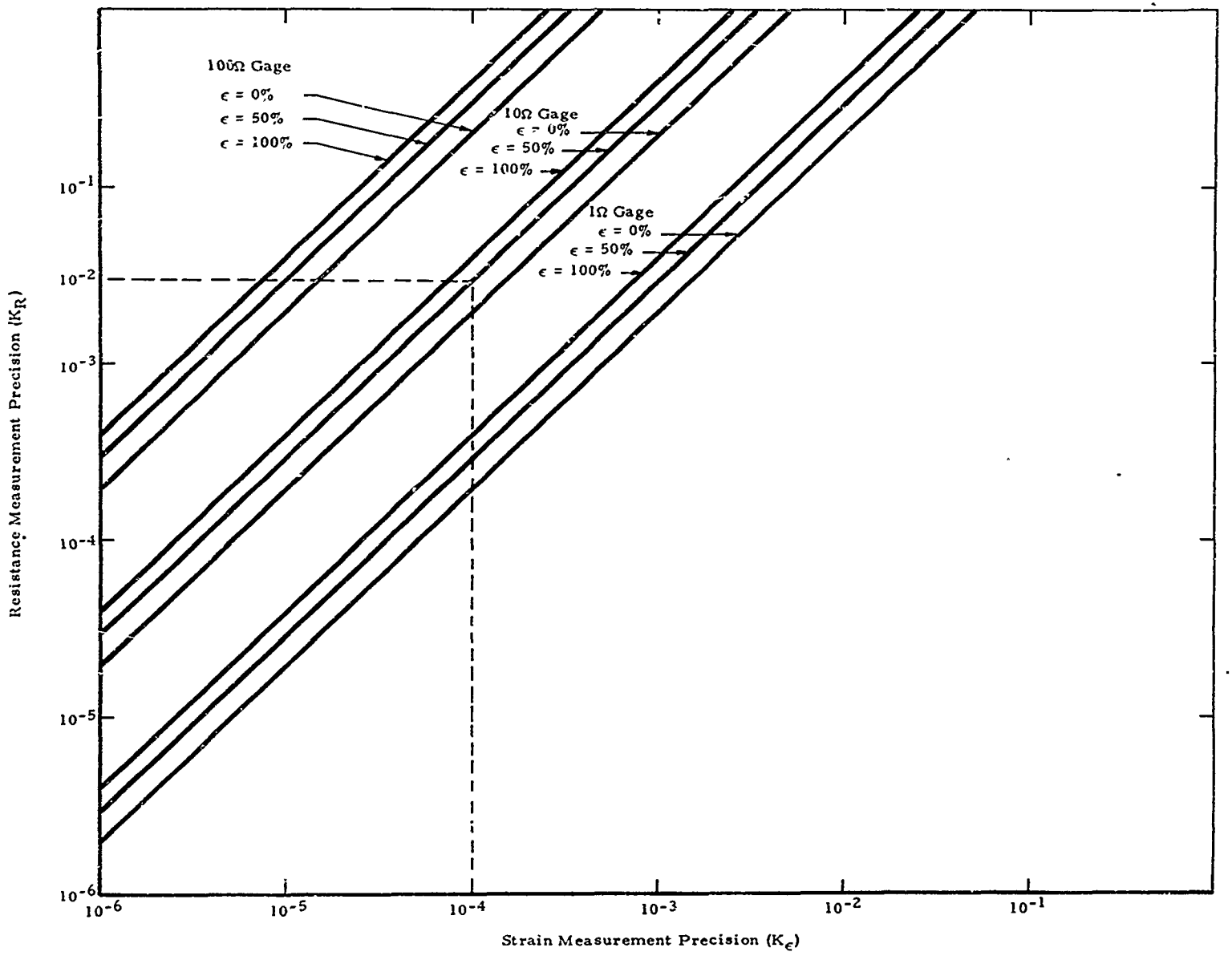


FIGURE A. 2 RESISTANCE MEASURING EQUIPMENT PRECISION REQUIREMENT

the temperature change must be known in order that the acquired resistance reading can be properly corrected.

Resistance change in a conductor is expressed by

$$R_T = R_R(1 + \alpha t) \tag{A.10}$$

where

R_T and R_R - conductor resistances (ohms) at temperature T and a reference temperature R, respectively

α - the temperature coefficient of resistance which is a material constant (percent change per °F)

t - change in temperature (T - R, in °F)

Modifying Equation (A.6') by utilizing R_T and R_R in lieu of R and R_o, the expression becomes

$$\epsilon_T = \sqrt{\frac{R_T}{R_R}} - 1 \tag{A.6''}$$

where ϵ_T is the apparent strain due to a gage temperature change. Combining this expression with Equation (A.10), the apparent strain can be shown to be a sole function of t and a material constant.

$$\epsilon_T = \sqrt{(1 + \alpha t)} - 1 \tag{A.11}$$

A graph of Equation (A.11) is shown in Figure A.3. A 4°F increase in temperature will produce a corresponding 0.1 percent strain (10^3 microstrains) for a mercury element. So, regardless of the gage's resistance,

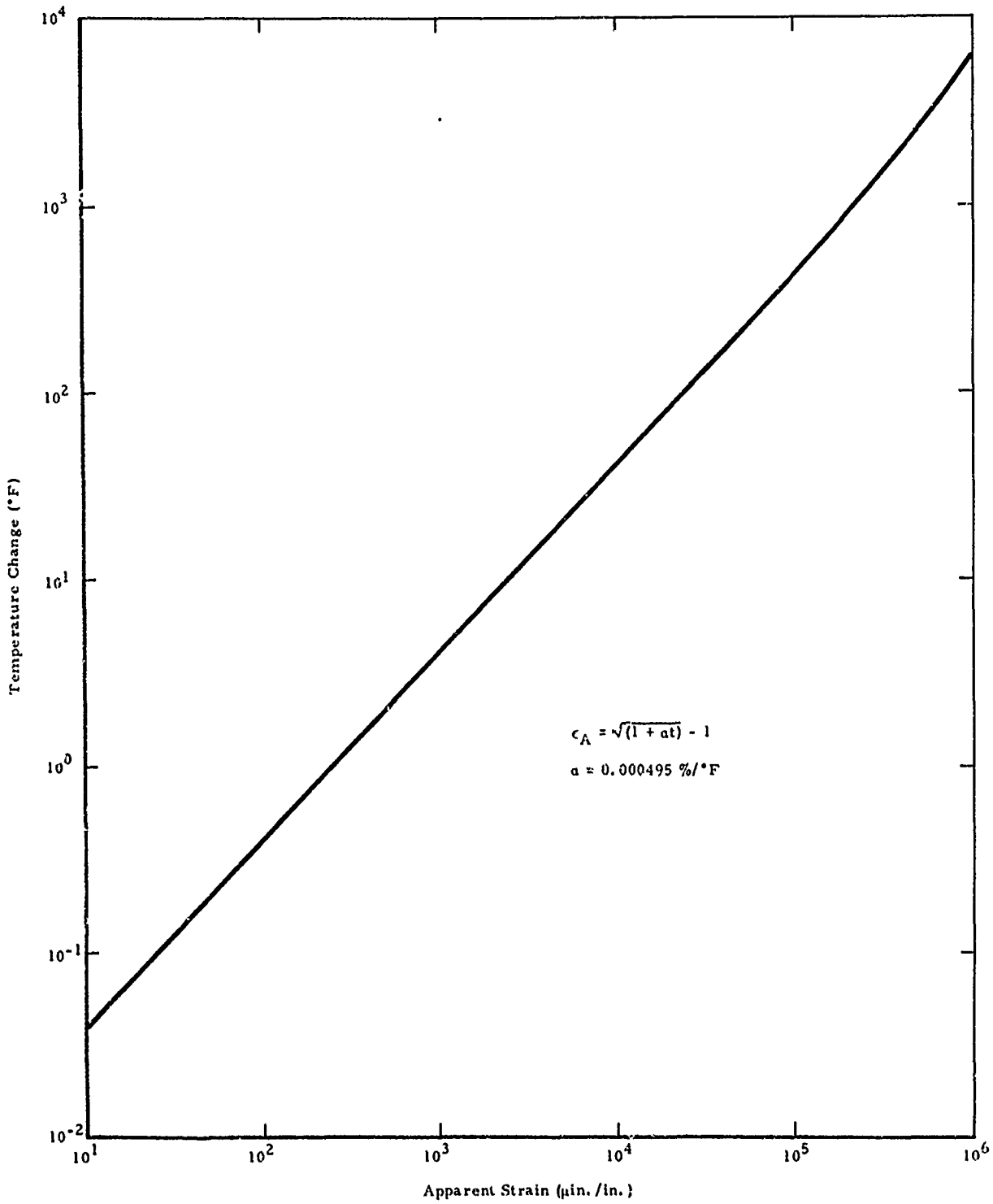
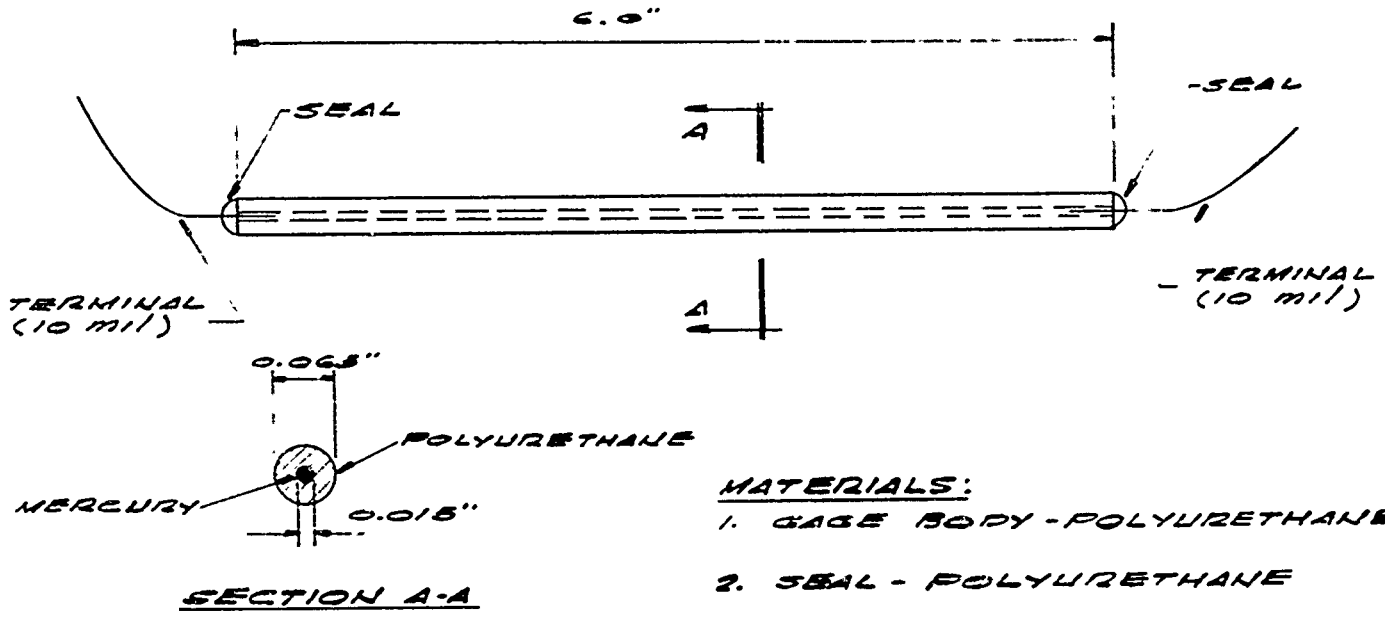


FIGURE A. 3 APPARENT STRAIN AS A FUNCTION OF TEMPERATURE (THEORETICAL)

the control of temperature is imperative in quasi-static tests; for dynamic loading where the deformation cycles are rapid as compared to the temperature change rate, the thermal phenomenon becomes less important.

APPENDIX B

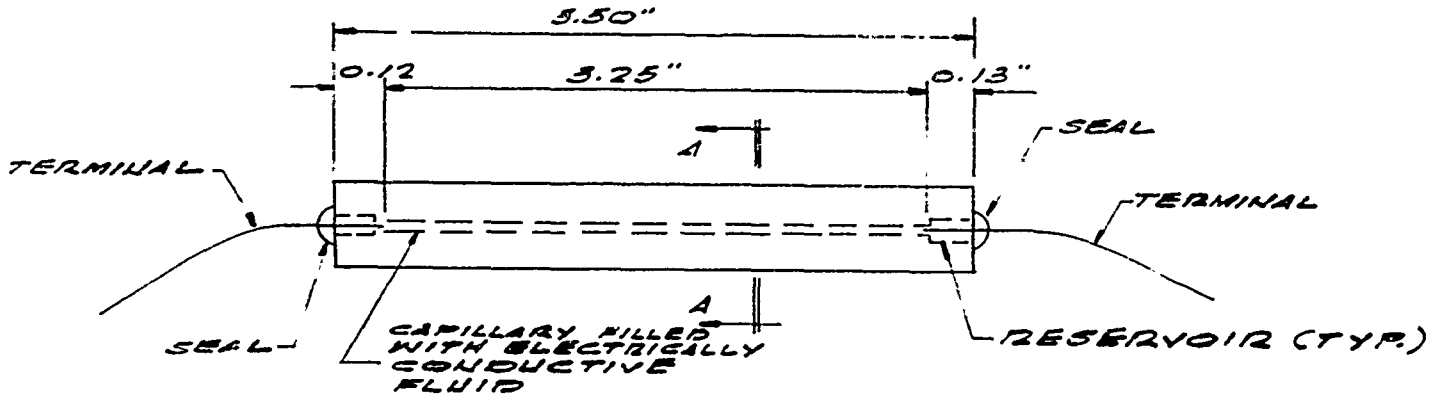
ELASTOMER STRAIN GAGE DESIGN DRAWINGS

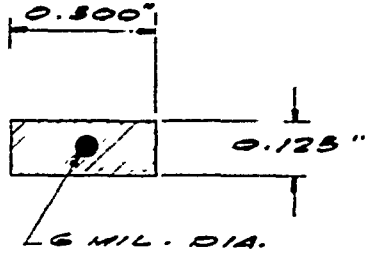


MATERIALS:

1. GAGE BODY - POLYURETHANE
2. SEAL - POLYURETHANE
3. FLUID ELEMENT - MERCURY
4. TERMINAL WIRE - COPPER

DATE 11-15-66 SCALE	ELASTOMER STRAIN GAGE "P1" CONCEPTUAL UNIAXIAL MODULE	
DRAWN BY L.S. GUILLOT		
DESIGNED BY E. ANDERSON	DEPARTMENT OF STRUCTURAL RESEARCH	DRAWING NUMBER
CHECKED BY J. MICHIE	SOUTHWEST RESEARCH INSTITUTE SAN ANTONIO, TEXAS	03-1043-04-100
APPROVED BY		



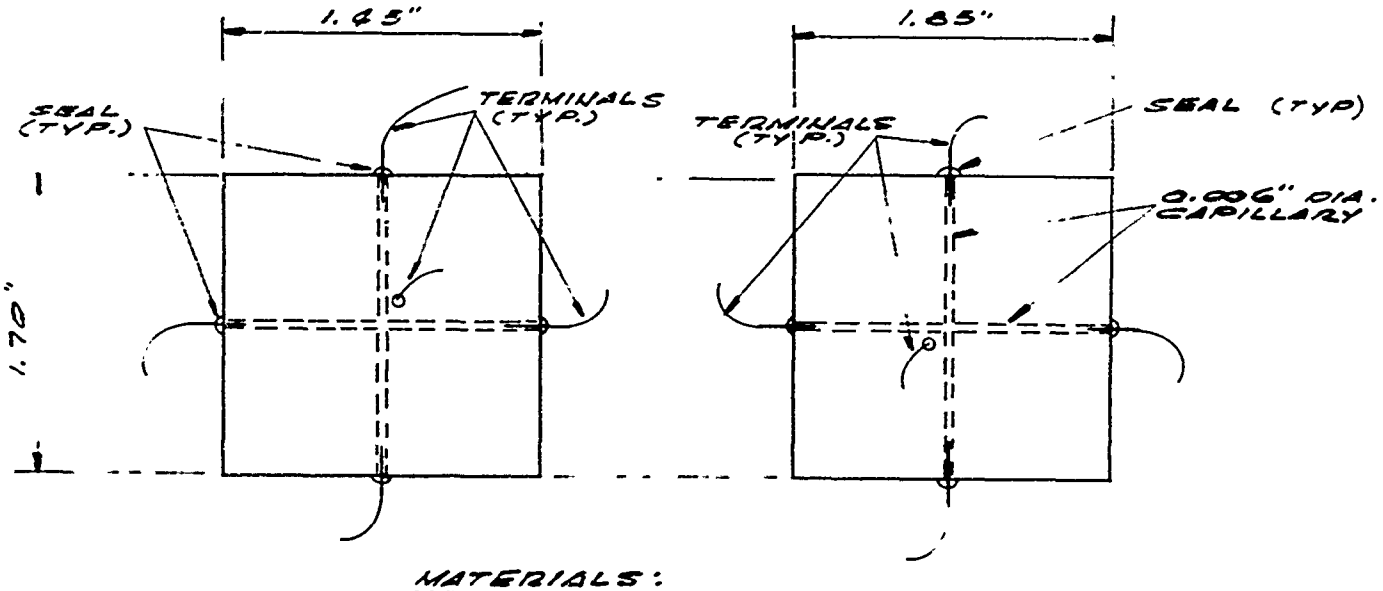


SECTION A-A

MATERIALS:

1. GAGE BODY - POLYURETHANE
2. SEAL - POLYURETHANE
3. CONDUCTIVE FLUID - MERCURY
4. TERMINAL - 10 MIL COPPER WIRE

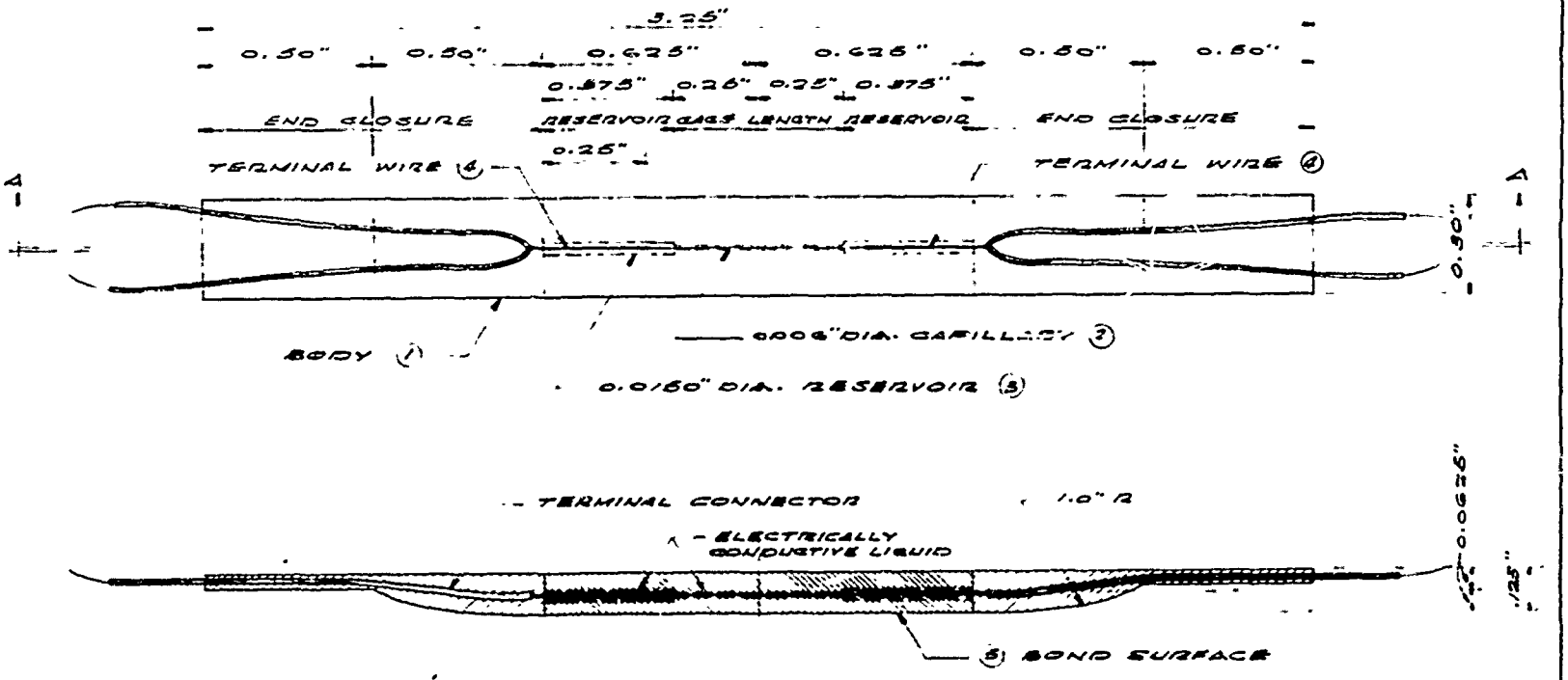
DATE 11-15-66 SCALE	ELASTOMER STRAIN GAGE "P2" CONCEPTUAL UNIAXIAL MODULE	
DRAWN BY L.S. GUILLOT		
DESIGNED BY E. ANDERSON	DEPARTMENT OF STRUCTURAL RESEARCH	DRAWING NUMBER
CHECKED BY J. MICHIE	SOUTHWEST RESEARCH INSTITUTE	03-1043-04-101
APPROVED BY	SAN ANTONIO, TEXAS	



MATERIALS:

1. GAGE BODY - POLYURETHANE
2. SEAL - POLYURETHANE
3. FLUID ELEMENT - MERCURY
4. TERMINAL - 10-MIL COPPER WIRE

DATE 11-15-66 | SCALE	ELASTOMER STRAIN GAGE "P3" CONCEPTUAL TRIAXIAL MODULE	
DRAWN BY L.S. GUILLOT		
DESIGNED BY E. ANDERSON	DEPARTMENT OF STRUCTURAL RESEARCH	DRAWING NUMBER
CHECKED BY J. MICHIE	SOUTHWEST RESEARCH INSTITUTE	03-1043-04-102
APPROVED BY	SAN ANTONIO, TEXAS	



SECTION A-A

GAGE RESISTANCE: 0.30 - 0.60 ohms

MATERIALS:

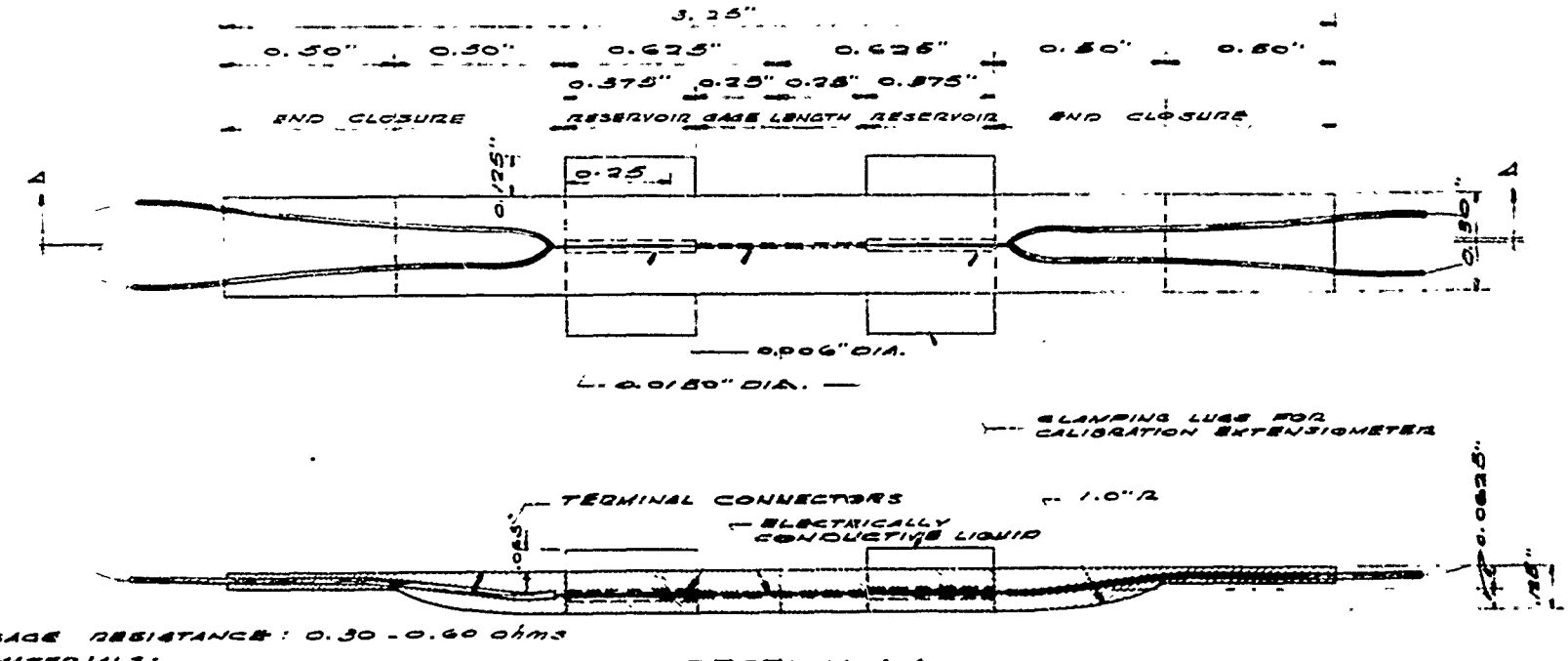
A. GAGE BODY - POLYURETHANE

B. ELECTRICALLY CONDUCTIVE LIQUID MERCURY BASE ALLOY.

C. TERMINAL CONNECTORS - COPPER WIRE

DATE 6-23-66	SCALE 1" = 0.50"	ELASTOMER STRAIN GAGE "A" 0.5-INCH GAGE LENGTH
DRAWN BY L. J. GUILLOT		
DESIGNED BY J. D. MICHIE		DEPARTMENT OF STRUCTURAL RESEARCH
CHECKED BY J. D. MICHIE		SOUTHWEST RESEARCH INSTITUTE
APPROVED BY L. U. GASTRELLI		SAN ANTONIO TEXAS

DRAWING NUMBER 03-1043-04-103



GAGE RESISTANCE: 0.30 - 0.60 ohms

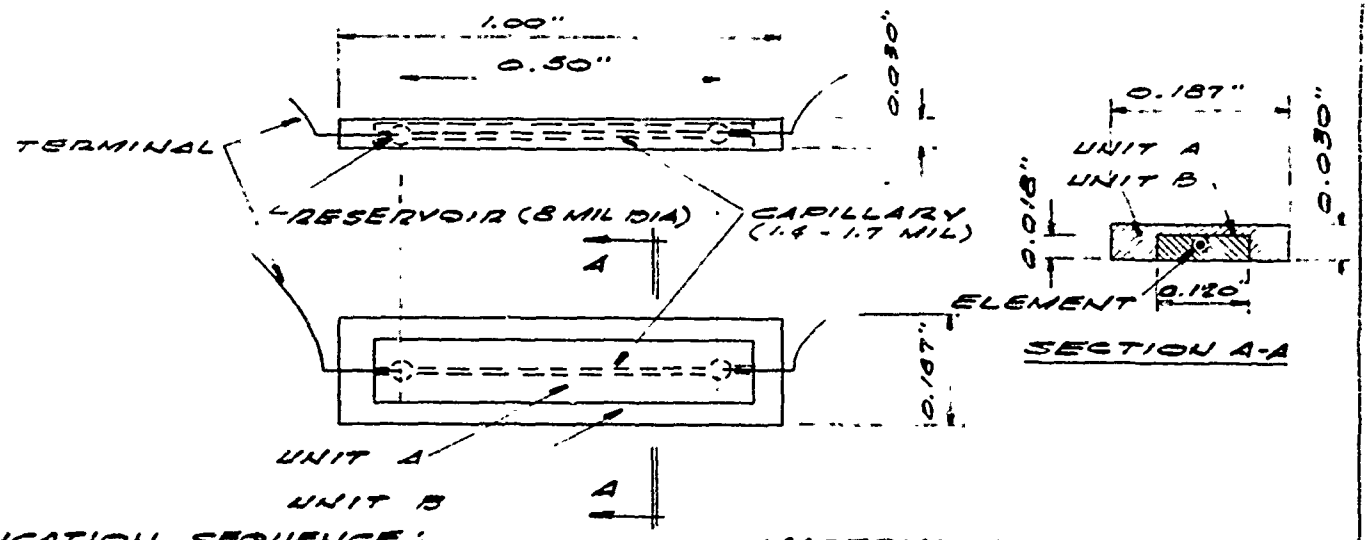
MATERIALS:

1. GAGE BODY - POLYURETHANE
2. ELECTRICALLY CONDUCTIVE LIQUID

SECTION A-A

DATE 9-30-64	SCALE	ELASTOMER STRAIN GAGE "H" 0.5-INCH GAGE LENGTH
DRAWN BY L.F. GUILLOT		
DESIGNED BY J.D. MICHIE		DEPARTMENT OF STRUCTURAL RESEARCH
CHECKED BY J.D. MICHIE		SOUTHWEST RESEARCH INSTITUTE
APPROVED BY L.W. GAETRELLI		SAN ANTONIO, TEXAS

DRAWING NUMBER 03-1043-04-104



FABRICATION SEQUENCE:

a. CAST BASIC UNIT A WITH CAPILLARY AND RESERVOIRS

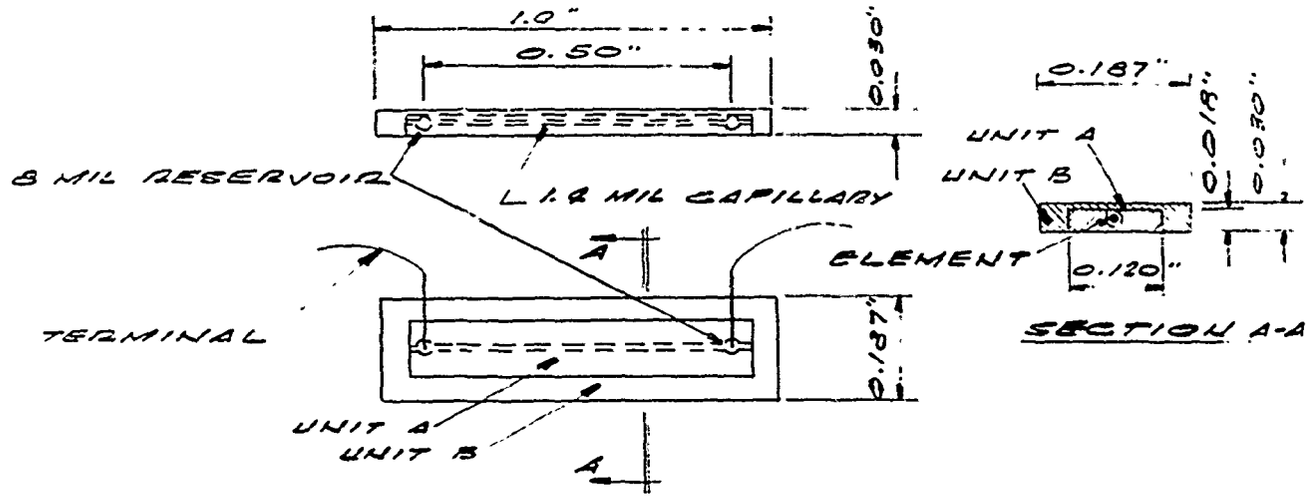
b. FILL CAPILLARY AND RESERVOIR WITH ELEMENT FLUID AND INSERT TERMINAL WIRES

c. ENCAPSULATE UNIT A IN ELASTOMER UNIT B TO SEAL FLUID ELEMENT AND SECURE TERMINALS

MATERIALS:

1. GAGE BODY - POLYURETHANE
2. ELEMENT - MERCURY ALLOY (TL - IN - HG)
3. TERMINAL - PLATINUM (0.005")

DATE 11-15-66 SCALE	ELASTOMER STRAIN GAGE "BS-1" UNIAXIAL, SINGLE ELEMENT MODULE	
DRAWN BY L. S. GUILLOT		
DESIGNED BY E. ANDERSON	DEPARTMENT OF STRUCTURAL RESEARCH	DRAWING NUMBER
CHECKED BY J. MICHIE	SOUTHWEST RESEARCH INSTITUTE	03-1043-04-105
APPROVED BY	SAN ANTONIO, TEXAS	



FABRICATION SEQUENCE:

a. CAST BASIC UNIT A WITH CAPILLARY AND RESERVOIRS

b. FILL CAPILLARY AND RESERVOIR WITH ELEMENT FLUID AND INSERT TERMINAL WIRES INTO RESERVOIRS

c. ENCAPSULATE UNIT A IN ELASTOMER UNIT B TO SEAL FLUID ELEMENT AND SECURE TERMINALS

MATERIALS:

1. GAGE BODY - POLYURETHANE
2. ELECTRICALLY CONDUCTIVE FLUID MERCURY ALLOY (TL-IN-HG)
3. TERMINALS - PLATINUM (0.005")

DATE 11-15-66 SCALE	ELASTOMER STRAIN GAGE "BS-2" UNIAXIAL, SINGLE ELEMENT	
DRAWN BY L. S. GUILLOT		
DESIGNED BY E. ANDERSON	DEPARTMENT OF STRUCTURAL RESEARCH	DRAWING NUMBER
CHECKED BY J. MICHIE	SOUTHWEST RESEARCH INSTITUTE	03-1093-04-106
APPROVED BY	SAN ANTONIO, TEXAS	

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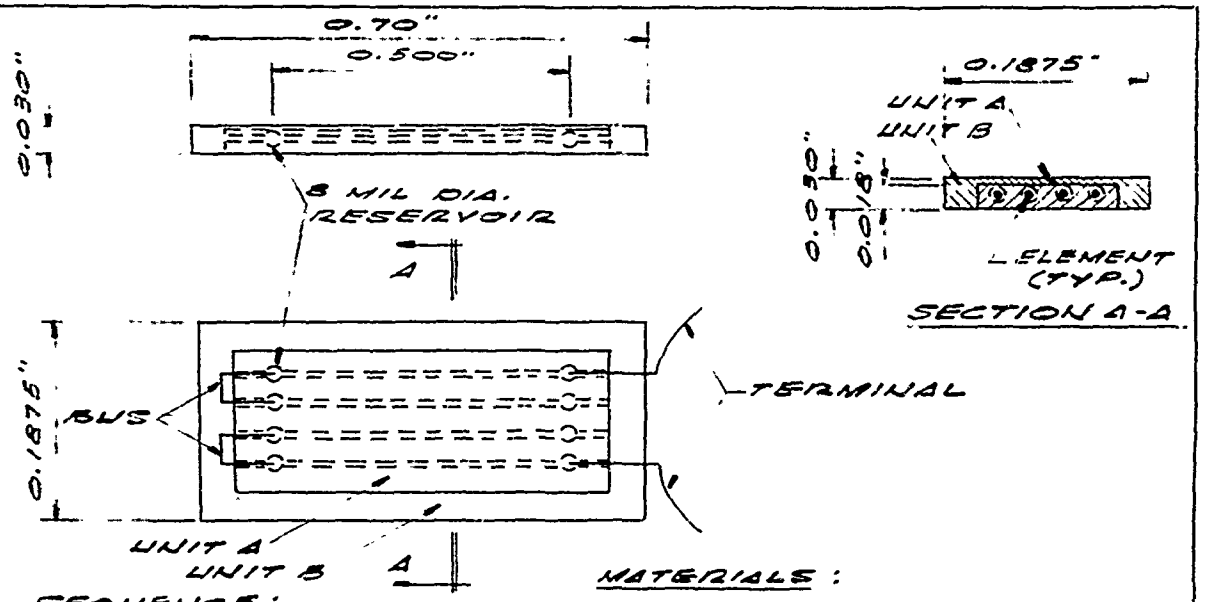

FABRICATION SEQUENCE:

a. CAST BASIC UNIT A WITH CAPILLARIES AND RESERVOIRS
b. FILL CAPILLARIES AND RESERVOIRS WITH ELEMENT FLUID AND INSERT TERMINAL WIRES
c. ENCAPSULATE UNIT A IN ELASTOMER UNIT B TO SEAL FLUID ELEMENTS AND SECURE BUS AND TERMINAL WIRES

MATERIALS:

1. GAGE BODY - POLYURETHANE
2. ELECTRICALLY CONDUCTIVE FLUID - MERCURY ALLOY (TL-IN-HG)
3. TERMINALS & BUS - PLATINUM (0.005")

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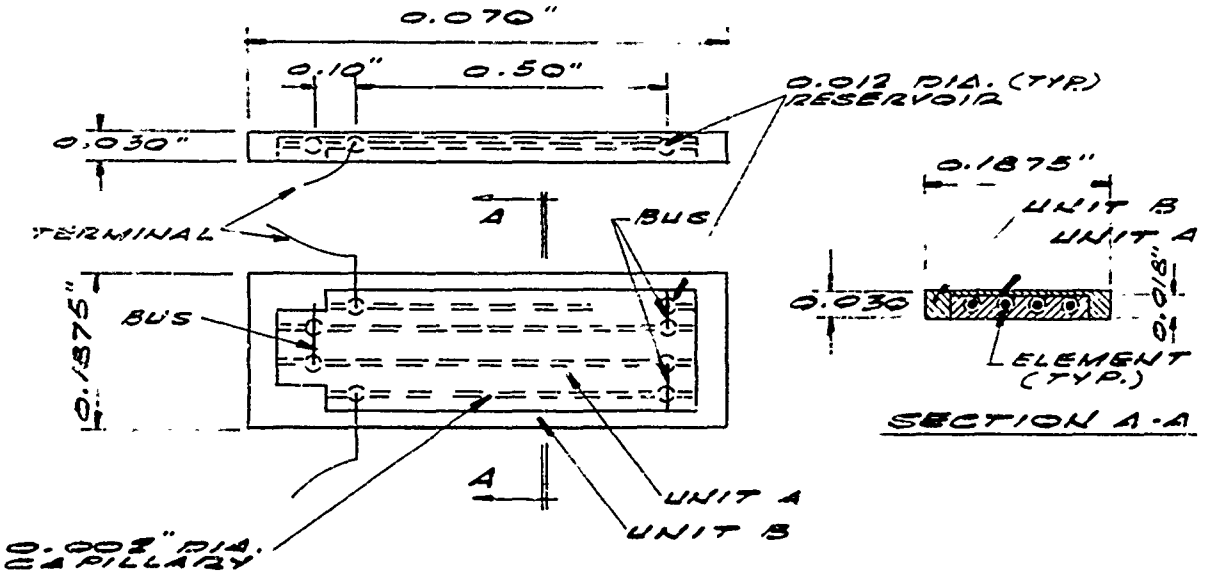
DATE 11-15-66	SCALE	ELASTOMER STRAIN GAGE "BM-1" UNIAXIAL, MULTI ELEMENT MODULE
DRAWN BY L. E. GUILLOT		
DESIGNED BY E ANDERSON		DEPARTMENT OF STRUCTURAL RESEARCH
CHECKED BY J. MICHIE		SOUTHWEST RESEARCH INSTITUTE
APPROVED BY		SAN ANTONIO. TEXAS

DRAWING NUMBER 03-1093-04-107



FABRICATION SEQUENCE:

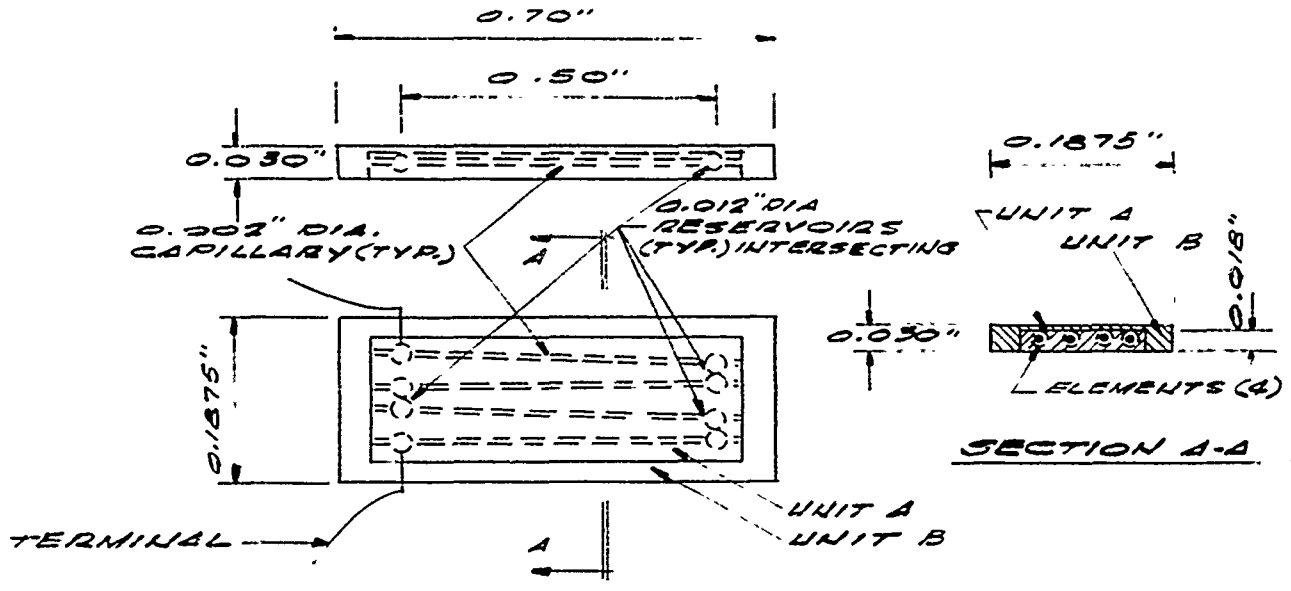
a. CAST BASIC UNIT A WITH CAPILLARIES AND RESERVOIRS
b. FILL CAPILLARIES & RESERVOIRS WITH ELEMENT FLUID AND INSERT BUS AND TERMINAL WIRES
c. ENCAPSULATE UNIT A IN ELASTOMER UNIT B TO SEAL FLUID ELEMENTS AND SECURE BUS AND TERMINAL WIRES

MATERIALS:

1. GAGE BODY - POLYURETHANE
2. ELEMENT FLUID - MERCURY ALLOY (TL-IN-HG)
3. TERMINAL & BUS 0.005" DIA. PLATINUM WIRE

Reproduced from best available copy.

DATE 11-15-66 SCALE	ELASTOMER STRAIN GAGE "BM 2" UNIAXIAL, MULTI-ELEMENT MODULE	
DRAWN BY L. S. GUILLOT		
DESIGNED BY E. ANDERSON	DEPARTMENT OF STRUCTURAL RESEARCH	DRAWING NUMBER
CHECKED BY J. MICHIE	SOUTHWEST RESEARCH INSTITUTE	03-1043-04-108
APPROVED BY	SAN ANTONIO, TEXAS	



FABRICATION SEQUENCE:

a. CAST BASIC UNIT A WITH CAPILLARIES AND RESERVOIRS

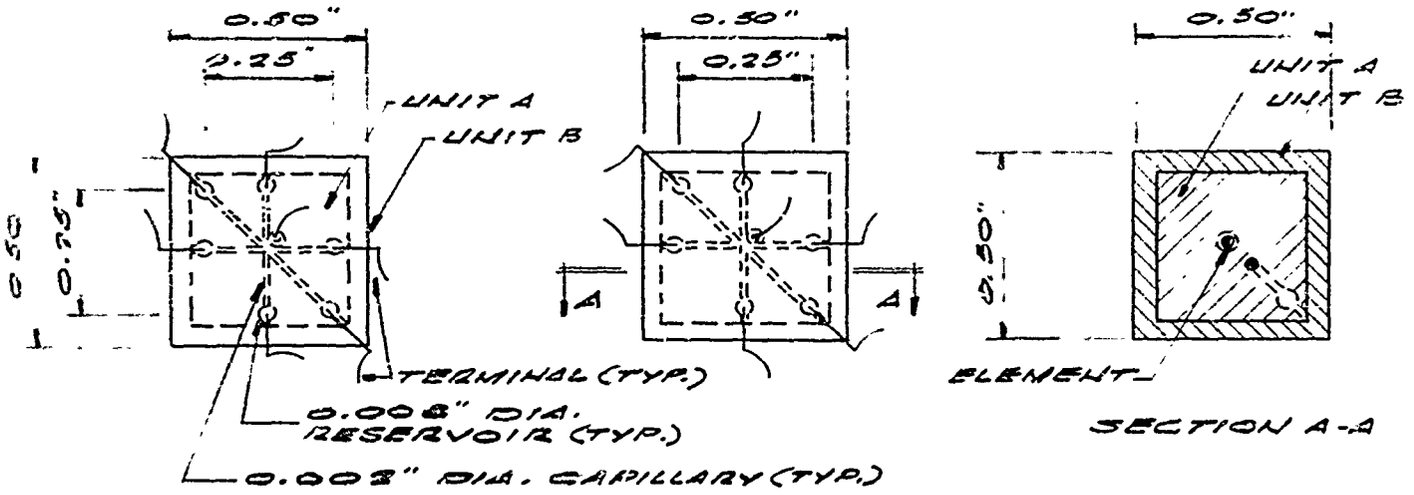
b. FILL CAPILLARIES & RESERVOIRS WITH ELEMENT FLUID AND INSERT TERMINAL WIRES

c. ENCAPSULATE UNIT A IN ELASTOMER UNIT B TO SEAL FLUID ELEMENTS AND SECURE TERMINAL WIRES

MATERIALS:

1. GAGE BODY - POLYURETHANE
2. ELEMENT FLUID - MERCURY ALLOY (TL-IN-HG)
3. TERMINAL - 0.005" PLATINUM.

DATE 11-15-66 SCALE	ELASTOMER STRAIN GAGE "BM 3" UNIAXIAL, MULTI-ELEMENT MODULE	
DRAWN BY L. E. GUILLOT		
DESIGNED BY E. ANDERSON	DEPARTMENT OF STRUCTURAL RESEARCH	DRAWING NUMBER
CHECKED BY J. MICHIE	SOUTHWEST RESEARCH INSTITUTE	03-1043-04-109
APPROVED BY	SAN ANTONIO. TEXAS	



FABRICATION SEQUENCE:

a. CAST BASIC UNIT A WITH CAPILLARIES & RESERVOIRS

b. FILL CAPILLARIES & RESERVOIRS WITH ELEMENT FLUID AND INSERT TERMINAL WIRES

c. ENCAPSULATE UNIT A IN ELASTOMER UNIT B TO SEAL FLUID ELEMENTS AND TO SECURE TERMINALS.

MATERIALS:

1. GAGE BODY - POLURETHANE
2. ELECTRICALLY CONDUCTIVE FLUID - MERCURY ALLOY (TL-IN-HG)
3. TERMINALS - 0.005" PLATINUM

DATE 11-16-66 SCALE	ELASTOMER STRAIN GAGE "T1" ORTHOGONAL MODULE	
DRAWN BY L. S. GUILLOT		
DESIGNED BY E. ANDERSON	DEPARTMENT OF STRUCTURAL RESEARCH	DRAWING NUMBER
CHECKED BY J. MICH	SOUTHWEST RESEARCH INSTITUTE	03-1043-04-110
APPROVED BY	SAN ANTONIO, TEXAS	

APPENDIX C

CHRONOLOGY OF ELASTOMER GAGE DEVELOPMENT MILESTONES

APPENDIX C

CHRONOLOGY OF ELASTOMER GAGE DEVELOPMENT MILESTONES

February 1961	Formulated concept of the conductive pigment impregnated elastomer which would sense deformations by means of resistance change.
April 1962	Constructed and tested gage element composed of aluminum powder dispersed in a polyurethane matrix. Element was nonconductive.
June 1962	Conceived, constructed and successfully tested first liquid metal element elastomer strain gage. The device was 6 in. long, 0.1875 in. OD, 0.015 in. ID, and filled with mercury.
October 1962	The elastomer gage body was altered to a rectangular cross section of 1/8 in. by 1/4 in. with a smaller diameter (6 mils) and shorter element capillary (0.5 to 1.0 in.). Also, cylindrical enlargements at the capillary ends were made to permit more stable electrical contact between the conductive liquid and the terminals. A strain module, consisting of a cube with elements perpendicular to each face, was fabricated.
October 1964	Began utilizing mercury alloy (Hg-In-Th) as the conductive fluid in lieu of pure mercury.

July 1965	Miniatruized elastomer gage. Principal changes were made in the gage body thickness (reduced to 0.018 in.) and the shape of the fluid reservoirs (from a cylindrical to a spherical configuration). Element capillaries were 4 to 6 mils in diameter.
September 1965	Constructed multielement, uniaxial gage. The device, having overall physical dimensions unchanged from previous gages, contained four parallel capillaries which were connected in series by means of buses. With an element diameter of 4 mils, the gage nominal resistance was quadrupled that of the single element configuration.
October 1965	Constructed and tested gage with a single element of 1.7-mil diameter.
January 1966	Fabricated cubical strain module with four elements of 2-mil diameter. Three of the four elements were orthogonal and had a 0.250-in. gage length. The cube had a 0 375-in. side dimension.
July 1966	Began fabricating gages with the terminal wires inserted into the reservoir cavities from a direction perpendicular to the gage's axis. This modification generally increased the strain range of a device to the point of gage body rupture.

August 1966 Altered multicapillary gage design by intersecting appropriate element reservoirs and thus eliminated the need for wire buses.

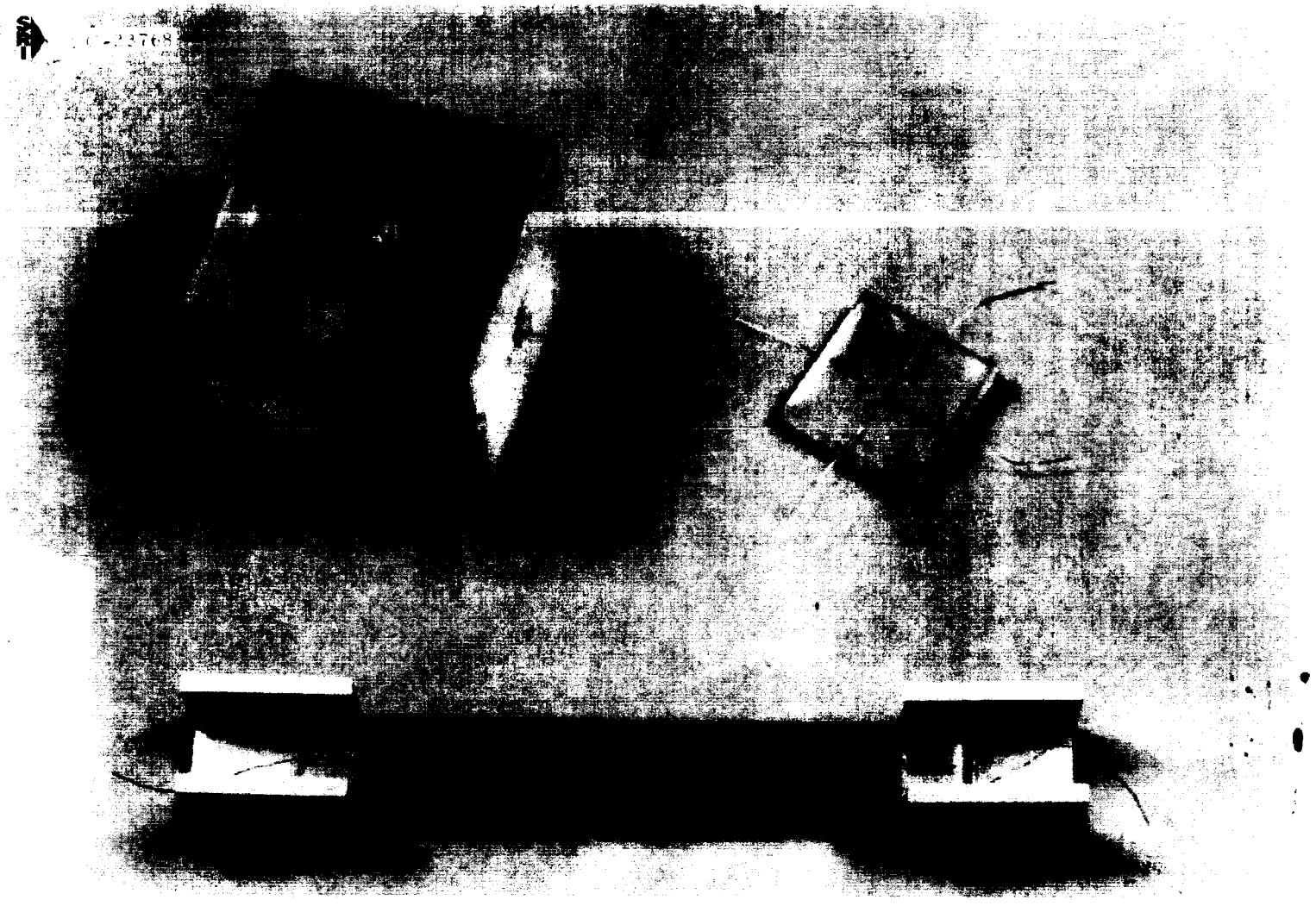


FIGURE 1. ELASTOMER GAGE PHOTOPYRIS

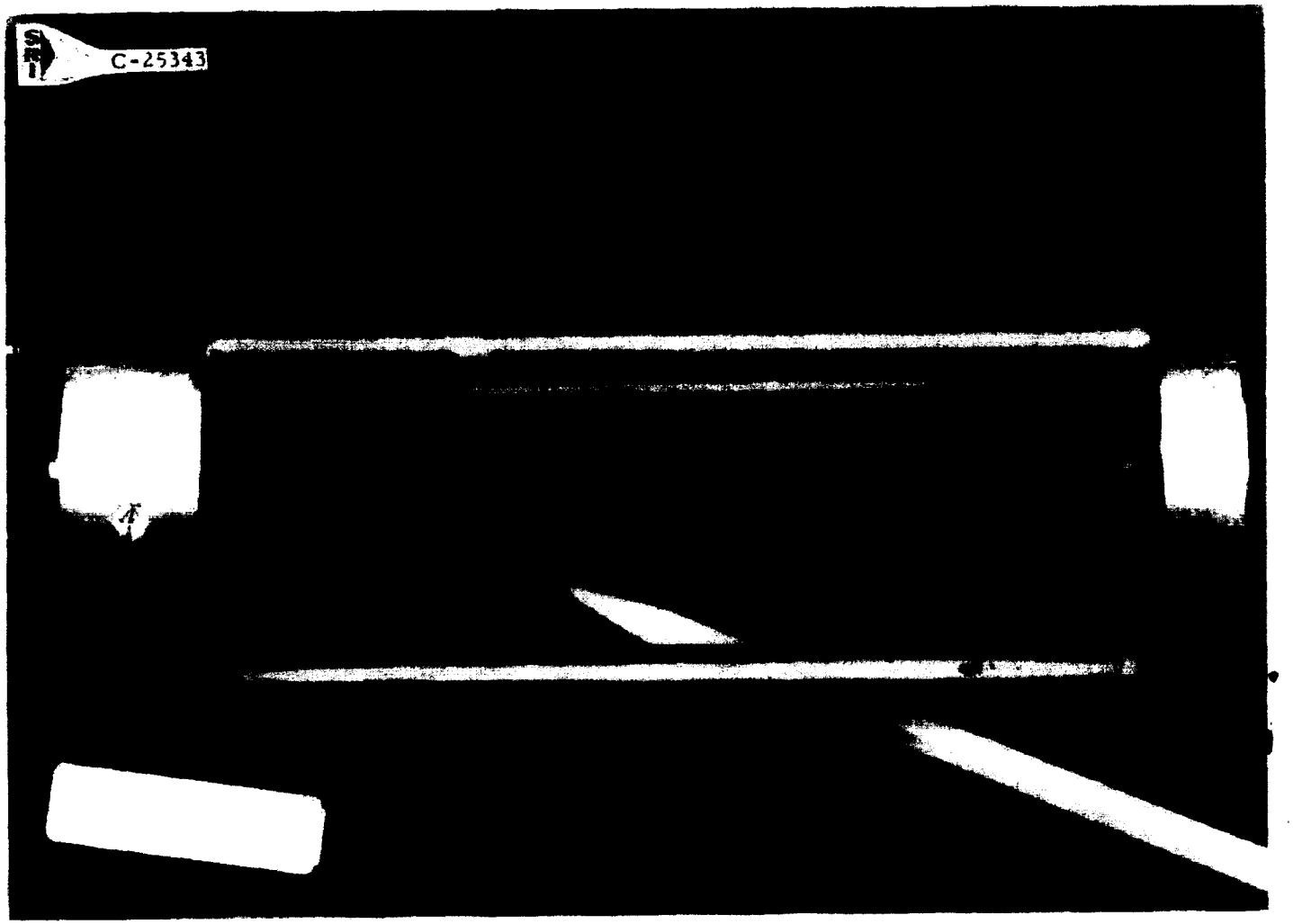
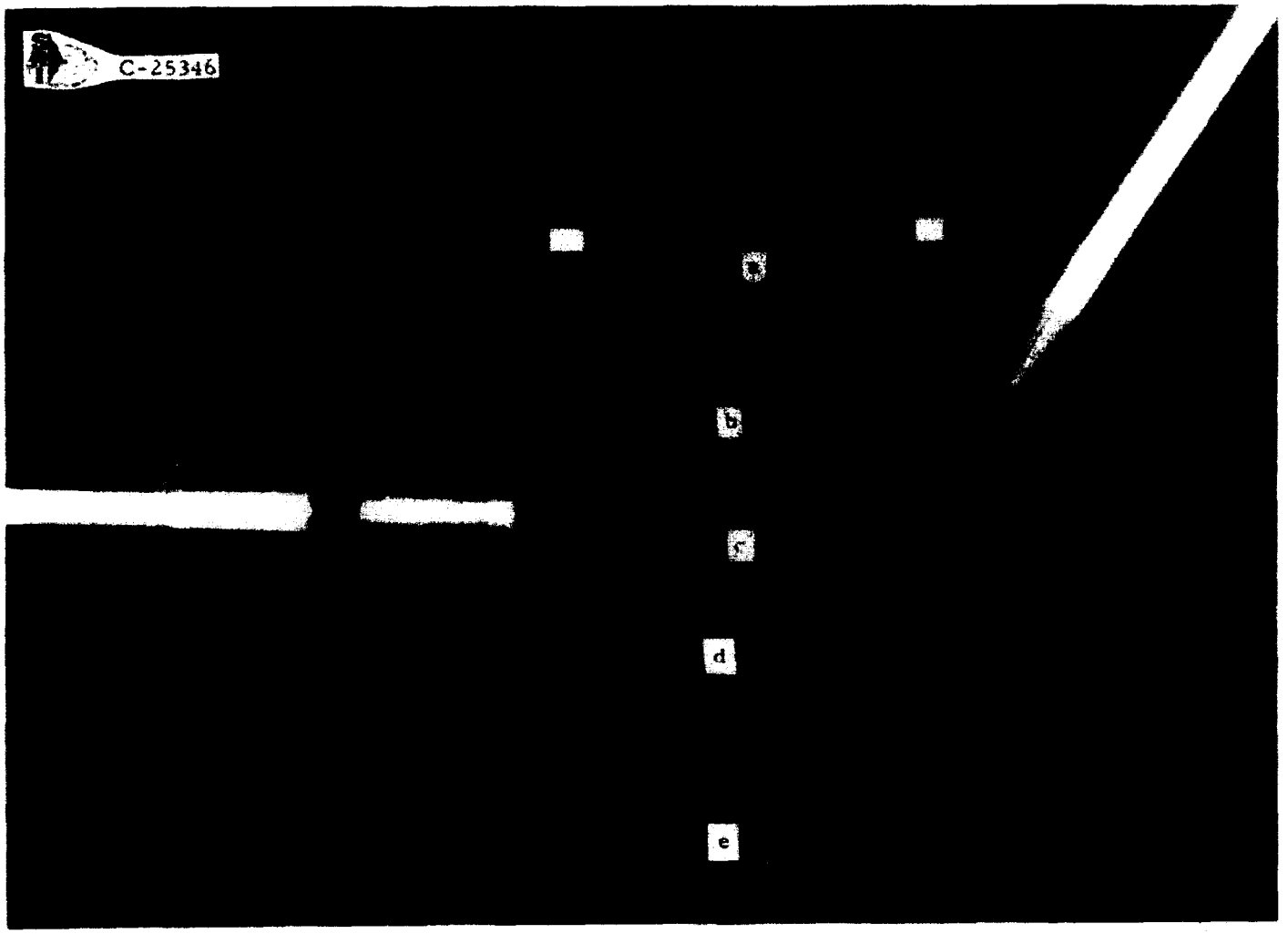


FIGURE 4. FINISH FOR APPLICATION OF PLASMA SPRAY MOLYBDENUM FILAMENTS



[illegible] ELASTOMER [illegible] VARIOUS [illegible]

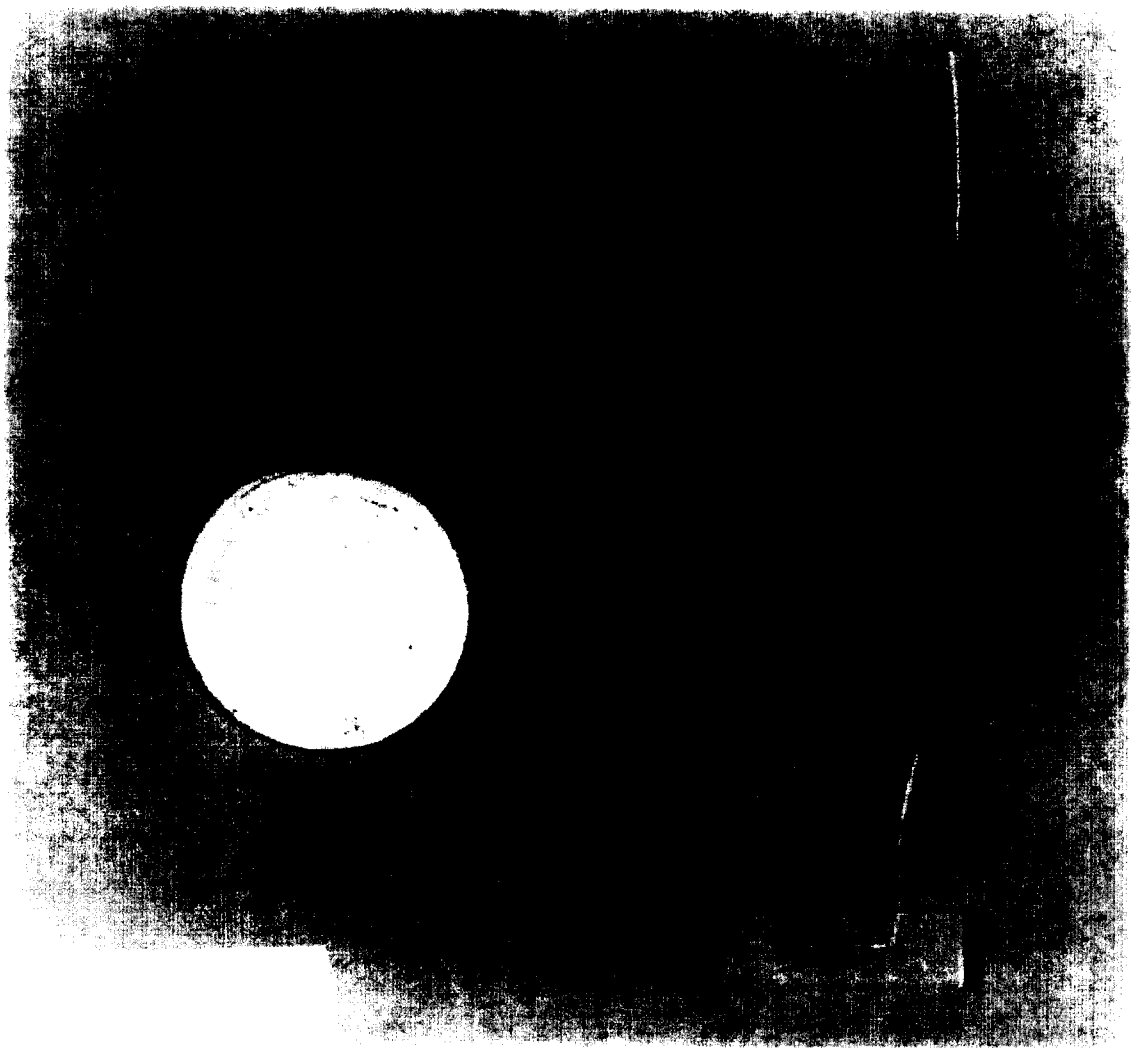


FIGURE [illegible] [illegible] ELEMENT ELASTOMER GAGES

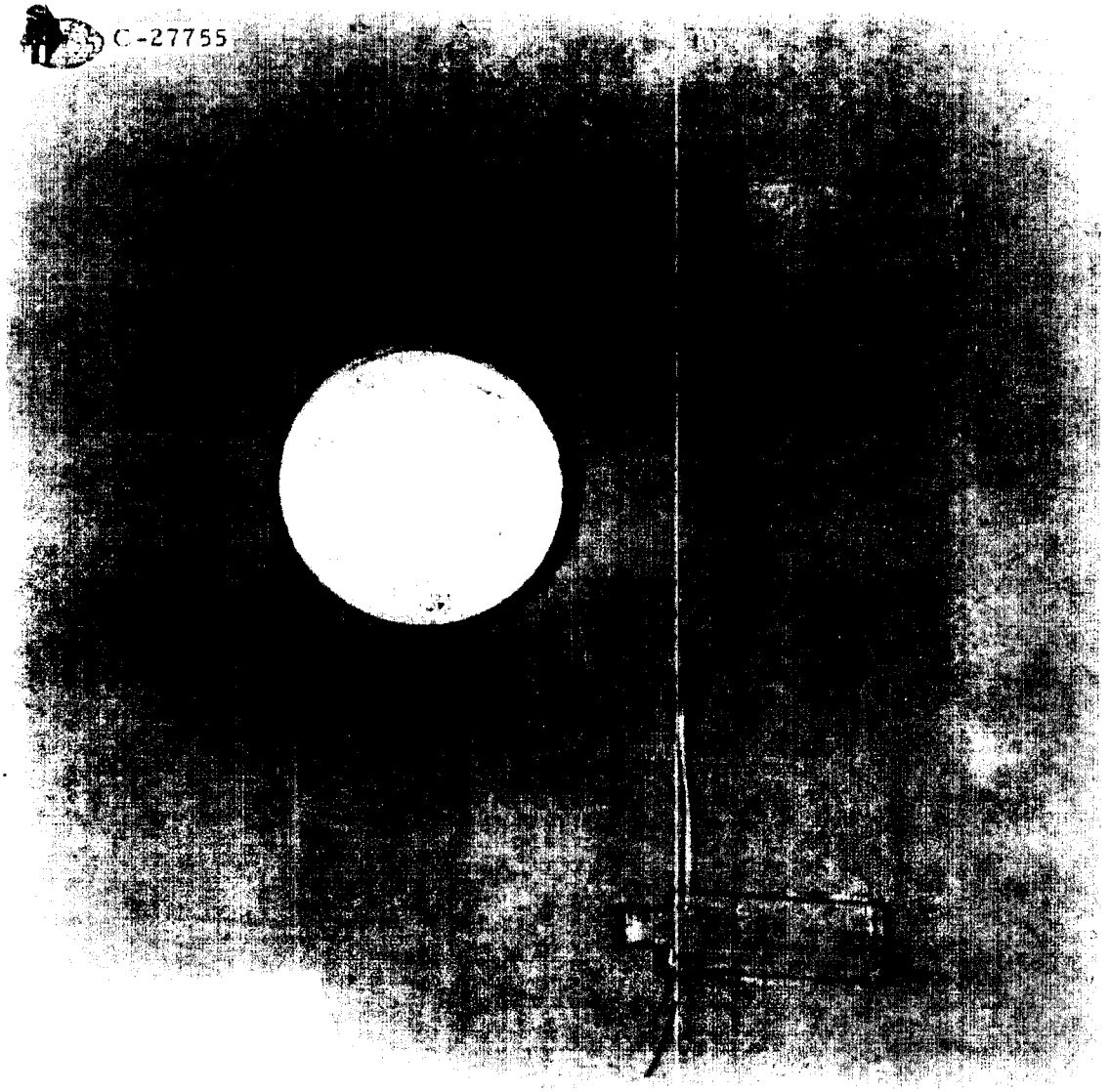


FIGURE [illegible] IELEMENT ELASTOMER GAGES

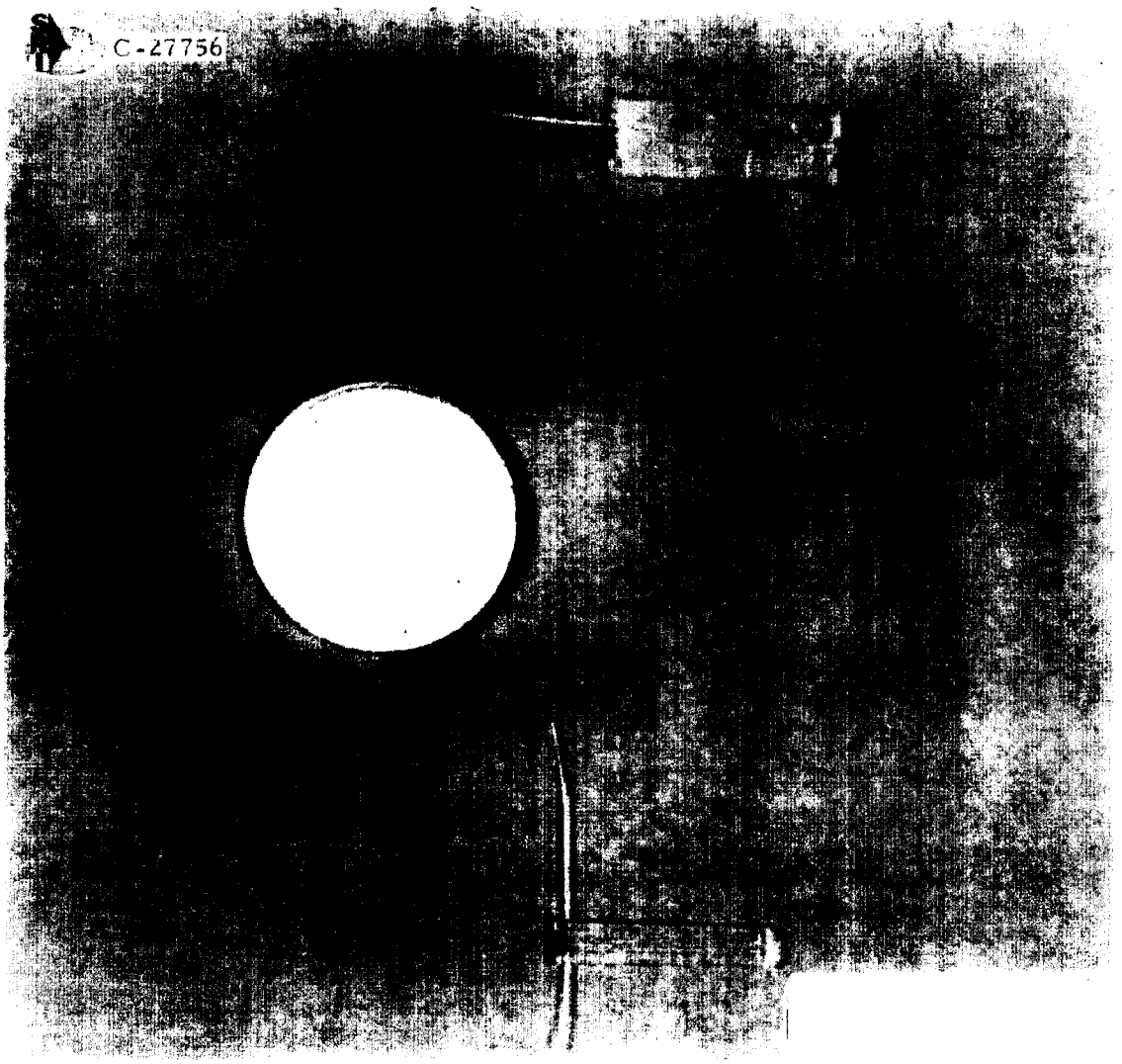


FIGURE 8. [illegible]HELEMENT ELASTOMER GAGES

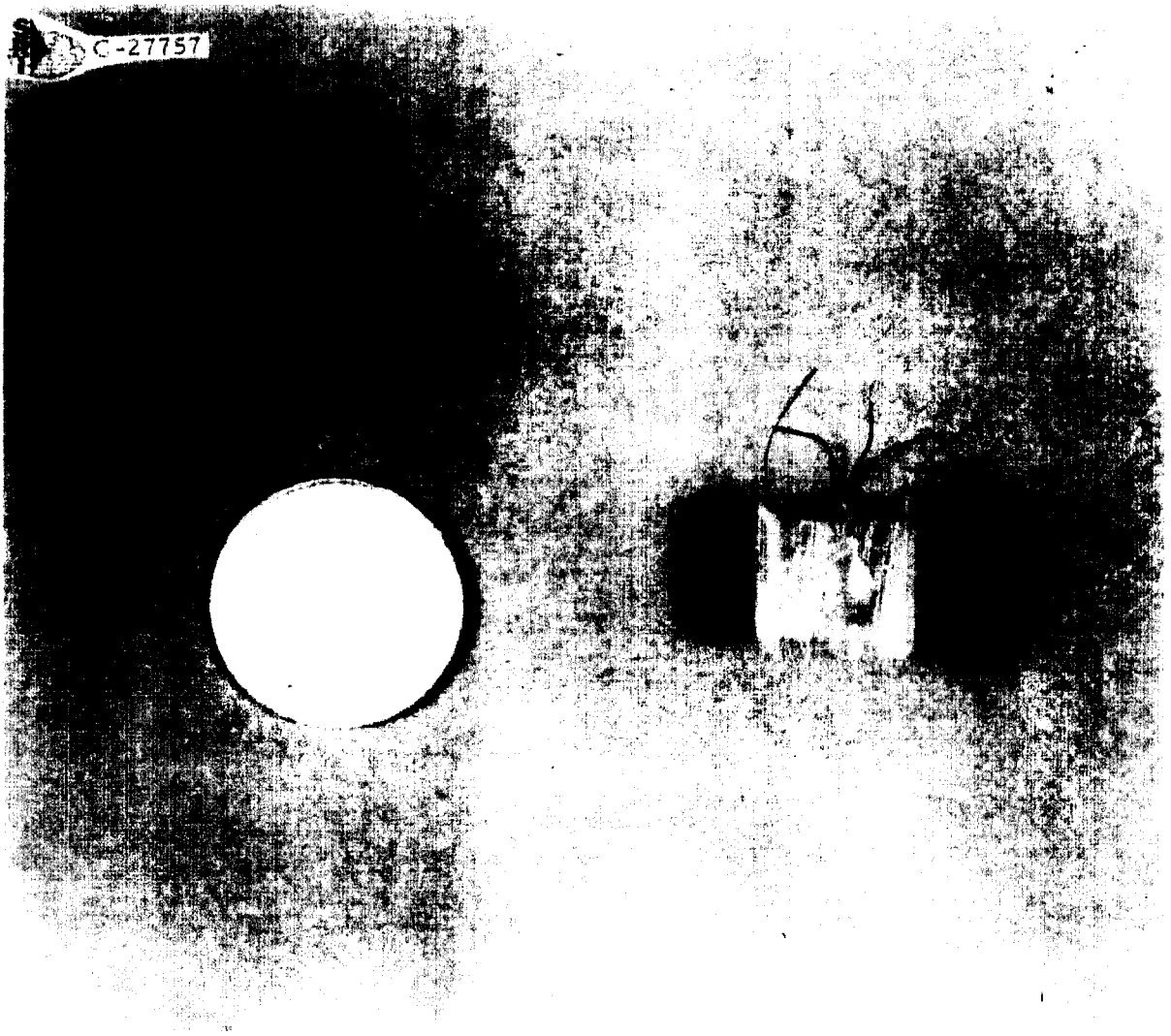
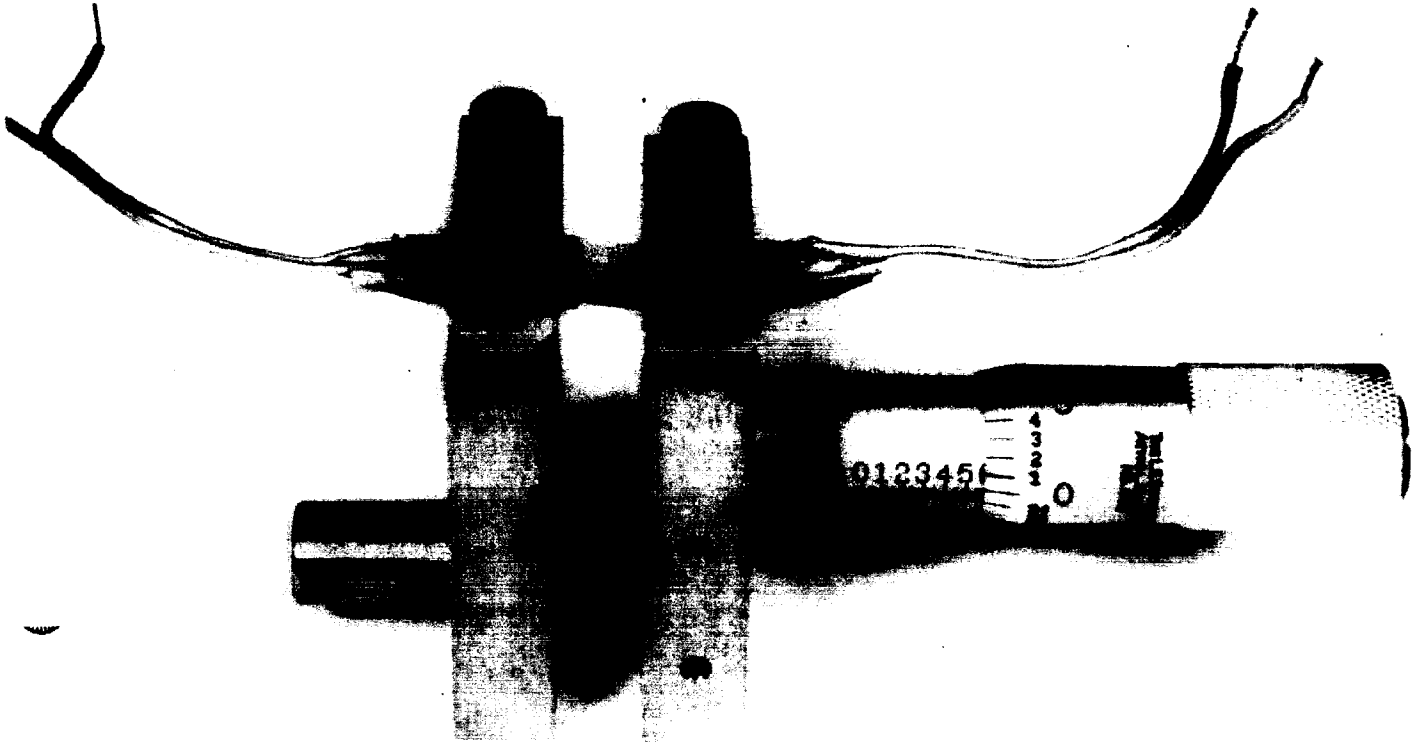


FIGURE 9. TRIELEMENT, ELASTOMER STRAIN MODULE



C-23389

FIGURE 17. CALIBRATION FIXTURE FOR "H" MODEL GAGES