NATIONAL BUREAU OF STANDARDS REPORT

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A STRAIN STANDARD FOR USE TO 3000 °F (1650 °C)

Technical Report

to

AF Flight Dynamics Laboratory
Air Force Systems Command
Order No. F33615-67-M-5005

U.S. DEPARTMENT OF COMMERCE

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A STRAIN STANDARD FOR USE TO 3000 °F (1650 °C)

by

R. L. Bloss, J. T. Trumbo, C. H. Melton and J. S. Steel
Engineering Mechanics Section
Mechanics Division
Institute for Basic Standards

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Foreword

There is a growing need for structural materials and configurations that will withstand significant forces while being subject to adverse environments, including very high and rapidly changing temperatures and large thermal gradients. Assigned missions and the need for efficient use of materials dictate the use of structures having the lowest possible weight. A knowledge of the properties of materials and the behavior of structural configurations under conditions encountered in actual use is therefore required.

Strain is one of the important parameters that must be measured to determine structural capabilities. To obtain meaningful results, the response of strain gages to hostile environments must be known. Operating temperatures approaching 3000 °F (1650 °C) and heating rates of 100 °F (55 °C) per second are predicted for the near future. A laboratory standard is needed for determining the capability of remote reading strain gages to function under these conditions.

The development of such a standard was supported by the Air Force Flight Dynamics Laboratory, Air Force Systems Command under Project 1347, Structural Testing of Flight Vechicles, Task 134702, Measurement of Structural Response.
Mr. James L. Mullineaux FDTE, provided the technical coordination.

L. K. Irwin, Chief
Engineering Mechanics Section

E. C. Lloyd, Acting Chief
Mechanics Division

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ABSTRACT

An extensometer for use as a laboratory standard at temperatures up to 3000 °F (1650 °C) was designed. This extensometer was to operate in normal atmosphere under static and transient mechanical and thermal conditions, including intense thermal radiation. A prototype system, extensometer and indicating unit, was constructed. Static tests at temperatures up to 1500 °F (815 °C) and dynamic tests to temperatures above 2500 °F (1390 °C) were conducted. The results of these tests show that the system has a range of at least 0.085 inch (2.2 mm), has a resolution of 10^{-5} inch, is linear to within about 0.1 percent of range, and has a random error of about 2×10^{-5} inch. The results indicate that the extensometer could probably be used at temperatures approaching 3000 °F (1650 °C) although it was not tested under these conditions. The design of the extensometer and indicator, materials used, description of components, methods of fabrication and assembly, and testing procedures are given.

Key words: Design, elevated temperature, extensometer, laboratory standard, performance, strain standard, transient temperature.

1. INTRODUCTION

The continuing requirements for structural materials and components to operate at elevated temperatures often exceed the capabilities of existing strain measuring devices to function in the service environments. The development of elevated temperature strain gages has been hampered by the lack of a reliable reference for use in evaluating improved or new concepts, devices and materials.

Although remote reading strain gages have been evaluated at temperatures as high as 1500 °F (815 °C)[1]*, such testing has been hampered by lack of a reliable laboratory strain standard capable of operating at high temperatures. This report describes an extensometer that has been developed for use at temperatures up to 3000 °F (1650 °C) and heating rates approaching 100 deg F (55 deg C) per second. Results are given for tests conducted at temperatures from 75 °F (24 °C) to above 2500 °F (1390 °C). Also, descriptions of components and procedures used in construction and assembly are given.

2. DESIGN OF EXTENSOMETER SYSTEM

2.1 General Criteria

The objective of this work was to develop and demonstrate a prototype system by which local, thermally and mechanically induced strains applied to remote reading strain gages can be measured at temperatures up to 3000 °F (1650 °C). The target performance requirements were as follows:

1. Measurement strain range of not less than $2(10)^{-3}$ (0.2 percent) at 3000 °F (1650 °C) exclusive of thermal strains.

2. Accuracy of 0.5 percent or better.

3. Strain resolution of 10^{-5} or 0.1 percent of range, whichever is larger.

4. Operate satisfactorily after repeated exposures to 3000 °F (1650 °C) for periods up to 30 minutes.

5. Meet the requirements for range, accuracy and resolution stated above while exposed to heating rates up to 100 deg F (55 deg C) per second at temperatures up to 3000 °F (1650 °C).

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*Numbers in brackets refer to the references at the end of the report.

A capacitive displacement sensor was chosen for the extensometer after a study of several types of devices that appeared to be applicable. The proposed high temperature extensometer system was described conceptually in an earlier report [2] and is shown in Figure 1. As the work progressed, some modifications were necessary. The final configuration is shown in Figures 2 and 5 with principal changes as described below.

(1) A reflective (silver) tube was inserted between the two tubes of the extensometer body. It was found that reflective coatings placed on the tubes did not provide the necessary protection after exposure to the more severe thermal environments.

(2) The fixed gage point was moved to the opposite side of the movable gage point from the sensor. This placed the sensor in a position to receive better cooling and permitted better attachment of the fixed gage point to the extensometer body.

(3) Thermocouples were mounted at various points within the extensometer to permit monitoring of critical temperatures so that testing could be terminated in case of danger of destruction of the device.

(4) Some of the materials were changed because of availability, to provide a lower coefficient of thermal expansion, and to make the parts compatible over a wide temperature range.

2.2 Capacitive Displacement Sensor

A capacitive displacement sensor was designed and constructed for this extensometer because it could be made small enough to allow good cooling in a device of reasonable size, should be reasonably linear over a major part of its range, would require very little force to operate, and could be used with relatively simple external instrumentation.

The type of capacitance unit chosen, shown schematically in Figure 3, is a three terminal device. The effective area of the capacitor depends upon the position of the sliding grid relative to the stationary grids. Over the center portion of the range, where edge effects would be minimal, the capacitance can be expected to be a nearly linear function of the grid position. The mechanical range of such a device is determined by the length of openings in the grids. The total capacitance, hence sensitivity, can be increased by the use of multiple openings in the movable grids. It should also be noted that multiple openings tend to improve performance by averaging the effect of minor variations in the individual openings.

The capacitive transducer used with the extensometer has three active sections. The active capacitor plates are separated by the stationary grids which have sufficient clearance between them to prevent binding of the sliding grid. Tantalum strips were placed between the stationary grids to provide proper spacing. The minimum practical spacing was used to increase the capacitance of the unit and allow for the maximum passage of cooling air around the sensor.

Electrically, one capacitor plate is connected to the power source (oscillator) and the other capacitor plate is connected to the readout instrumentation. These connections are made with small, flexible coaxial cables. The stationary grids, sliding grid, capacitor shielding and coaxial cable shielding are connected to the common instrument ground.

In its final form the capacitance unit had dimensions of 2.0 x 0.35 x 0.025 inches (51 x 8.9 x 0.64 mm), spacing between the plates of 0.0065 inch (0.17 mm), and a capacitance range of 0.4 to 1.0 picofarad for the usable displacement of 0.085 inch (2.6 mm).

2.3 Extensometer Indicator

A unit was designed and assembled to provide direct readout for static extensions (or strain) and terminal connections for recording dynamic extensions (or strain). The indicator is a capacitance to voltage converter with output voltage varying linearly with capacitance. For convenience, the excitation source for the capacitive sensor, an oscillator, was assembled with the other components. A functional representation of the extensometer indicator is shown in Figure 4. As constructed, the extensometer indicator is small, portable and operates from a 115 volt, 60 Hz power source.

An operating frequency of about 1200 Hz was selected to avoid the harmonics often associated with 60 Hz and lower multiples of this frequency. Precise frequency control is not required for the proper operation of this type of sensor. Power for the readout circuits also comes from this oscillator through a rectifier. This reduces the effects of small variations in oscillator signal amplitude and avoids the problems associated with differences in two driving sources.

When static strains are measured, a galvanometer is connected to the output terminals, and the galvanometer is balanced to zero by adjusting the Kelvin-Varley divider. The zero adjust potentiometer provides the tare adjustments. The Kelvin-Varley circuit consists of a 10-position switch and a 10-turn potentiometer with a 1000 division dial. This provides a scale length of 10,000 divisions and hence a resolution of 1 part in 10,000. The sensitivity of the indicator can be adjusted by changing the value of R_{39} (see Figure 4) to accomodate larger or smaller ranges of the extension sensor.

To measure dynamic strain, the output terminals are connected to an oscillograph or other suitable recorder, and the Kelvin-Varley divider may be used for tare adjustments.

A more detailed description of the extensometer indicator, a circuit diagram, and a parts list are given in the Appendix.

3. SELECTION OF MATERIALS

The various materials used in this extensometer were chosen because of their availability, machineability, and the particular properties that were required.

The tubes for the body of the device are made of high purity silica glass (Vycor™)† . This material was selected because it was readily available in suitable sizes, is transparent to radiation of the wave length of interest, has a very low coefficient of thermal expansion, has a high melting point, and can be machined if reasonable care is taken.

The reflective tube was made of silver since it was primarily a radiation shield. Silver has a very high reflectivity, is easily formed in the annealed state, and is available in sheets of suitable size and thickness.

The parts that contact the specimens and are exposed to the most severe thermal environment were made of a high purity, fine grained alumina (Lucalox™). This material has a high melting point, good strength at high temperatures, low thermal conductivity, low coefficient of thermal expansion, and good resistance to thermal shock. It must be machined by special techniques, usually with diamond tools. A good finish can be obtained and close tolerances can be held.

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†Materials referred to in this report by trade names or trade marks are described more completely in a later section.

The various cements, epoxy and ceramic, were chosen for their ability to withstand temperatures, handling characteristics, and required curing temperatures.

Tantalum was used to maintain the spacing between the capacitor plates because of its low coefficient of thermal expansion. It was readily formed to the desired size by flattening wires of a slightly larger diameter. These spacers were critical items since the capacitance of the unit would vary greatly with changes in plate spacing.

The other materials used were generally chosen because they were readily available from local sources and were found to be satisfactory in preliminary tests.

4. AUXILLIARY EQUIPMENT

4.1 Mechanical Apparatus

In order to evaluate the extensometer, it was necessary to have a means of producing known displacements at the elevated temperatures. A system that could be adapted to produce both static and dynamic (periodic) displacements was deemed desirable. To meet these requirements, a system was assembled consisting of three parallel tubes of high purity alumina supported at the ends by flexures. Appropriate displacement generating devices could be used with this system. The outer tubes were held stationary, except for thermal expansion, by being held against a fixed support by a suitable spring. These tubes were connected at each end to assure rigidity and avoid relative motion. The center tube was free to move parallel to the other tubes. Side motion was restricted by the flexure supports. This center tube was held against a motion producing device by a suitable spring and pivoted connecting bar. Air could be passed through the tubes to provide cooling when desired. Figure 5 shows this system with a precision micrometer as a motion producing and measuring device. Figure 6 shows the system connected to an electrodynamic vibrator for dynamic tests.

The micrometer shown in Figure 5 is a Boeckeler Model 10-CR. It has a resolution of 10^{-5} inch and a repeatability of about 2×10^{-5} inch. This micrometer has a non-rotating spindle. The vibrator shown in Figure 6 is an MB Model C31. For this use it was powered by a special low frequency system. The usual operating frequency was one hertz with a double amplitude displacement of about 0.020 inch (0.51 mm).

4.2 Thermal Apparatus

In order to obtain the intense thermal radiation needed to produce the desired environment, the special furnace shown in Figures 6 and 7 was constructed. This furnace consists of a double walled aluminum cylinder, sealed at both ends, with ports to permit circulating cooling water between the walls. The cylinder has an inside diameter of 12 inches, (305 mm) an outer diameter of 14 inches, (356 mm) and a length of 10 inches (254 mm). The inner surface of the aluminum cylinder was coated with "Scotch" brand pressure sensitive gold reflective tape No. Y-9184. This was done to increase the reflectivity of the surface and to concentrate the radiation from the eighteen radiant heat lamps (General Electric type 1000T3CL) which are mounted on a 10 inch (254 mm) circle concentric with the aluminum cylinder. Each lamp is enclosed in a tube to permit passing air past the lamp to assist in keeping the lamp terminals cool. The ends of the lamps and their surrounding tubes were held by cement-asbestos board supports outside of the heated zone. The lamps are connected in a delta configuration to a three phase power supply. There are six lamps in each leg of the delta circuit. The controller for the power supply furnished a maximum voltage of about 440 volts and has a rating of 100 amperes per phase. The lamps are rated at 1000 watts per lamp at 250 volts. Current and voltage measurements made while operating at the maximum voltage of the controller showed that the maximum power input to the furnace was about 45 kilowatts.

During use, the ends of the furnace were insulated with Kaowool insulation to reduce convective losses from the furnace. This material is capable of withstanding temperatures of 2300 °F (1260 °C).

One of the more difficult problems was to measure the thermal environment within the furnace. Since the extensometer and the displacement devices were cooled, temperature measurements taken from these systems would not be indicative of a specimen under normal test conditions. In order to provide some indication of the thermal environment and to provide a control for static temperature tests up to 1500 °F (815 °C), special temperature sensing units were constructed. These units consisted of thermocouples sandwiched between wafers of high temperature ceramic. The ceramic wafers were made by mixing a pigment, lamp black, with a high temperature ceramic cement. Thin ceramic wafers were made by filling Teflon molds with the above mixture and allowing it to air dry at room temperature for 24 hours.

Fine wire, 0.010 inch (0.25 mm), chromel-alumel and platinum-platinum 10 percent rhodium thermocouples were placed between two of these wafers in a small additional amount of this ceramic mixture. This assembly was air dried as above. The thermocouple wires were attached by spotwelding to heavier wires of the same materials that passed through porcelain supporting tubes. The wafer assembly was attached to this tube with more of the cement mixture.

The final unit consisted of thermocouples in the center of a ceramic wafer having dimensions of 1.5 x 0.5 x 0.06 inches (38 x 13 x 1.5 mm). The pigment provided a high (though undetermined) emissivity. The size of the unit provided a small mass and large surface area. The output of the thermocouple was expected to be indicative of the temperature of a thin structure subjected to similar radiant heating.

Experience with these temperature sensors indicated that they provided only approximate temperature values above about 2000 °F (1090 °C). This was due to the apparent increase in electrical conductivity of the ceramic material and probable contamination of the thermocouple material. However, these temperature sensors were used over the full range of test to indicated temperatures of 2590 °F (1420 °C). It is probable that the indicated temperature was lower than the actual temperature of the wafer because of the above effects.

5. TESTING PROCEDURE

The extensometer was subjected to two types of tests. One type, referred to as static tests, involved maintaining a constant temperature while comparing the reading from the Kelvin-Varley circuit with displacements produced and measured by the micrometer (see Figure 6). The other type, referred to as dynamic tests, involved recording the output voltage from the readout circuit while the movable element of the extensometer was subjected to periodic displacements and transient or changing temperatures.

Except as noted in Table 1, air was passed through the extensometer while tests were being made. This air flow was to help keep the capacitive element cool. Although the thermocouple in the capacitive element was inoperative, the temperature of the inner Vycor tube was kept below 100 °F (38 °C). A suitable flow obtained with pressure drops of about 1.5 psi (10,300 N/m^2) through the outer Vycor tube and 3.5 psi (24,100 N/m^2) through the inner Vycor tube.

5.1 Static Tests

For the static tests the extensometer was assembled with the displacement generating and measuring system as shown in Figure 6. Care was taken to aline the extensometer properly and to provide suitable spring forces to hold it firmly onto the contact cylinder. A total force of about 2.2 lbf (9.8 N) was applied by low spring constant helical springs 0.2 lbf/in. (35 N/m) to the outer Vycor tube. The springs were located about 10 and 13 inches (254 and 330 mm) from the extensometer legs outside of the heated area. Flexible tubing was used to connect the Vycor tubes of the extensometer to the cooling air source. This tubing was supported by a flexible spring to minimize the force it imposed on the extensometer. The electrical leads were connected to the appropriate readout and monitoring instruments.

After the installation of the extensometer was complete, its performance was examined using the following program. After initial readings were recorded, the Kelvin-Varley circuit was changed a predetermined amount, usually 1000 divisions. This was for operational convenience rather than displacing the movable element of the extensometer preselected distances. Then, the movable element of the extensometer was displaced by adjusting the micrometer until a null was indicated by the galvanometer. Kelvin-Varley circuit and micrometer readings were recorded. These steps were repeated to cover the full range of displacement for which the extension indicator had been adjusted. This process was repeated until three sets of displacement versus indicator reading data were obtained. Tests were conducted at 75, 500, 1000 and 1500 °F (24, 260, 540 and 815 °C).

The temperatures referred to for these tests were measured with the ceramic encased thermocouples described previously.

The observed displacements from three similar sets of data were averaged and fitted to polynominals in displacement of degree 1, 2 and 3 using the method of least squares and a digital computer. Subroutines of the OMNITAB [3] program were used for the data reduction and to display some of the features of the resulting relationships. The information that was examined included the displacements computed from the curves represented by the polynominals, the deviations of the average experimental displacements from the fitted curve, estimates of the standard deviation of the experimental points from the fitted curve, and estimates of the standard deviation of the coefficients of the equation of the fitted curves.

A history of the static testing and repair of the extensometer is given in Table 1.

5.2 Dynamic Tests

The dynamic tests were conducted with the equipment shown in Figure 7. The extensometer was carefully mounted as described for the static tests. The output of the readout circuit was connected to one channel of a Sanborn Model 322 dual channel d-c amplifier-recorder. A ceramic encased thermocouple was connected to the other recorder channel through a Dana Model 3400 amplifier. The vibrator controller was set for the desired frequency and amplitude, usually 1 Hz and 0.020 in. (0.5 mm) peak to peak. With the recorder adjusted for suitable sensitivity and chart speed, power was applied to the furnace and the output of the extensometer was recorded as the system was exposed to the changing thermal environment. The amplitude and shape of the extensometer signal are indicative of the performance under these conditions.

6. RESULTS

6.1 Static Tests

The results of the static tests are summarized on Figures 8, 9, 10 and 11 and in Table 2. Comparisions between the fitted curves and the experimental data for one test can be made from the displacements given in Table 2. The third degree polynominal was clearly a better representation of the displacement versus indicator reading relationship than a straight line. Figure 8 is a plot of the indicator reading as a function of the observed displacement of 6 tests at various temperatures. Comparisions of the differences between observed displacements and calculated displacements for the six tests, Figures 9 and 10, show that third degree polynominals are good representations of the transfer functions for this extensometer-indicator system operating under static thermal and mechanical conditions up to 1500 °F (815 °C). The effect of temperature on the sensitivity of the extensometer is shown in Figure 11.

6.2 Dynamic Tests

The dynamic tests to which the extensometer was subjected are listed in Table 3. Eighteen of these tests were conducted to temperatures of 2000 °F (1090 °C) or more. The maximum indicated temperature during these tests was 2590 °F (1420 °C). During these tests the extensometer was subjected to radiant heating for periods of 1 to 14 minutes, and the indicated temperature was above 2000 °F (1090 °C) for more than 45 minutes and above 2500 °F (1370 °C) for about 15 minutes.

The test record for one of these tests is shown in Figure 12. The thermocouple signal indicates that the heating rate to 2000 °F (1090 °C) was in excess of 200 deg F (110 deg C) per second. The extensometer record clearly shows the characteristics of the driving mechanism. The change of magnitude of the extensometer signal during this test indicated a sensitivity change of about 2.5 percent from room temperature to 2530 °F (1390 °C). This is in good agreement with the results of the static tests. However, the average of the results of four tests at an indicated temperature of 2500 °F (1370 °C) gave a sensitivity change of less than one percent. The magnitude and shape of the records make precise determinations of sensitivity changes difficult at best. Static tests were made at room temperature after dynamic tests 13 and 21. The sensitivity values from these tests were within 0.3 percent of the average room temperature sensitivity value. This indicates that being subjected to the high temperature, intense thermal radiation, and dynamic testing did not affect the extensometer adversely.

7. DISCUSSION

7.1 Static Tests

The results of the static tests at temperatures to 1500 °F (815 °C) indicate that the design goals were probably met although actual test data was not taken for temperatures up to 3000 °F (1650 °C). For a displacement range up to 0.085 inches (2.2 mm), the non-linearity was about 0.1 percent, see Figure 9, and there is a region of about 0.025 inches (0.64 mm) indicated where a straight line can be fitted with deviations less than 2×10^{-5} inches (5×10^{-4} mm).

If better representations of the transfer functions are required, third degree curves are indicated by Table 2 and Figure 10 where the deviations of the averaged experimental data from fitted polynominals of degree 3 were usually within 2×10^{-5} inches (5×10^{-4} mm).

It should be noted that the resolution of the extension indicator and the micrometer are each about 10^{-5} inches (2.5×10^{-4} mm). Thus, scatter of experimental data of about 2×10^{-5} inches (5×10^{-4} mm) probably should be considered to be within the limits of random experimental errors.

The sensitivity factors shown on Figure 11 are the slopes of the fitted first degree polynominals. The linear decrease in sensitivity with increasing temperature was probably due to thermal expansion and conduction of heat through the Lucalox legs which extend into the furnace to contact specimens. If required, some improvement in this characteristic may be possible by redesign.

The large apparent spread of sensitivity values from room temperature tests is mostly due to including the results from one test (No. 19). If the value for this test (8.477) is ignored, the average value would be 8.570 and the extreme values from eight tests would differ from this by 0.35 and 0.39 percent.

7.2 Dynamic Tests

The results of the dynamic tests and of the static tests that were made after dynamic testing clearly indicate that the extensometer is capable of operating at high temperatures and under conditions of intense thermal radiation. Although an accurate determination of the change of sensitivity at the higher temperatures could not be made due to the quality and sensitivity of the test record, an extrapolation from the values obtained in static tests would seem to be reasonable.

The performance at the highest test temperature used also indicates that the system should be usable at higher temperatures, probably to 3000 °F (1650 °C). The close agreement of results from static tests conducted before and after the dynamic tests further confirm the ability of the extensometer to operate in extreme thermal environments without degrading its performance.

7.3 Temperature Measurements

As mentioned previously, the measurement of the thermal environment to which the extensometer was exposed was a difficult problem. The output of the ceramic encased thermocouple was recorded and might be indicative of the temperature of a thin structure of high emissivity under similar heating conditions. At temperatures above 2000 °F (1090 °C) the indications from these thermocouples were approximate because of the conductivity of the ceramic and possible contamination of the thermocouple elements. An increase in conductivity of the ceramic would tend to act as a shunt and reduce the output voltage at the terminals of the thermocouple resulting in a lower indicated temperature than actually existed at the location of the temperature sensing junction.

The thermal input to the extensometer might be estimated from the power input to the furnace and estimated efficiencies, reflectivities, and losses. Based upon a maximum power input to the furnace of 45 kilowatts and an assumed efficiency of 75 percent, it is estimated that the extensometer was subjected to a thermal flux of up to 80 BTU/(ft^2 sec) during these tests.

7.4 Extensometer Mounting

Although it was beyond the scope of this investigation, the method of mounting the extensometer onto the test equipment was of concern and presented some difficulty. The experience also indicated that mounting extensometers for use in high temperature environments may be a significant problem.

The method of mounting used with the present extensometer involved cementing cylinders of high temperature material to the test apparatus. Vee grooves in the legs of the extensometer were placed on these cylinders. The results obtained indicate that this was a satisfactory system for the particular test conditions encountered. However, considerable care was required to insure that the cylinders were parallel. It should also be noted that an exact gage length would be difficult to determine, and cementing to some materials may not be practical. The use of sharp points or knife edges on the extensometer may be possible in some instances, but problems with maintaining sharp edges and possible damage to materials, especially coate refractory specimens, would seem to preclude this technique for genera use. Considerable attention to this detail may be required.

8. CONCLUSIONS

A prototype extensometer and indicator was designed for use in measuring strains on specimens subjected to static and transient temperatures up to 3000 °F (1650 °C). The extensometer was constructed and operated satisfactorily at static temperatures to 1500 °F (815 °C) and indicated transient temperatures to above 2500 °F (1370 °C). The extension sensor is of the three terminal variable capacitor type with a displacement range of at least 0.085 inches (2.2 mm). The extensometer indicator utilizes a Kelvin-Varley circuit with a resolution of 1 part in 10,000 for static operation and oscillograph recorders for dynamic operation.

The test results indicate that the extensometer system is probably capable of meeting the design goals. However, tests were not made at the maximum desired temperature of 3000 °F (1650 °C), and records obtained at temperatures above 1500 °F (815 °C) could not be readily analyzed to insure that the design goals were met.

9. REFERENCES

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Table 1 - Static Testing and Repair of Extensometer

Date	Static test No.	Test temperature* °F	Comments
11-7 and 11-8-67	01 and 02	75	Preliminary check out of extensometer.
11-9 to 11-13-67	-	-	Fixed leg was repaired several times.
11-14 to 11-26-67	03 to 06	75	There was evidence of extreme backlash in the extensometer. It was completely disassembled, repaired and reassembled. The outer Vycor tube was broken and repaired during this process. Preliminary tests were made. and read out instrumentation was adjusted.
11-27-67	07	75	Functional check of repaired extensometer.
11-29-67	08 and 09	75	Poor results were traced to a loose alumina tube in the displacement transfer mechanism.
11-30-67	10	75	Functional check following modification of hold down method and adjustment of read out instrumentation.
12-1-67	11	75	Satisfactory test without air passing through the extensometer**.
12-1-67	12	75	Satisfactory test.

continued

Table 1 - Continued

Date	Static test No.	Test temperature* °F	Comments
12-4 and 12-6-67	13 and 14	500 75	Poor results traced to moveable leg not contacting transfer mechanism properly.
12-6-67	15	75	Satisfactory test.
12-6-67	16	500	Satisfactory test followed by functional check at 75 °F.
12-7-67	17	1000	Satisfactory test followed by functional check at 75 °F.
12-7-67	18	1500	Poor results. Fixed leg was loose after test.
12-10-67	-	-	Fixed leg was repaired.
12-11-67	19	75	Satisfactory test without air passing through the extensometer. Hold down system was adjusted before test.
12-11-67	20	75	Satisfactory test.
12-12 to 12-18-67	-	-	A static evaluation test at 2000 °F was attempted. This test temperature was maintained for about 3 hours. Satisfactory results were not obtained. After this test the fixed leg was loose. The fixed leg was modified to include a dowel in the joint between the leg and foot.
12-19-67	21	75	Functional check of repaired extensometer.

continued

Table 1 - Continued

Date	Static test No.	Test temperature* °F	Comments
12-20-67	22	75	Satisfactory test.
12-20-67	23	500	Satisfactory test.
12-20-67	24	1000	Satisfactory test.
12-21 to 12-29-67	-	2000	Attempted static tests at 2000 °F resulted in repeated failure of the joint in the fixed leg. The dowel was modified and the leg was reassembled. A new fixed leg was designed. eliminating the troublesome joint, and its construction was started.
1-2-68	25	75	Satisfactory test.
1-2-68	26	75	Satisfactory test.
1-2-68	27	1500	Satisfactory test.
1-2-68	28	1500	Satisfactory test.
1-5 to 1-12-68	-	-	Dynamic tests Nos. 1 through 11 (see Table 2).
1-13 to 1-16-68	-	-	Examination after poor results from dynamic and static tests showed that the fixed leg was again loose. The newly designed leg was installed.

continued

Table 1 - Continued

Date	Static test No.	Test temperature* °F	Comments
1-18-68	29	75	Satisfactory test.
1-19 to 1-26-68	-	-	Dynamic tests Nos. 12 through 21 (see Table 2).
1-29-68	30	75	Satisfactory test. This was a final test to check room tempeature performance after all elevated temperature and dynamic testing was complete.

*Unless otherwise noted, tests at temperatures above 75 °F involved holding the test temperature constant for about 90 minutes.

**Unless otherwise noted, all tests were made with air passing through the extensometer.

Table 2 - Results of Static Test No. 29. Test Temperature = 75 °F (24 °C)

Extensometer indicator reading	Average displacement[(a)]	Calculated displacement from polynominals of various degrees		
		Degree 1	Degree 2	Degree 3
div	in.	in.	in.	in.
0	0×10^{-6}	-7×10^{-6}	-39×10^{-6}	6×10^{-6}
1000	8,570	8,582	8,569	8,560
2000	17,143	17,171	17,173	17,140
3000	25,730	25,760	25,773	25,738
4000	34,347	34,349	34,368	34,347
5000	42,960	42,938	42,960	42,960
6000	51,567	51,528	51,547	51,568
7000	60,167	60,117	60,130	60,164
8000	68,743	68,706	68,708	68,741
9000	77,290	77,295	77,282	77,291
10000	85,807	85,884	85,852	85,807
Estimate of standard deviation (σ)		39	35	6

[(a)] Results of three test runs were averaged.

Table 3 - Dynamic Tests

Test No.	Duration	Maximum indicated temperature
	min	°F
1	3	1500
2	3	1500
3	3	1500
4	3	2500
5	3	2500
6	3	2500
7	2	2300
8	2	2500
9	3	2500
10	3	2500
11	3	2500
12	2	2500
13	2	2000
14	1	2590
15	4	2500
16	4	2500
17	4	2500
18	4	2500
19	>14	2000
20	> 6	2000
21	>10	2250

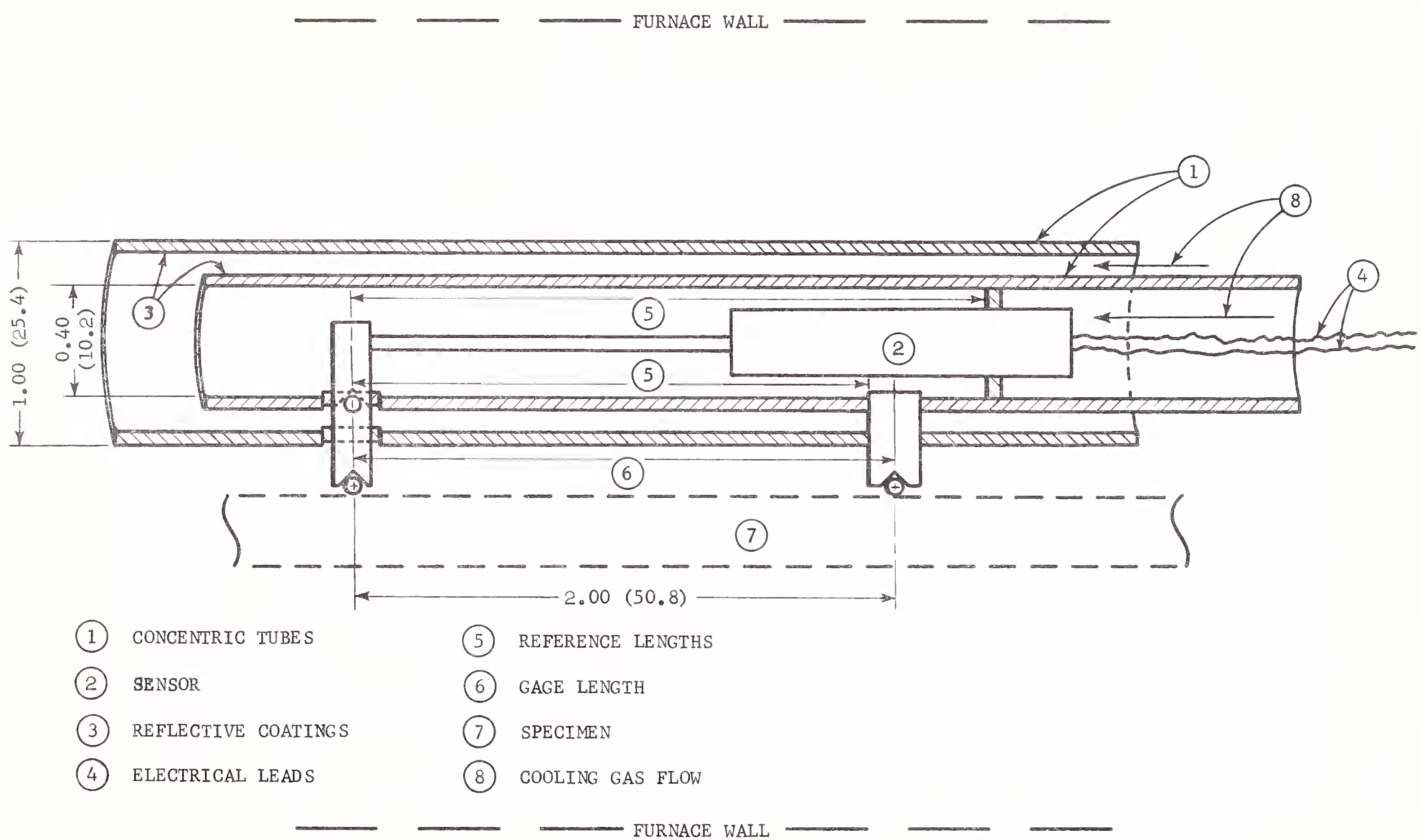

Figure 1. Schematic of extensometer system (sectional view). Dimensions are shown in inches and parenthetically in millimeters unless indicated otherwise.

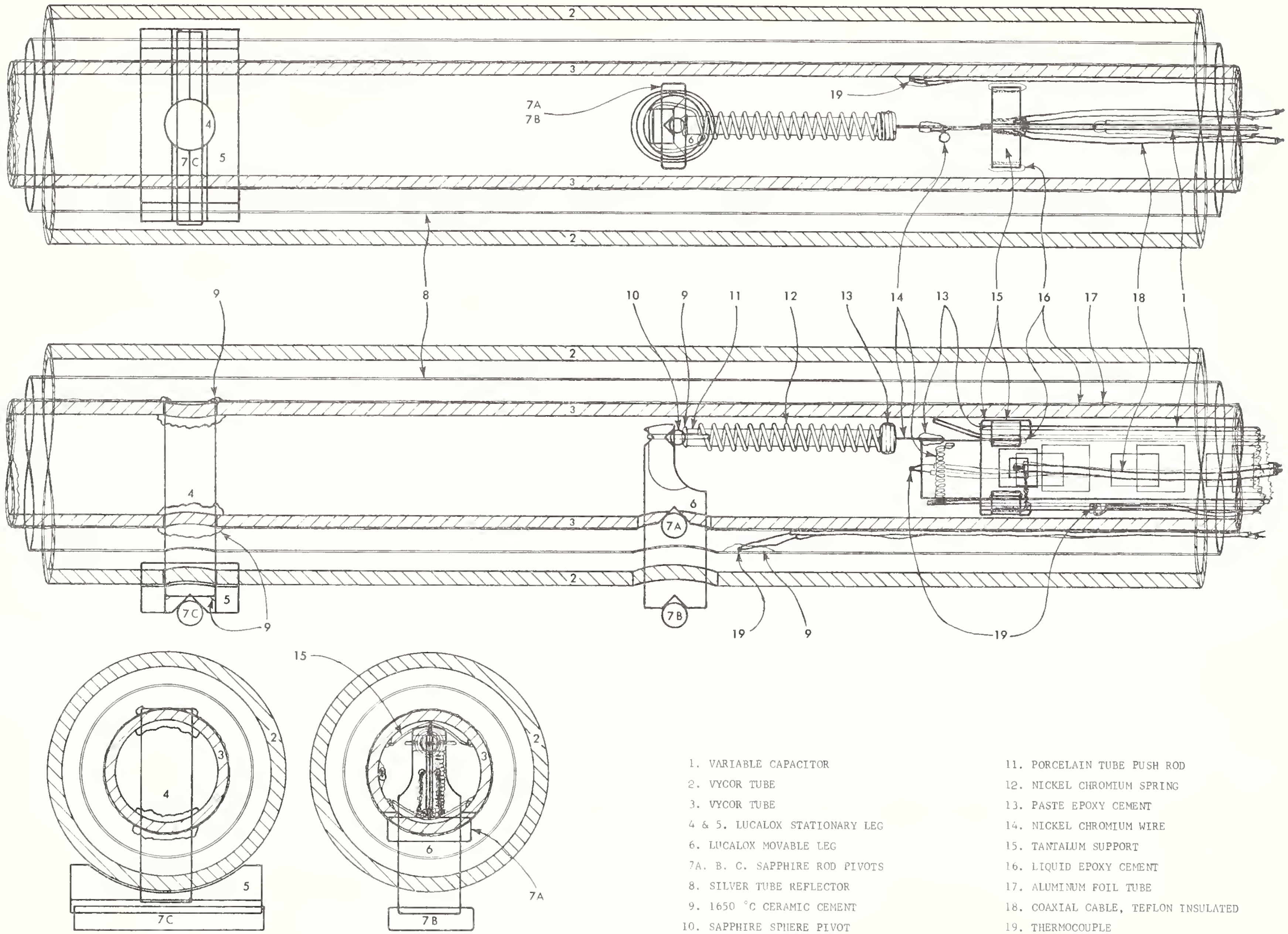

Figure 2. Sectional views of the assembled extensometer

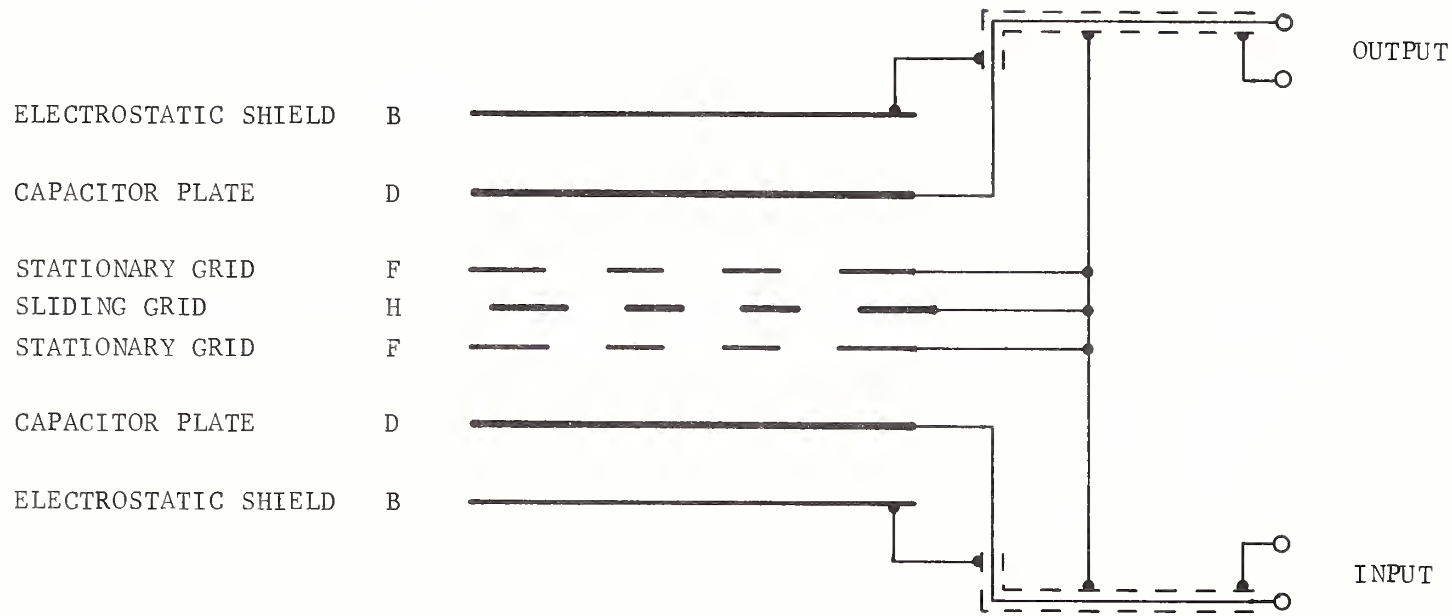

Figure 3. Schematic of the variable capacitor

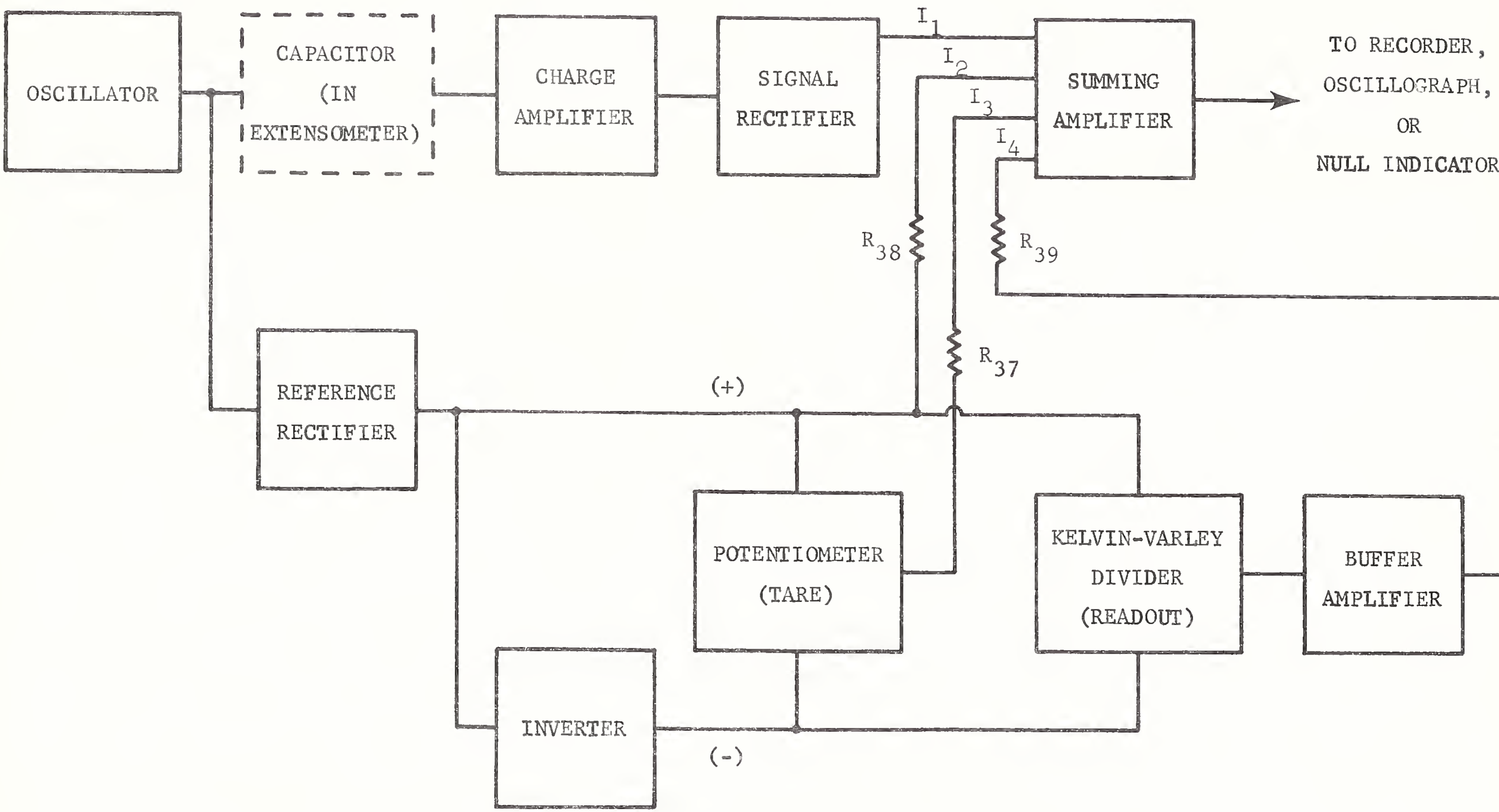

Figure 4. Functional diagram of the extensometer indicator

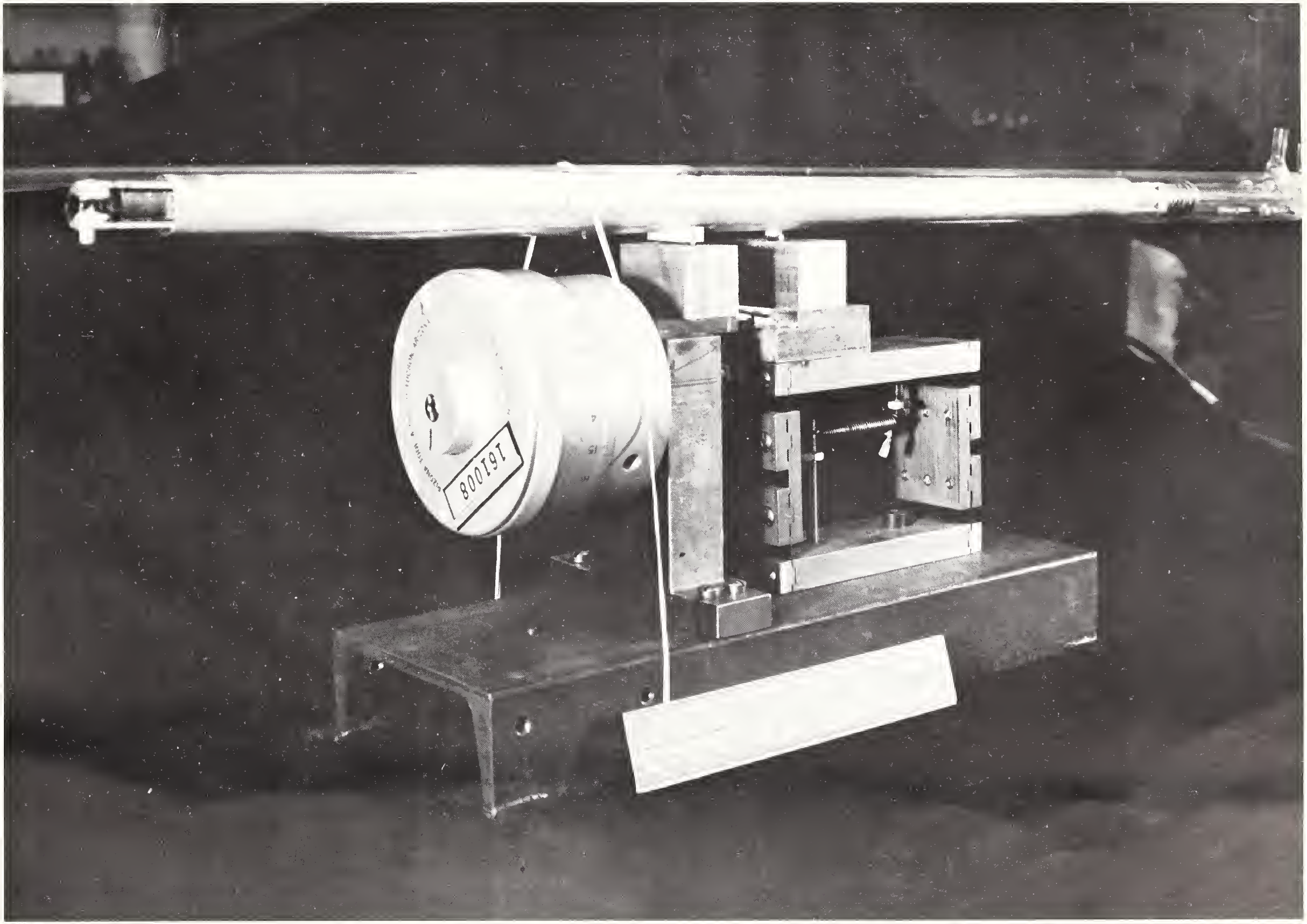

Figure 5. Closeup view of the extensometer on a calibrator

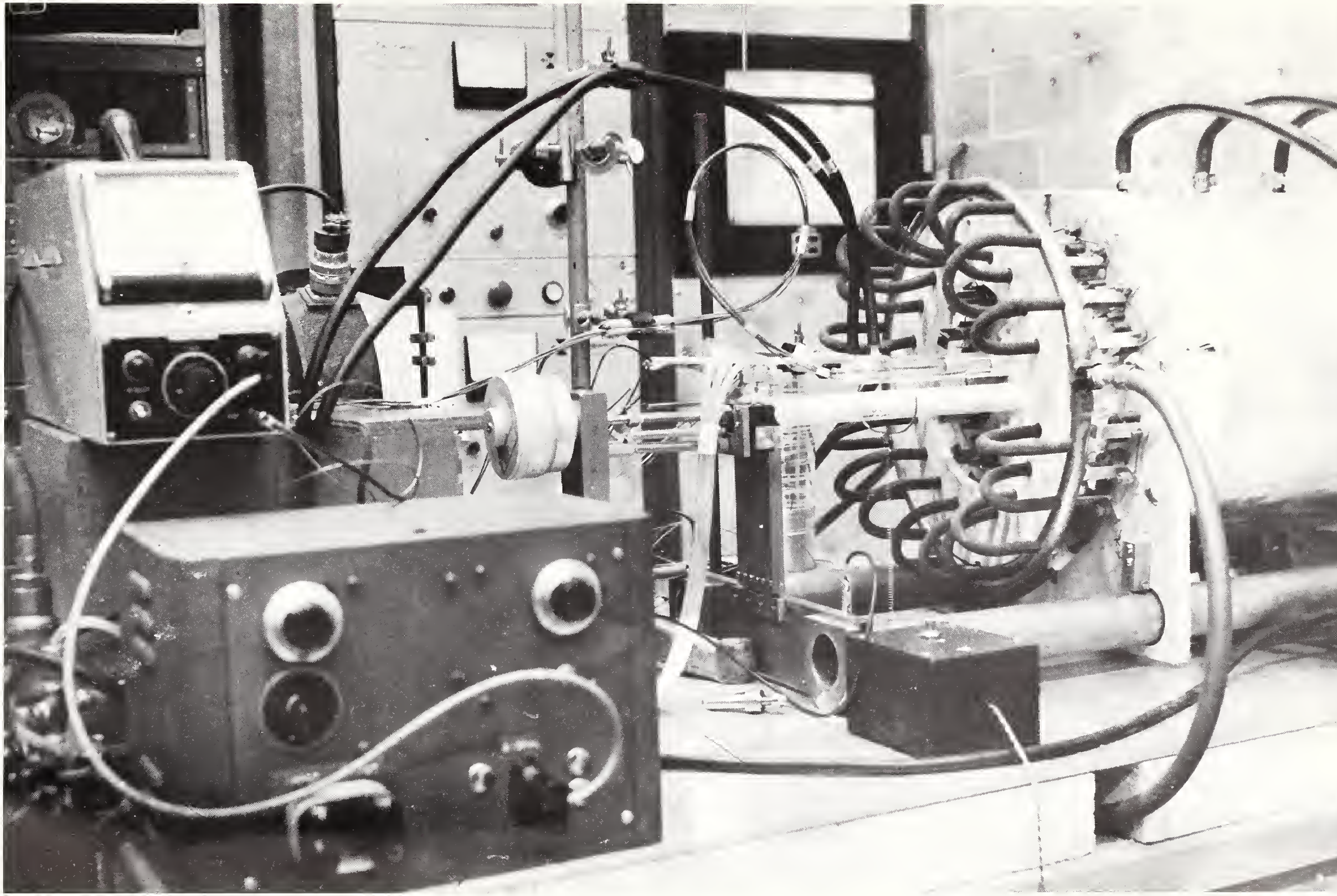

Figure 6. Laboratory setup for static tests

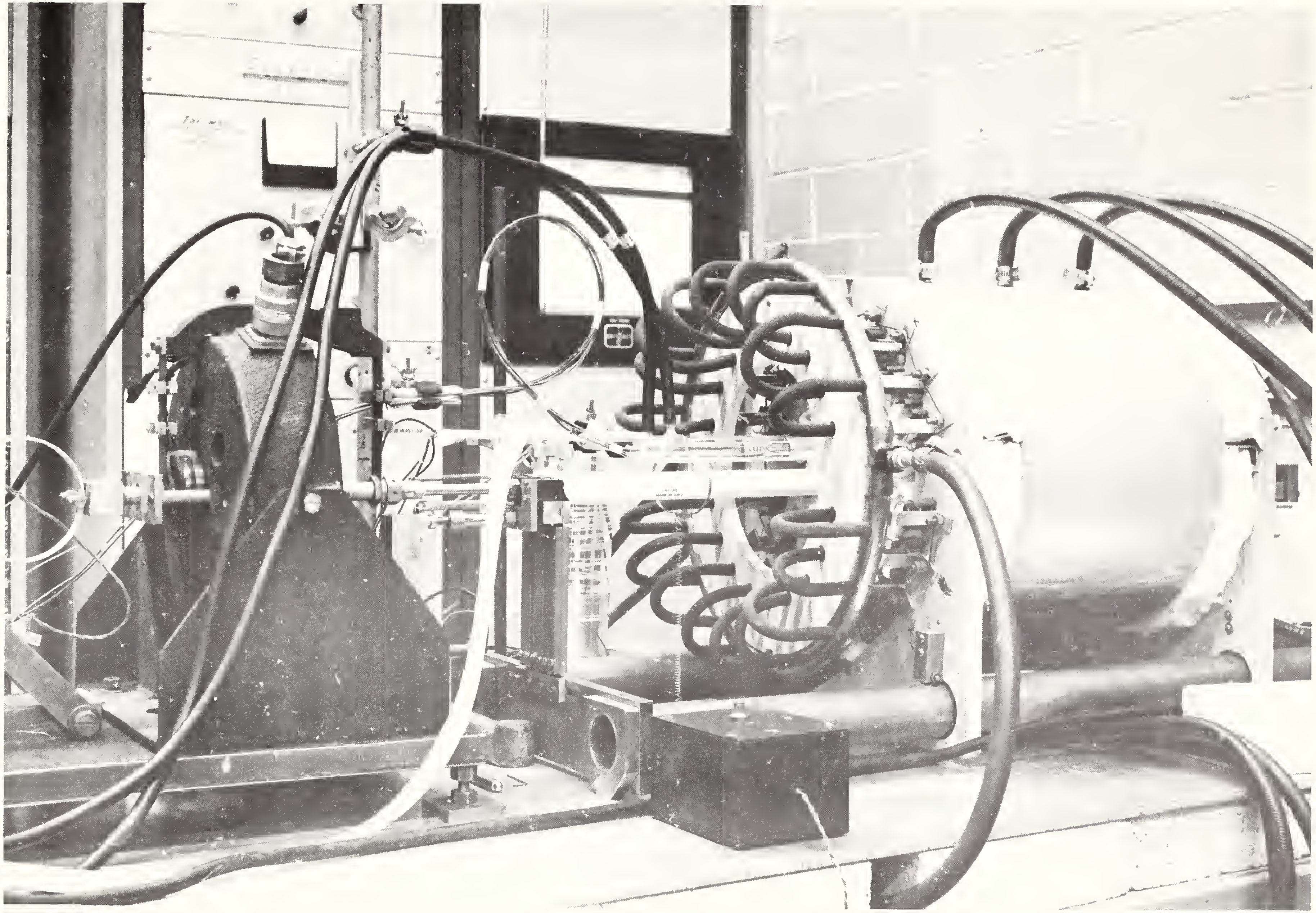

Figure 7. Laboratory setup for dynamic tests

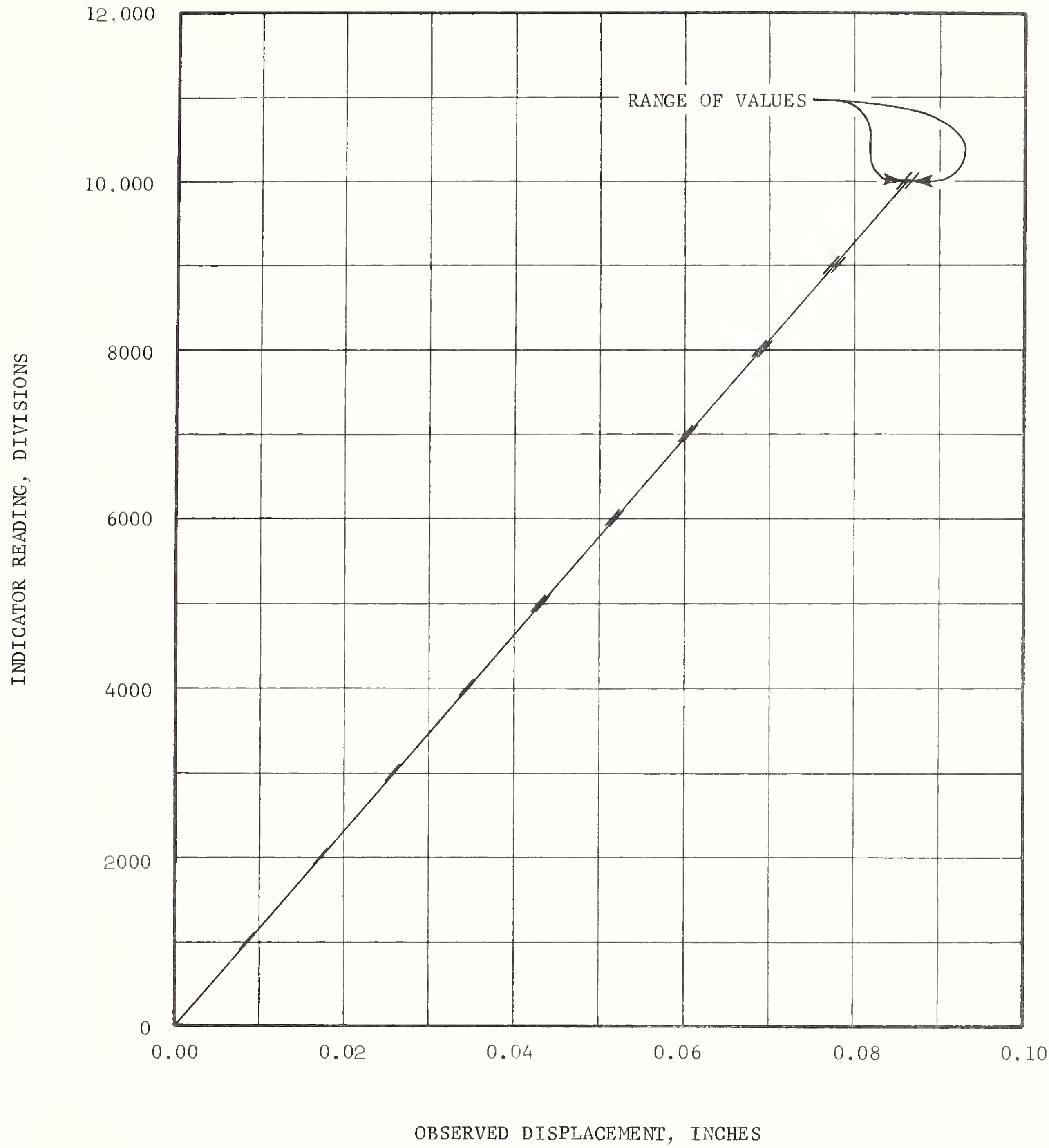

Figure 8. Performance of extensometer at 75, 500, 1000, and 1500 °F

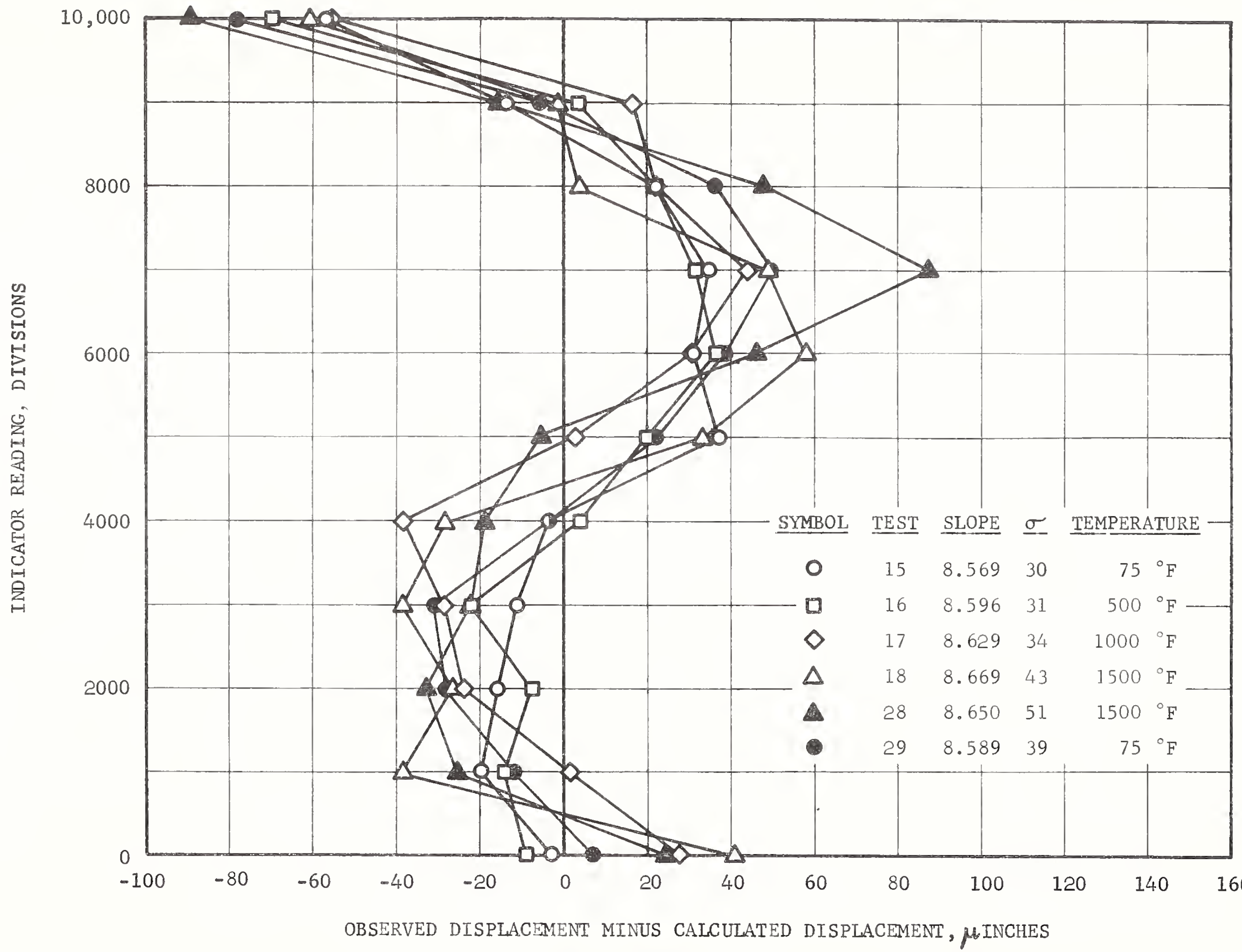

Figure 9. Deviations of experimental displacements from displacements calculated using fitted polynomials of degree 1

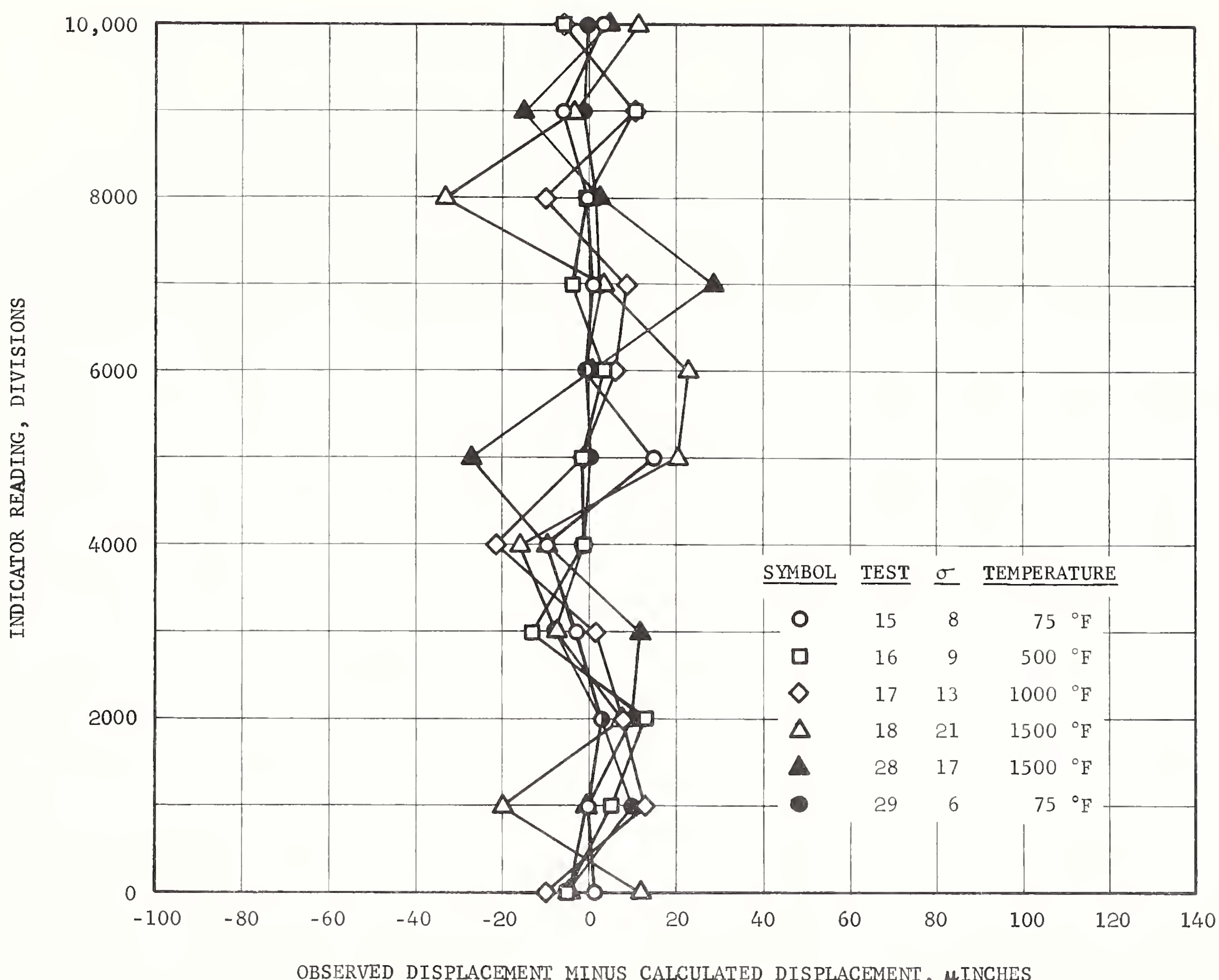

Figure 10. Deviations of experimental displacements from displacements calculated using fitted polynomials of degree 3

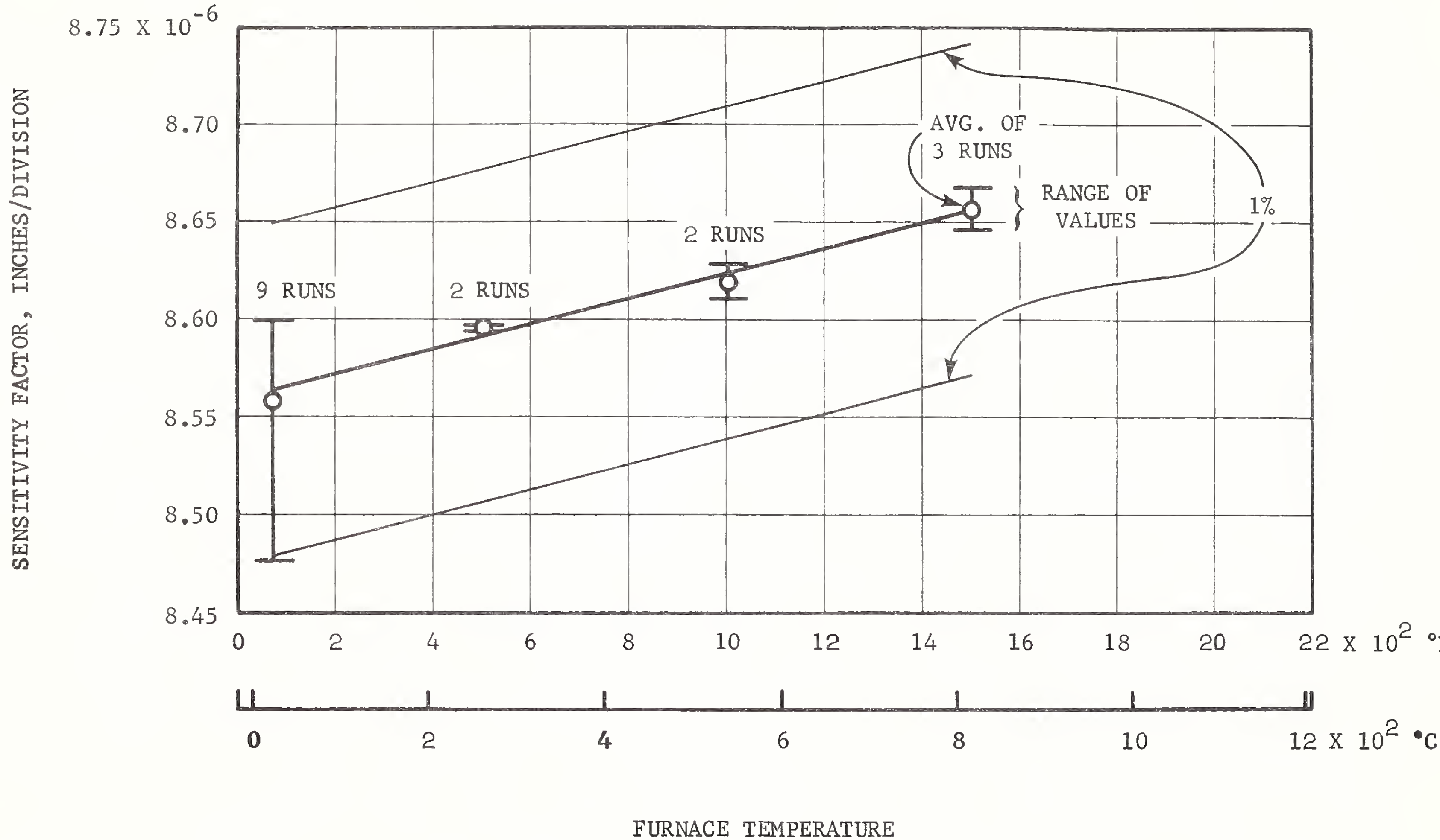

Figure 11. Effect of temperature on extensometer sensitivity

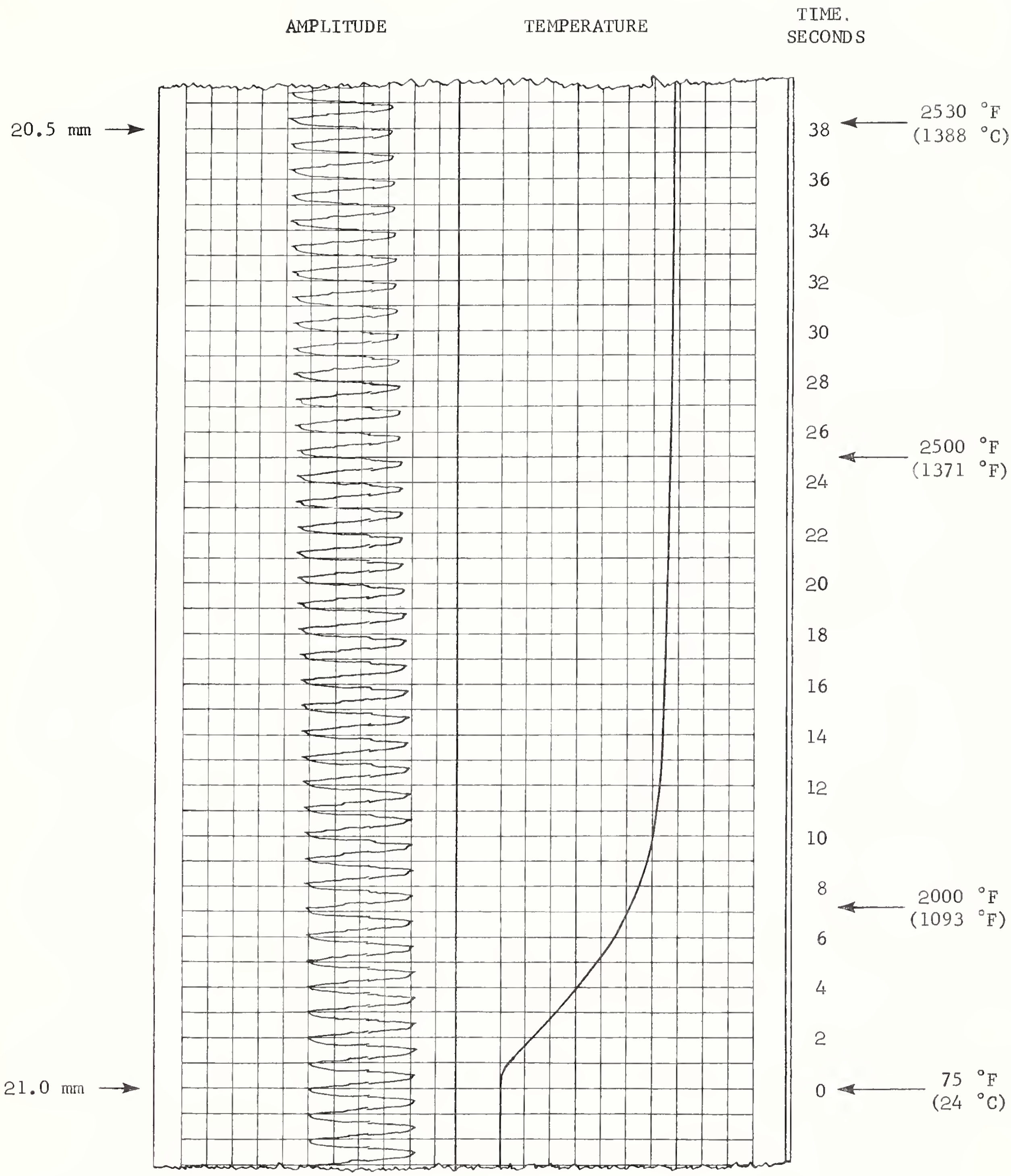

Figure 12. Facsimile of records showing dynamic response of extensometer while temperature increased to 2530 °F (1388 °C)

APPENDIX

The success of the extensometer system was largely due to care and skill with which the machining and assembly was done. Since it is expected that any future extensometers of this design would be specially built items, the procedures and techniques that were used are described in the following sections.

A1 Machining

The machining of the materials used in the construction of the extensometer required the use of a number of techniques such as grinding, ultrasonic machining (cavitron), glassblowing, and silver soldering.

A1.1 Lucalox Parts

The various parts made from Lucalox were produced by conventional machining and grinding methods. Since this material is a dense, fine grained, hard alumina; diamond cutting and grinding techniques were used exclusively.

A1.2 Vycor Parts

Holes in the Vycor tubing were produced with a cavitron in order to minimize chipping around the edges. Sharp notches in the edges were avoided by flame polishing the sides of the holes following the cavitron operation. Small tubes for attaching air lines to the Vycor tubes were installed using usual glass blowing techniques.

A1.3 Sapphire Parts

Sapphire rods were obtained in the proper diameter. These rods were then cut to the desired length using diamond cutting tools. The sapphire ball was purchased with the desired size.

A1.4 Silver Tube

The silver reflective tube was made from sheet material. The sheet was annealed at 1400 °F (760 °C) for 5 minutes, formed around a Vycor mandrel, and joined by silver soldering.

A1.5 Capacitor Parts

In general, the parts for the capacitive unit were made with hand tools, frequently using toolmaker's and binocular microscopes to lay out and observe the work. Since the construction of this unit was considered to be most critical, a detailed description of the construction steps is given in the following paragraphs. The various parts of the capacitor unit are shown in Figure A1 and the materials used are listed in Table A1. Its position in the extensometer and the method of connecting it to related parts are shown in Figure 2.

Spring steel was selected for the sliding grid and active plates, parts H and D of Figure A1, because this material is flat, the edges are parallel and smooth, and it was available in suitable widths and thicknesses. A toolmaker's microscope, a clamped stationary plastic triangle, and a pointed surgical knife were used to lay out the pieces with fine scribe lines. A hole was punched in each rectangle of part H to allow entrance of a small file. With the strip clamped under a 7 power binocular microscope, the holes were enlarged to the desired rectangular shape. Each hole is 0.2 x 0.14 in. (5 x 3.6 mm). Errors in the hole positions were found not to exceed 0.0012 in. (0.030 mm). Fine abrasive cloth was used on the flat surfaces to remove all sharp edges and burrs.

Parts F (stationary grid) and B (electrostatic shield) were made of household aluminum foil 0.0006 in. (0.015 mm) thick. Thinner aluminum was tried, but it tore easily. The foil was smoothed onto a microscope slide and cut with the point of the surgeon's knife in the same manner that parts H and D were scribed.

The capacitor plates, part D, were enveloped in electrostatic shielding as follows. Thin lens tissue paper was soaked in a high temperature unfilled liquid epoxy cement. Parts B, D, and F were cleaned with toluene and acetone, allowed to dry, and rubbed with a mixture of epoxy and pumice powder on a cotton swab to assure good wetting on the sides to be cemented. The epoxy-impregnated lens tissue was squeezed against parts B and F between sheets of 0.002 in. thick Teflon by rubbing on the Teflon while using a microscope slide as a backing. This removed bubbles and excess cement and placed the foil in close contact with the lens tissue. The lens tissue was trimmed with scissors to the same size as the aluminum foil adhering to it. Part D was coated with epoxy and the combination of parts B and C was applied to one side and parts F and E to the other side with the lens tissue toward part D. The parts were positioned with the aid of the binocular microscope and pressure was applied through Teflon sheets. The alinement of the parts was checked through the translucent Teflon. The ends of parts E and F were curled around part D and overlapped with parts B and C. Epoxy was applied to the square holes of part F to fill the shallow cavities.

The several parts were stacked and alined to be clamped for curing of the epoxy cement. Pieces were stacked in the following order from bottom to top: steel block, 0.06 in. (1.6 mm) Neoprene pad, 0.002 in. (0.05 mm) Teflon sheet, parts B, C, D, E, F, Teflon sheet, microscope slide (for a flat, smooth surface of F against H later), Teflon sheet, parts F, E, D, C, B, Teflon sheet, Neoprene pad, steel block, and helical compression spring. These were bolted together so that the spring exerted a pressure of about 65 $lbf/in.^2$ (4.5×10^5 N/m^2). Curing of the high temperature epoxy cement for two hours was limited to 300 °F (150 °C) to avoid any possible decomposition of the lens tissue.

In order to make electrical contact with the capacitor plate D, a hole 0.08 in. (2 mm) square was cut with the surgeon's knife through parts B and C near one end. To prevent shavings or bent edges of the foil, B, from making contact with plate D, a 0.24 in. (6 mm) square was cut very carefully through part B concentric with the first hole. Light force was applied to the surgeon's knife to avoid cutting through part C. After each cutting, the foil was peeled off carefully with small pointed forceps. Leakage resistance between each plate and the shielding was checked to be greater than 200 megohms.

Spacing and guiding for the sliding grid, part H, between the shielded capacitor plates was provided by two 0.0065 in. (0.17 mm) thick tantalum ribbons, parts G. These ribbons were made by flattening 0.010 in. (0.25 mm) diameter tantalum wire between hardened steel plates.

A2 Assembly

The assembly of the capacitance unit and the extensometer were critical operations. Much of the work was tedious, and it required a high degree of skill, ingenuity, patience and the development of special techniques. Since the proper assembly was of such importance to the successful operation of the extensometer, the assembly steps are described in detail in the following paragraphs.

A2.1 Capacitance Unit Assembly

The sliding grid, part H, with a tantalum spacer wire on each side of it were laid between the shielded capacitor plates. Ten tiny spring clips, shaped like lyres, were made from 0.01 in. (0.25 mm) diameter wire and placed over the edges of both shielded plates to clamp them together. The 7 power binocular microscope was used for better visibility. The spacer wires were pushed against the sliding grid by inserting a knife point between the shielded plates in several places. After the sliding grid was moved back and forth a few times to loosen the spacer wires from it, the slider was removed to prevent it from accidentally becoming cemented in place. The same epoxy cement as was described above was applied to the spacer wires in small droplets by inserting a fine wire in the outside slots on the sides.

Only a minute amount of cement was applied and it was spread along the spacer wires so as to be drawn between them and the stationary grids by capillary action. A small rectangle of tantalum, 0.0065 in. (0.17 mm) thick was cemented in the slot of each side at the end with the spring steel exposed through the square holes. Excess cement was removed from both edges of each ribbon by blotting. A fine wire thermocouple was insulated with epoxy impregnated paper and pushed into the slot. After curing, the lyre shaped springs were removed and the excess cement which accidentally ran into the slider space was removed with the rough edge of a piece of brass shim stock.

The performance of the capacitor was checked by fastening it temporily with cellulose cement to a fixture driven by a precision micrometer. The position of the center of the linear range of the capacitor was marked by a scratch made on the sliding grid at the edge of the plate shielding.

For attaching the capacitor to the extensometer tube a notch was filed in each tantalum rectangle to receive a metal strip support. Each of these supports was a strip of tantalum bent to the form of part 15 in Figure 2. These were cemented to the capacitor with room temperature curing paste epoxy cement while held in position in a tube having the same inside diameter as the inner tube of the extensometer. These supports were designed to have a slight vertical flexibility, high rigidity in the axial direction of the capacitor, low thermal conductivity, and low thermal expansivity (to be compatible with Vycor). The ends of the supports would exert some force against the inner Vycor tube, part 3 in Figure 2, to which they would be cemented later. Centering of the other end of the capacitor was effected by bending the protruding ends of the tantalum spacer ribbons outward against the tube.

Linkage between the sliding grid and the movable leg, part 6 of Figure 2, was provided by a short strut having ball joint and flexure connections. For the ball joint a 0.062 in. (1.6 mm) diameter sapphire ball with 25 μin. (0.64 μm) sphericity was attached to the end of a 0.075 in. (1.9 mm) o.d. 0.01 in. (1/4 mm) i.d., porcelain tube 0.85 in. (22 mm) long. These are shown as parts 10 and 11 in Figure 2. Ceramic cement was used for this attachment to provide resistance to high temperature. Around the porcelain tube was placed a spring, part 12 of Figure 2, made by winding a 0.0125 in. (0.318 mm) diameter nickel-chromium wire on a 0.72 in. (1.8 mm) diameter mandrel. The end of the spring at the ball had a loop to hold the movable leg, part 6, against the ball.

At the other end the spring was bent around the end of the porcelain tube. A 0.005 in. (0.13 mm) diameter nickel-chromium wire 0.3 in. (0.8 mm) long was inserted 0.1 in. (2.5 mm) into the tube at this end. Paste epoxy cement was used to anchor the spring and the straight wire to the porcelain. The sliding grid was cemented to the wire 0.1 in. (2.54 mm) from the porcelain tube. This short piece of wire formed a flexural connection.

Miniature high temperature (Teflon insulated) coaxial cable was used for lead wires to the capacitor. The central conductor was spot-welded to one spring steel capacitor plate, part D of Figure 3 and Figure A1, through the square hole in the shield. Spot welding was desirable for a strong mechanical connection so that the capacitor could later be pushed into position through the Vycor tube by the leads. Electrically conductive silver paint was used to connect a "pig tail" of the cable braid to the capacitor support and shielding. In a similar manner another cable was connected to the other side of the capacitor. Silver paint was used to electrically connect each shield to a stationary grid (parts B and F, see part A in Figure 3 and Figure A1), the braid of the cables to one tantalum support strip and both shields (part B), and the shields to the tantalum spacer ribbons (part G). After the sliding grid (with attached linkage) was inserted into the capacitor, it was electrically connected to one of the spacer ribbons by spot-welding the ends of a small helix made from 0.005 in. (0.13 mm) diameter nickel-chromium wire (part 14 in Figure 2). This was attached so as not to interfere with the motion of the sliding grid. Paste epoxy cement was applied over the spot-welds to insure a good mechanical, fatigue resistant connection.

A2.2 Extensometer Assembly

A glass tube 0.28 in. (7 mm) o.d. 0.2 in. (5 mm) i.d., and 12 in. (305 mm) long was used to hold the lead wires away from the inner Vycor tube, part 3 of Figure 2, to keep them as cool as possible. See Figures 6 and 7 for a view of the lead wires in the small glass tube. Through this tube were passed the two capacitor cables, the leads of a thermocouple embedded in the capacitor, and the leads of a thermocouple to be cemented to the inner Vycor tube. Near each end of the tube carrying the lead wires, four porcelain spacer beads were attached with paste epoxy cement to keep this tube concentric with the inner Vycor tube. Similarly four spacer beads were attached to the outside of the inner Vycor tube near the outer end to keep that end concentric with the outer Vycor tube (the other end would be supported by a Lucalox rod of the fixed leg of the extensometer).

The sapphire axle, part 7a of Figure 2, was cemented into the movable Lucalox leg, part 6 of Figure 2, with a ceramic cement. The excess cement was immediately washed off the exposed parts of the axle.

For installing the capacitor, the inner Vycor tube, part 3, was temporarily inserted in the outer Vycor tube, part 2. The capacitor assembly was pushed into the inner Vycor tube by the leads and the tube surrounding them until the sapphire ball of the linkage was at the "race track-shaped" hole in each of the two tubes, 2 and 3. The movable leg and its axle, parts 6 and 7a, were inserted through these holes. To make this possible, one tube had to be translated relative to the other so that one end of the axle, and then the other, could drop through the hole in tube 2. The stationary leg rod, part 4, was inserted into the round holes of the Vycor tubes to position the tubes relative to each other. After the movable leg was rotated so that the cone in it faced the sapphire ball and the axle was seated in the vee groove of the inner tube, a long wire was moved down the inner tube from the end opposite the lead wires. The end of the wire inside the tube had been bent slightly more than a right angle at a point about 0.1 in. (2.5 mm) from the end. This hook was engaged with the loop formed at the end of the linkage spring at the sapphire ball. Manipulation of the wire hook and the movable leg seated the ball in the cone, extended the spring, and seated its loop in the notch of the movable leg. This provided a tight linkage to transfer the motion of the movable leg to the capacitor slider.

A rubber band was placed around the extensometer tube and passed through the vee groove of the projecting end of the movable leg to hold the axle firmly in its seat in the inner tube. A soft spacer was placed on each side of the movable leg in the hole to hold the leg at the midpoint of its travel. Final adjustment of the capacitor position was made by pushing it with the leads until the scratch on the sliding grid lined up with the edge of the plate shielding, thereby centering the mechanical range and the linear electrical range of the system. The spring loop was carefully disengaged from the movable leg with the hooked wire, and the movable leg, stationary leg rod, and outer Vycor tube were removed. Only friction held the capacitor in the adjusted position. The capacitor was cemented in place with a pipette made from a glass tube about one foot long and a few millimeters in diameter. The tip was tapered and bent on an angle, and a hose was attached to the other end.

With a few drops of the high temperature liquid epoxy cement in the glass tube, the tube was inserted in the inner Vycor tube and about one drop was deposited carefully where each of the four ends of the capacitor tantalum supports contacted the Vycor tube. The thermocouple that touched the inside of the tube was also cemented in place. After curing of the cement at 300 °F (150 °C) for two hours, the position of the capacitor was checked. (Removal of the capacitor was possible by breaking the cement joint between the supports and the Vycor tube with a long metal rod flattened and sharpened on one end. Repairs were made using this procedure.)

Aluminum foil was applied to the outside of the inner Vycor tube, Figure 2, part 3, except for the end having the hose connector. This foil served as a reflector to protect the capacitor from thermal radiation, and it was also used for electrostatic shielding. This foil was applied by brushing a thin coat of the high temperature liquid epoxy cement onto the Vycor tube except around the vee groove and at the hose end. Then household aluminum foil was wrapped around the tube and pressed into intimate contact with the cement. The foil was cut out at the holes with the pointed surgeon's knife. A fiber glass insulated thermocouple was cemented along the bottom side of the aluminum so that the junction was near the "race track-shaped" hole but positioned so that it would later be in contact with the silver tube. Fine wire was wrapped around the Vycor tube to hold the thermocouple in place until the cement was cured. The usual procedure for curing of the epoxy cement was followed.

The primary thermal reflector is the silver tube, part 8 of Figure 2. Spacers between the silver tube and the inner Vycor tube were made from 0.073 in. (1.85 mm) o.d. porcelain tubing. Four pieces, each about 2 in. (51 mm) long, were attached with the 3000 °F (1650 °C) ceramic cement to the aluminum foil in the two areas where an end of the silver tube would be. After the ceramic cement dried, the inner Vycor tube, with aluminum covering and porcelain spacers, was slid into the silver tube so that the similarly shaped holes of the two tubes were alined. For maintaining the orientation between the tubes, the stationary leg rod, part 4, was placed temporarily in its position through the holes. A copper wire attached to the silver tube was wrapped around the aluminum foil on the inner Vycor tube a few times to form a helix, and the helix was enlarged somewhat so as not to touch the foil. Electrically conductive silver paint was used to connect the end of the wire electrically to the foil. A wire was soft soldered to the copper wire for grounding both the silver and aluminum tubes as precautionary electrostatic shields for the variable capacitor and its connections. The thermocouple was attached to the inside of the silver tube just inside the "race track" hole with ceramic cement. The silver tube was wiped with toluene and acetone to remove substances that might discolor from heat, the stationary leg rod was removed, and the assembly was inserted into the outer Vycor tube, part 2.

The "race track-shaped" holes in the three tubes, parts 2, 8, and 3 were alined, and the previously used wire hook was passed through the open end of the inner Vycor tube. It was again hooked into the loop at the end of the capacitor linkage. The movable leg and axle, parts 6 and 7a, were passed through the holes as before by moving the inner tube slightly so that one end of the axle at a time passed through the hole in the outer Vycor tube, part 2. By a 90° rotation of the movable leg the cone in the inside end was positioned to face the sapphire ball and the axle was seated in the vee groove of the inner Vycor tube. The stationary leg rod was re-inserted to maintain alinement. Manipulation of the movable leg and pulling on the wire hook seated the ball in the cone, extended the spring to load the ball against the cone, and seated the loop on the end of the spring in the vee groove opposite the cone on the same end of the movable leg. See Figure 2. The silver tube prevented the leg from dropping far from its proper position.

During one assembly the wire loop caught on the cone side of the movable leg, and the flexure wire was accidentally bent. Backlash in the extensometer resulted. The bent wire was also observed with the aid of a miniature optical prism and a cystoscope. The extensometer was disassembled, including the removal of the capacitor, in order to replace the flexure wire and push rod. The ability of the extensometer to be disassembled without damaging it was thereby confirmed.

The stationary leg was formed by joining the rod, part 4, and the foot, part 5, with 3000 °F (1650 °C) ceramic cement. Care was taken to position the rod in the foot so that the end of the rod would not touch the 0.1 in. (2.54 mm) diameter sapphire rod, part 7c, during operation. After the cement was thoroughly dry, the leg was inserted in the appropriate holes in the extensometer, and the inner Vycor tube was temporarily centered in the outer Vycor tube by a bead and a wedge on opposite sides between the two tubes. A small spotlight was focused on the outside end of the translucent stationary leg to make the rod plainly visible when observed through the open end of the inner Vycor tube. Ceramic cement was deposited on the rod at the two holes in the inner Vycor tube by means of the pipette used earlier for installing the variable capacitor. By rotation and translation of the outside end of the rod, the cement was worked into the holes between the rod and tube wall. (No cement was used on the rod at the hole in the outer Vycor tube because of the hazard of cracking the tube due to differential thermal expansion in this hot area. This hazard was verified by a simulation test.)

With the toolmaker's microscope the foot was alined and clamped by a spring so that a 0.1 in. (2.54 mm) rod placed in its vee groove was parallel with a similar rod held in the vee groove of the movable leg. After the cement was allowed to air dry and was baked at 300 °F (150 °C) to insure dryness, the wedge and bead were removed, and a spacer bead of porcelain was positioned on the bottom between the two Vycor tubes. Bending of the inner tube was necessary for insertion of the bead. A little of the ceramic cement was applied to secure the bead to the inner tube. Thus, the inner tube was positioned vertically by compressive force on the bead and tensile force on the stationary leg. Horizontal centering was maintained by the fit of the curved surface of the stationary foot against the outer Vycor tube.

The design of the stationary leg shown in Figure 2 is a modification adopted late in the program. The earlier, more complex, design consisted of a shorter rod that was cemented into the inner Vycor tube with the silver tube in position. The rod was short enough to permit inserting the assembly into the outer Vycor tube. A small Lucalox button was cemented to the end of this rod with the ceramic cement, and the foot was cemented to this button. Repeated failures of the joint between the rod and the button resulted in the redesign of this part. For disassembly the rod can be twisted loose from the inner Vycor tube and, after removing the excess cement from the rod with abrasive cloth inserted into the tube on a long slender rod, it can be removed.

Last in the extensometer assembly was sealing of the tubes at the hose connection end. Room temperature vulcanizing silicone rubber was injected between the lead wire carrying tube and the inner Vycor tube, part 3. A thin seal of the same rubber was made between the two Vycor tubes, parts 2 and 3.

A3 Readout Instrumentation

A block diagram of the extensometer indicator is shown in Figure 4, Figure A2 is a detailed schematic diagram of the unit, and Table A3 gives a list of the parts used in its construction. The circuits follow common operational amplifier practice [4].

As shown in Figure 4, an oscillator supplies an a-c signal to the capacitance unit of the extensometer and to the reference rectifier. The output signal from the extensometer is fed to a charge amplifier. The charge amplifier effectively grounds the capacitor output, thereby making the unit independent of cable capacitance, and produces an output voltage amplitude proportional to the resulting current. This signal is then rectified. The rectifier output, I_1, is directly proportional to the capacitance in the extensometer, and it goes to the summing section where currents from the reference section are added to it. The output of the summing amplifier is the system output.

The reference rectifier and the inverter are used to supply the Kelvin-Varley divider circuit. This circuit is used for direct reading of static strain, and as a zero suppression in the measurement of dynamic strains. The output of the Kelvin-Varley circuit is connected to a buffer amplifier to prevent nonlinearity that would be caused by loading the divider. The output of the buffer amplifier is connected to the summing amplifier through a suitably chosen resistor (R_{39}).

Since the output signal (I_1) of the extensometer does not go through zero, an offset signal to balance the center position output is necessary. This signal is the current (I_2) in Figure 4. In addition, the zero set potentiometer (P_2) in parallel with the Kelvin-Varley divider can be used to zero the extensometer over about 15 percent of the range. The output current (I_3) from this potentiometer and the offset current (I_2) are connected to the summing amplifier along with the extensometer signal and the Kelvin-Varley divider output. A voltage proportional to the algebraic sum of these currents is obtained at the output terminals.

The relationship between the range of the Kelvin-Varley divider and the range of the capacitance change in the extensometer can be adjusted by changing resistor R_{39}. R_{37} should be changed at the same time to keep the tare potentiometer at about the same sensitivity level as the Kelvin-Varley divider potentiometer. The offset is adjusted by the selection of R_{38}.

Potentiometer P_2 (in Figure A2) is used to compensate for the input offset current of amplifier A_2. It is set to make the d-c component of the output of A2 between $\pm$ 1 volt.

Table A1 - Extensometer Parts and Materials

Part No.	Identification	Size, amount or remarks
1	Variable capacitor	See figure A1
2	Vycor tube	0.98 o.d. x 0.87 i.d. x 30 in.
3	Vycor tube	0.51 o.d. x 0.42 i.d. x 26 in.
4	Lucalox rod	0.25 dia x 3 in.
5	Lucalox cube	1 in. cube
6	Lucalox rod	0.25 dia x 3 in.
7a	Sapphire rod	0.1 dia x 0.5 in.
7b	Sapphire rod	0.1 dia x 0.5 in.
7c	Sapphire rod	0.1 dia x 1.0 in.
8	Silver tube reflector	2.1 dia x 18 x 0.01 in.
9	Ceramic cement	1 quart Sauereisen No. 78
10	Sapphire pivot	0.0625 dia in. ball
11	Porcelain tube	0.075 o.d. x 0.01 i.d. x 0.85 in.
12	Nickel chromium spring	0.0125 dia x 24 in. Tophet A wire
13	Paste epoxy cement	Hysol epoxi-patch kit 1c
14	Nickel chromium wire	0.005 dia x 6 in. Tophet A
15	Tantalum sheet	0.010 x 1 x 1 in.
16	Liquid epoxy cement	Type GA 61
17	Aluminum foil	0.0006 x 12 x 24 in. (household foil)
18	Coaxial cable	Teflon insulated, Micro Dot, Inc. cable No. 250-3819
19	Thermocouple	Chromel-Alumel, No. 28 and 0.003 in. dia

Note: The dimensions given in this table may be converted to SI units by use of the relationship 1 inch = 0.0254 meter.

Table A2 - Source for Materials

Item	Source
Lucalox (fine grain, high purity, polycrystalline alumina)	General Electric Company Lamp Glass Dept Marketing 670 Nela Park Cleveland, Ohio 44112
Kaowool (ceramic fiber thermal insulation)	Babcock and Wilcox Refractories Division Augusta, Georgia
Sauereisen cement No. 78 (ceramic cement)	Sauereisen Cement Co. 1043 N. Canal Street Pittsburgh, Pennsylvania 15215
GA-61 cement (high temperature, unfilled epoxy cement)	Instruments Division The Budd Company P. O. Box 245 Phoenixville, Pennsylvania 19460
Hysol cement kit 1c (room temperature, paste epoxy cement)	Hysol Corporation 1100 Seneca Avenue Olean, New York 14760
Sapphire (rods and balls)	Arnco Manufacturing Company Div of M. A. Miller Mfg. Company 4th and Church Street Libertyville, Illinois 60048
Teflon (0.002 inch thick sheet)	Reed Plastic 317 Cedar Street, N. W. Washington, D. C. 20012
Coaxial cable	Microdot Inc. Cable Division 220 Pasadena Avenue South Pasadena, California 91030
Other items	National Bureau of Standards storeroom or local purchase

Table A3 - Parts List for Indicator

Resistors:

R_1 = 1 kohm, 1%
R_2 = 1 kohm, 1%
R_3 = 226 ohm, 1%
R_4 = 1620 ohm, 1%
R_5 = 112 Mohm, 20%
R_6 = 168 Mohm, 20%
R_7 = 1 kohm, 1%
R_8-R_{12} = 10 kohm, 1%
R_{13} = 5 kohm, 1%
R_{14} = 4.7 kohm, 5%
R_{15} = 2.7 kohm, 5%
R_{16}-R_{20} = 10 kohm, 1%
R_{21} = 5 kohm, 1%
R_{22} = 4.7 kohm, 5%
R_{23} = 2.7 kohm, 5%
R_{24}-R_{25} = 10 kohm, 1%
R_{26}-R_{36} = 10 kohm, 0.5% (matched to 0.03%)
R_{37} = 1 Mohm, 1%
R_{38} = 80 kohm, 0.5%
R_{39} = 150 kohm, 0.5%

Potentiometers:

P_1 = 100 kohm, carbon
P_2 = 20 kohm, 10 turn
P_3 = 20 kohm, 0.1% linearity (selected to be twice the resistance of R_{26})

Capacitors:

C_1 = 0.047 µfd
C_2 = 0.047 µfd
C_3 = 6.6 - 7.6 pfd
C_4 = 0.22 µfd
C_5 = 0.1 µfd
C_6 = 0.22 µfd
C_7 = 0.1 µfd
C_8 = 0.01 µfd

Diodes:

CR_1 - CR_4 = 1N2067

Operational amplifiers:

A_1 - A_8 = Union Carbide type H6010C

Stabilizing lamp:

L_1 = General Electric type 344

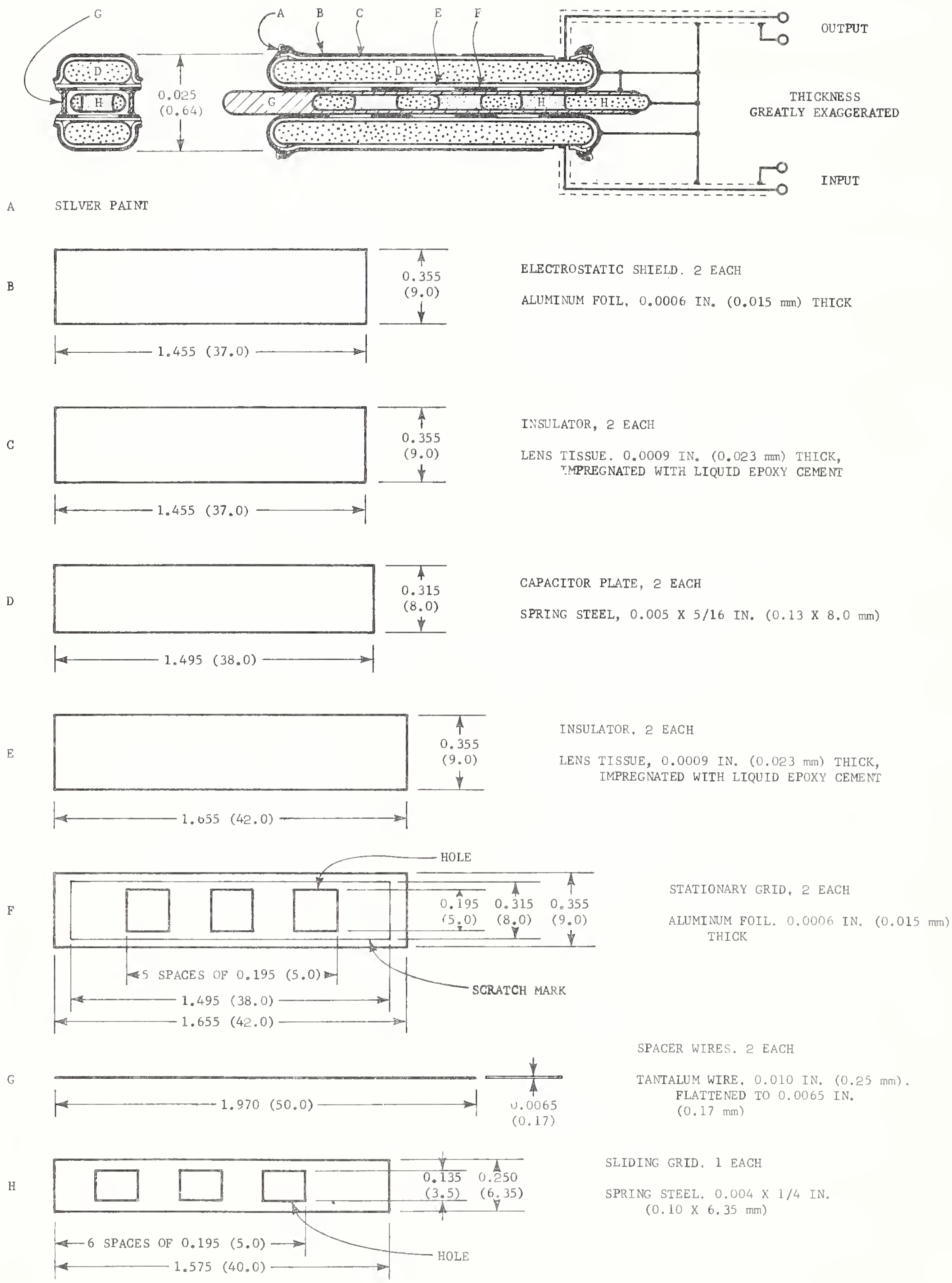

Figure A1. Schematic (sectional view) of the variable capacitor and descriptions of the components

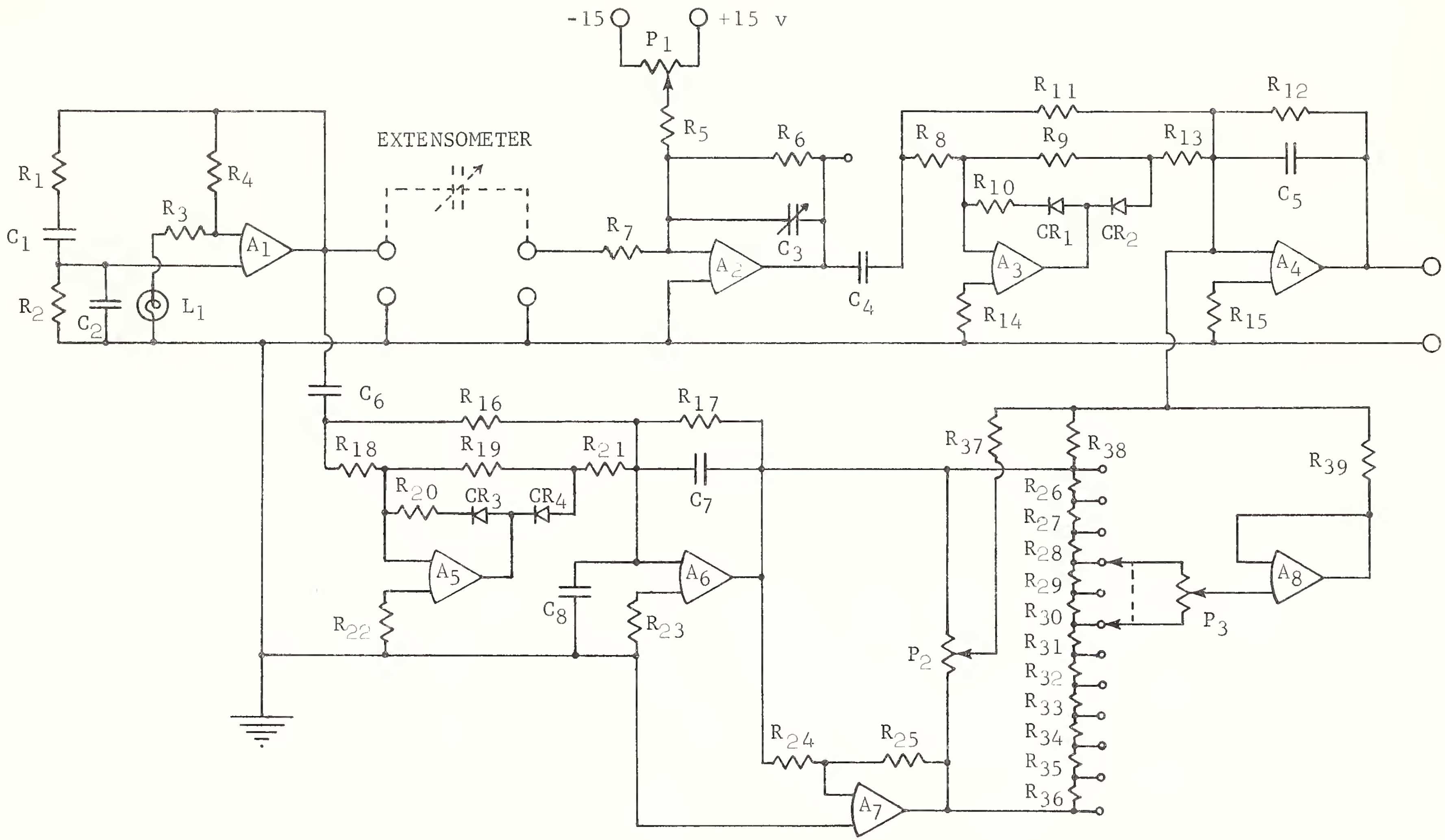

Figure A2. Circuit diagram for the extensometer indicator

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