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EVALUATION OF THE KULITE SEMICONDUCTOR STRAIN GAGE, MODEL M(6) EP-120-500W, SPOTWELDED TO P-110 PIPE MATERIAL

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ABSTRACT

The Kulite dual-element, semiconductor strain gage, weldable model M(6)-EP-120-500W, was evaluated in laboratory tests under simulated Nevada Test Site conditions.* Two gages were installed on P-110 line-of-sight pipe material. Tension was applied to the test samples to 50% of yield (about 2000 microstrain). Immediately following, compression was applied to 100% of yield (about 6000 microstrain). The Kulite gages were powered by a dual constant current signal conditioner. Measurements obtained with metal foil strain gages served as reference standards for the Kulite strain gage measurements.

The output voltages of the Kulite gages were relatively linear from zero to +2000 microstrain and in the subsequent compression to -2500 microstrain. Below -2500 microstrain, the output voltages from the Kulite gages became decidedly nonlinear and also differed significantly from each other. We feel that the gage spotwelds were failing at strains below -2500 microstrain and consequently that data obtained below this level are not reliable enough to calculate pipe forces. The stated gage factor (Kulite factory) of 220 is about 33% higher in tension than the measured gage factor and about 15% higher in compression.

Adhesive-bonded, metal foil strain gages are recommended for reliable pipe force measurements on future Nevada Test Site events. Metal foil gages consistently are linear and reliably measure strains in excess of ±10 000 microstrain.

INTRODUCTION

To evaluate the Kulite semiconductor strain gage, we used a standard tensile specimen made of P-110 casing-grade steel. Two Kulite strain gages and six metal foil strain gages were installed on the specimen. The metal

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

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foil gages were bonded very close to the Kulite gages so the surface strains in the vicinity of the Kulite gages could be determined accurately. Because the performance characteristics of the metal foil type gages are well established, these were used to determine the actual strain applied to the Kulite strain gages. To duplicate the strain levels of a downhole line-of-sight pipe, the specimen was cycled to 50% of yield stress in tension followed immediately by compression to 100% of yield stress.

TEST SYSTEM

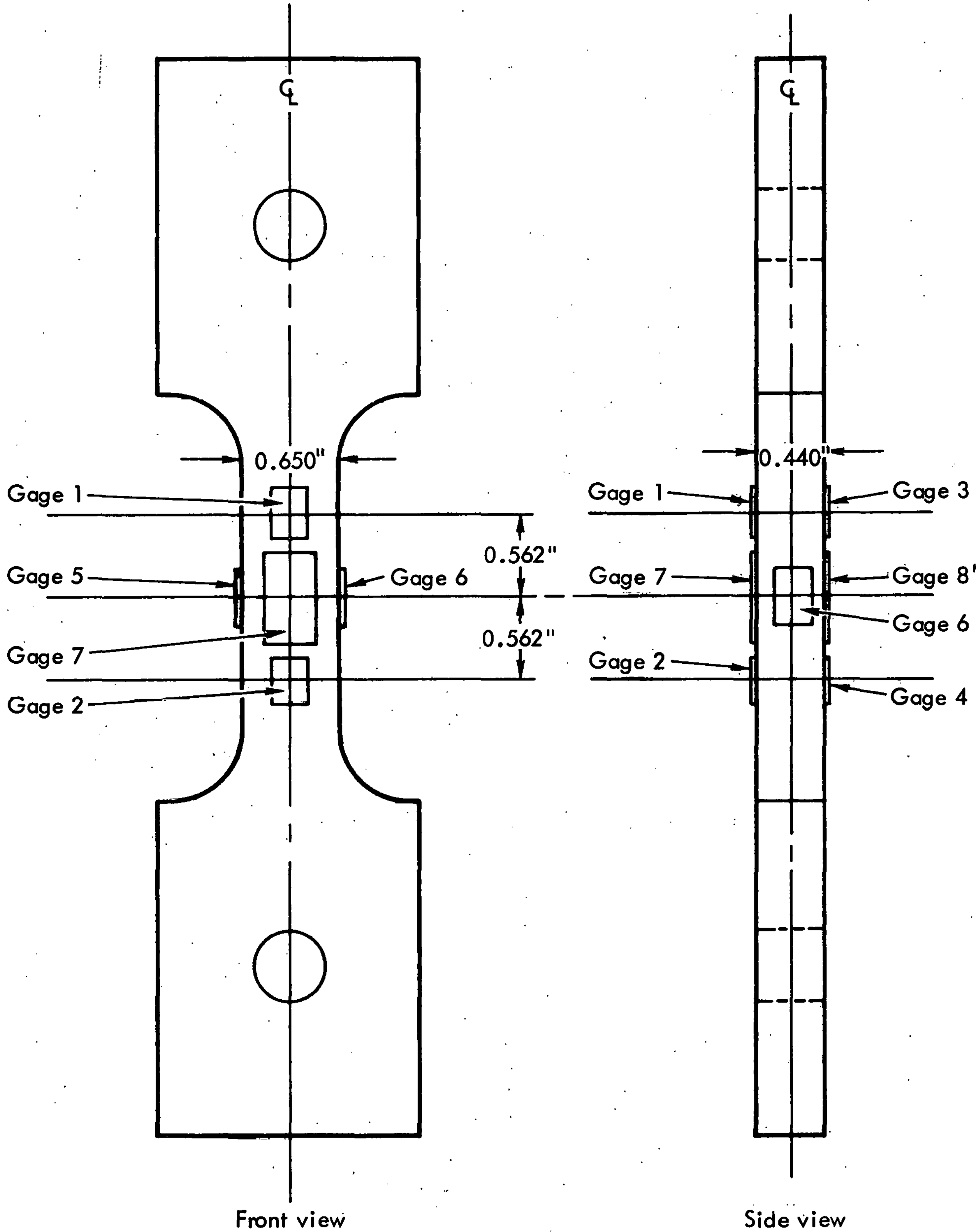
Components

The experimental Kulite weldable, semiconductor strain gages, model M(6)-EP-120-500W (Kulite Semiconductor Products, Inc.), have two active elements with opposite "resistance vs strain" coefficients. The gage factor on the manufacturer's package is 220 ± 5%. The nominal gage resistance is 120 Ω per element. The Kulite gages were powered by a dual constant current signal conditioner, Endevco Corp. model 4409M-1. The Endevco conditioners, which were on loan from E G & G, Inc., Las Vegas, are the same ones as used in the field.

The six metal foil strain gages employed as reference standards were model CEA-01-125 UM-120 from Micro-Measurements, Inc. The gage factor was 2.105 ± 0.5% and the gage resistance was 120 Ω. The metal foil gages were powered with a pulsed constant current power supply (B & F Instruments, Inc.). These gages will accurately measure strains in tension and in compression to 3% (30,000 microstrain).

For testing we used a standard tensile specimen made of casing grade P-110 steel. Since this grade was not available in flat bar stock, a tensile specimen of rectangular cross-section was designed (with the help of Bob Brady of the Materials Test and Evaluation Section) that could be made from wall sections of available P-110 pipe, 244 mm o.d. × 14 mm wall (9.625 in. o.d. × 0.55 in. wall). Refer to Fig. 1.

The test was run in our Materials Engineering Division on the 100 K testing machine of MTS Systems, Inc. To help eliminate bending in the compressive mode, a special "self-centering, flat, pinhole specimen grip" was employed. The load on the specimen was applied at the rate of approximately 31.1 kN/min (7000 lb/min) in tension and 62.3 kN/min (14 000 lb/min) in compression.



Specimen

Fig. 1. Strain gage locations on P-110 casing-grade steel specimen. All gages were aligned to measure vertical strains. Gages 1-6 were metal foil strain gages. Gages 7-8 were Kulite weldable semiconductor strain gages.

The data acquisition system was composed of a D-112 computer (Digital Computer Controls, Inc.), a Vidar digital voltmeter, a crossbar scanner and a Kennedy Co. incremental tape recorder.

Installation of Gages on Specimen

Two Kulite strain gages were installed on the specimen, one in the center of the front (gage 7) and the other in the center of the back (gage 8), each being directly opposite the other (see Fig. 1). The Kulite strain gages were spot welded to the test specimen using a dual range Unitek 1059B spot welder and a setting of 12 J (12 W-sec) and a probe pressure setting of 2-1/2. The spot welds, 1.51 mm (1/16 in.) apart, formed a double row down each side and three rows across the bottom end. No welds were made across the top end due to interfering lead wires. This weld schedule is in accordance with the Micro-Measurements Instruction Bulletin B-131. Because the Kulite semiconductor strain gages are sensitive to the light and to temperature changes caused by air currents, they were covered with Barrier "E" (BLH Electronics, Inc.).

Since the performance characteristics of the metal foil type strain gages are well established, these were used to determine the actual strain applied to the Kulite gages. Six metal foil strain gages were used. They were applied to the specimen with M-Bond 200 adhesive. One was placed above and one below each of the Kulite strain gages on the vertical axis. The other two foil strain gages were bonded on the sides of the tensile specimen and were centered on the same horizontal plane as the Kulite gages with the active direction being on the vertical axis (refer to Fig. 1). The metal foil strain gages were bonded very close to the Kulite gages so that surface strains in the vicinity of the latter could be determined as accurately as possible. All of the strain gages were located on the test specimen as shown in Fig. 1.

Test Setup and Calibrating Procedures

The D-112 Computer was programmed to plot load vs strain in order to obtain a quick evaluation. The raw data, stored on tape, then allowed us at a later time to plot the load vs voltage output, average strain, etc. The load was recorded from the load cell of the MTS testing machine. Two extensometers monitored the displacement which was recorded on an X-Y plotter.

To duplicate the strain levels of a downhole line-of-sight pipe, we cycled the specimen to 50% of yield stress in tension followed immediately by compression to 100% of yield stress using the same testing machine. For P-110 steel this represents a stress of 344.7 MPa (55 000 psi) in tension and 758.4 MPa (110 000 psi) in compression.

To satisfy two of the variables used in the equation to determine strain, we monitored the currents for each of the two power supplies on separate channels. To aid in validating the data from the foil gage channels, we employed a separate check channel that simulated a strain gage with an equivalent known strain. The channels for the foil strain gages were also shunt calibrated before the test. The calculated strain agreed with the measured strain from the shunt calibrations and with that from the check channel to within $\leq$0.6%. Since the Kulite strain gages have two active elements, the only simple way to check the program and system for integrity was to shunt one element with a resistance calculated to simulate the equivalent differences of the two expected delta resistances of the active elements. Since the error was found to be only 2%, confidence in the experimental channels was established.

For the Kulite semiconductor strain gages, the equation used for determining strain was:

$$\varepsilon = \frac{e_0 + I_1 R_A - I_2 R_B}{GF_T(I_2 R_B + I_1 R_A)}$$

Constants:

R_A = initial resistance of the "N" element

R_B = initial resistance of the "P" element

GF_T = total gage factor of both elements as specified by Kulite.

Measured Variables:

e_0 = output voltage increment due to strain

I_1 = current in the "N" element

I_2 = current in the "P" element.

For the metal foil gages, the equation used for determining strain was:

$$\varepsilon = \frac{2 \times 10^6 (N+1) E_1}{GF(R_g NE_2 - E_1)}$$

E_1 = volts out minus the shorted input

E_2 = the voltage across the current monitor minus shorted input

R_g = initial resistance of the gage

N = $10^4/R_g$ ratio for nonsymmetrical bridge.

These equations were programmed into the plotting routine.

Channel Identification and Strains Measured

Channels 1 and 2 measured the response of the metal foil strain gages on the front of the specimen while channel 7 monitored the Kulite strain gage between them. The data from channels 1 and 2 were used to determine the average strain at the location of Kulite channel 7. Channels 3 and 4 monitored the foil strain gages on the back with channel 8 responding to the Kulite strain gage located between them. Channels 3 and 4 were used to determine the average strain at the location of Kulite channel 8. Channels 5 and 6 monitored the foil strain gages on the sides of the specimen adjacent to the Kulite gages. These channels provided information regarding possible bending as well as comparisons for the average strains on the front and back of the specimen. Since channel pairs 1 and 3 (as well as 2 and 4) were on opposite sides, they also provided data on bending.

Performance Characteristics

The overall performance of the experiment was excellent; all channels functioned properly and an accurate evaluation could be made. The metal foil strain gages will be considered first. Their measured strains are identified as ε_1, ε_2, etc. For comparing strains, the tension mode is better because of its reduced specimen bending but the comparison is valid for compression as well. Since metal foil gages Nos. 5 and 6 were redundant, they provided additional backup data, which reinforced our confidence in the accuracy of the metal foil strain gages.

At any load, the direct tension/compression stress, as calculated by force/area, was the same throughout the strain-gage section of the specimen. Each individual strain gage typically measures a combination of direct strain and bending strain. Any back-to-back pair of gages can be averaged to cancel out the bending strains and we can then obtain the direct strain values. If all six metal foil strain gages are functioning properly, the values for direct strain should be the same for all pairs of back-to-back strain gages. See equation below:

$$(\varepsilon_1 + \varepsilon_3)/2 = (\varepsilon_5 + \varepsilon_6)/2 = (\varepsilon_2 + \varepsilon_4)/2.$$

Since this equality was satisfied for large values of both tension and compression, all six metal foil gages were accurate.

The surface strain at a weldable strain gage location was calculated from the average of the strains measured by the metal foil strain gages located one above and one below the weldable gage.

$$\varepsilon_7 = \frac{\varepsilon_1 + \varepsilon_2}{2} \qquad \varepsilon_8 = \frac{\varepsilon_3 + \varepsilon_4}{2}$$

Since the Kulite gage 7 lies on the same surface and between metal foil gages No. 1 and 2, then the strain measured by Kulite 7 represents the average strain measured by the metal foil gages. The situation is the same with respect to Kulite gage 8 and metal foil gages Nos. 3 and 4.

RESULTS

Figures 2 through 7 show the individual tension and compression plots of the metal foil strain gages. Figures 8 and 9 show the plots for Kulite strain gages. In Figs. 10 through 13, plots were made of the output voltage of the Kulite gages vs the average strain of the two metal foil gages on the same surface as the Kulite gage. Figures 10 and 11 are the tension data and Figs. 12 and 13 are the data for the subsequent compression.

For both Kulite gages, the end-point nonlinearity between zero and 2000 microstrain in tension was less than 60 microstrain. By substituting the factory-supplied gage factor of 220 into the Kulite strain gage equation, a linear approximation can be derived. For Kulite strain gage No. 7, the deviation from the linear approximation was 400 microstrain at a true strain of 2000 microstrain. For Kulite strain gage No. 8, it was 600 microstrain at a true strain of 2000 microstrain. (Refer to Figs. 10 and 11.) The actual best fit linear gage factor, referenced to initial zero, was 177 at +2000 microstrain and 194 at −2500 microstrain for Kulite gage 7 and 154 at +2000 microstrain and 190 at −2500 microstrain for Kulite gage 8. The gage factor quoted on the Kulite strain gage package is not correct, being about 33% too high in tension to +2000 microstrain and 15% too high in compression to −2500 microstrain.

In compression, we noted bending of the test specimen and yielding of the spotwelds because of the higher magnitude of strain which was about 5800 microstrain. No attempt was made to determine the endpoint nonlinearity in the compression phase below −2500 microstrain because of the extreme hysteresis of the Kulite gages. From zero to −2500 microstrain in compression, both

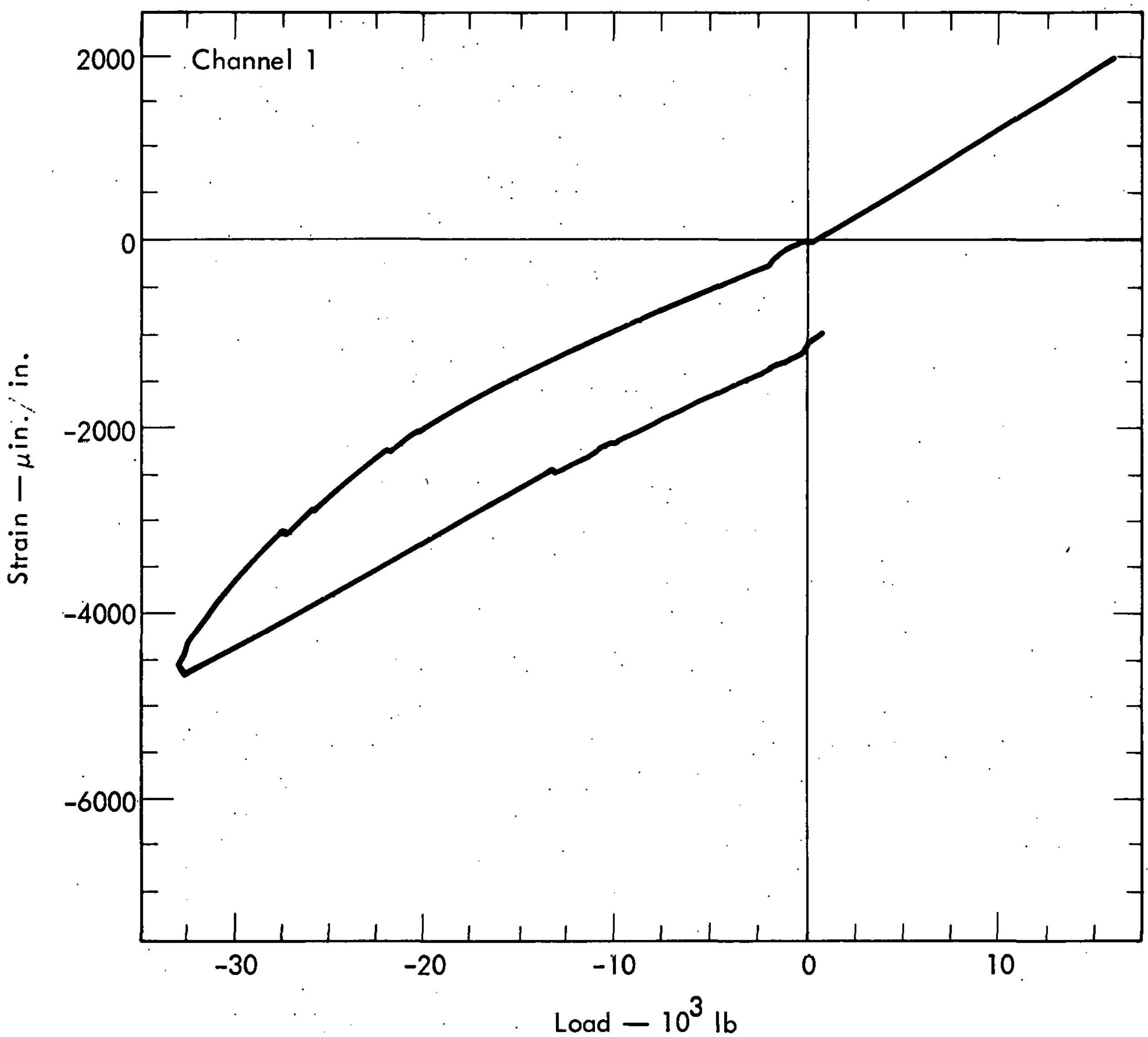


Fig. 2. Tension and compression plot of metal foil strain gage No. 1.

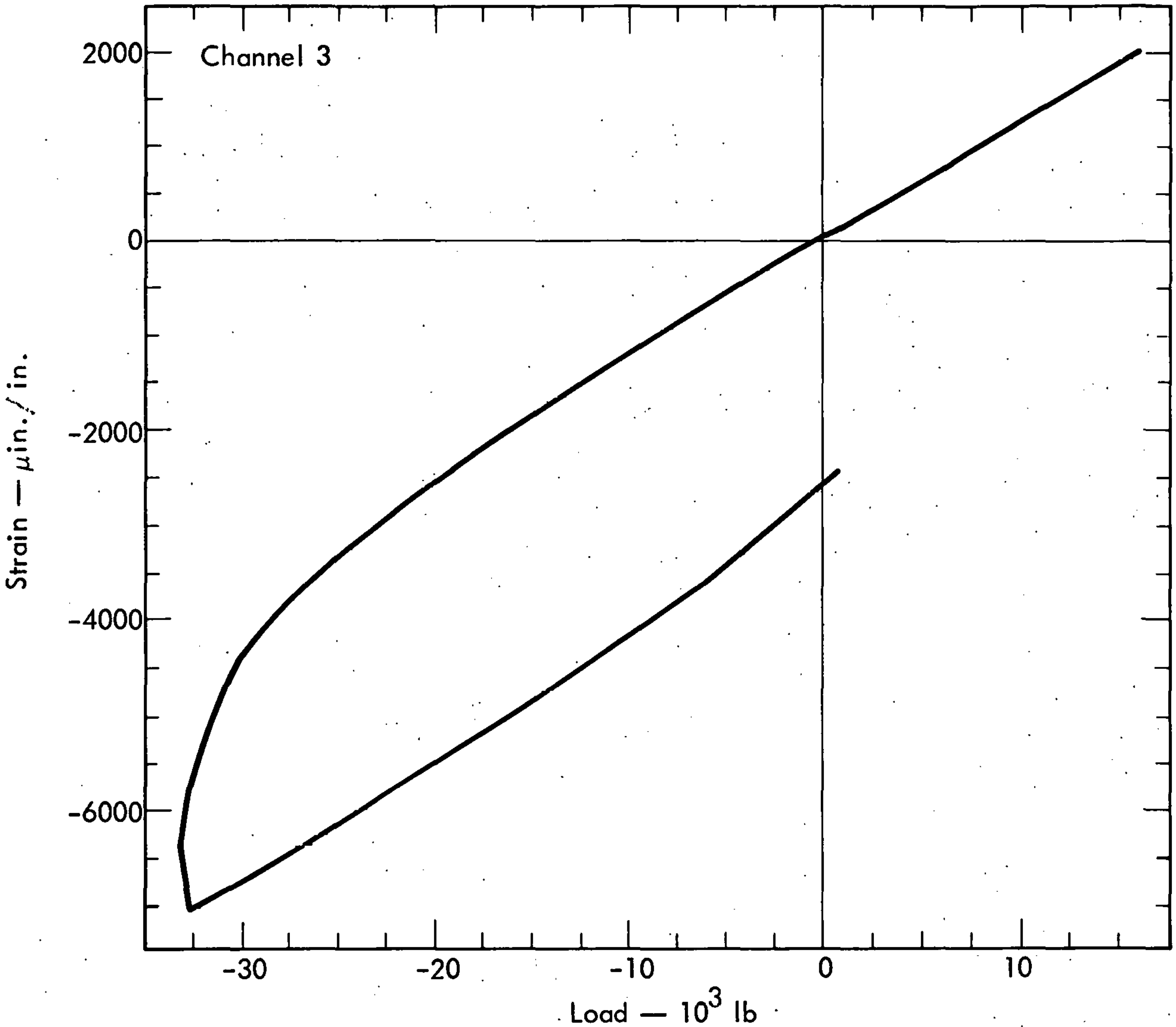


Fig. 3. Tension and compression plot of metal foil strain gage No. 2.

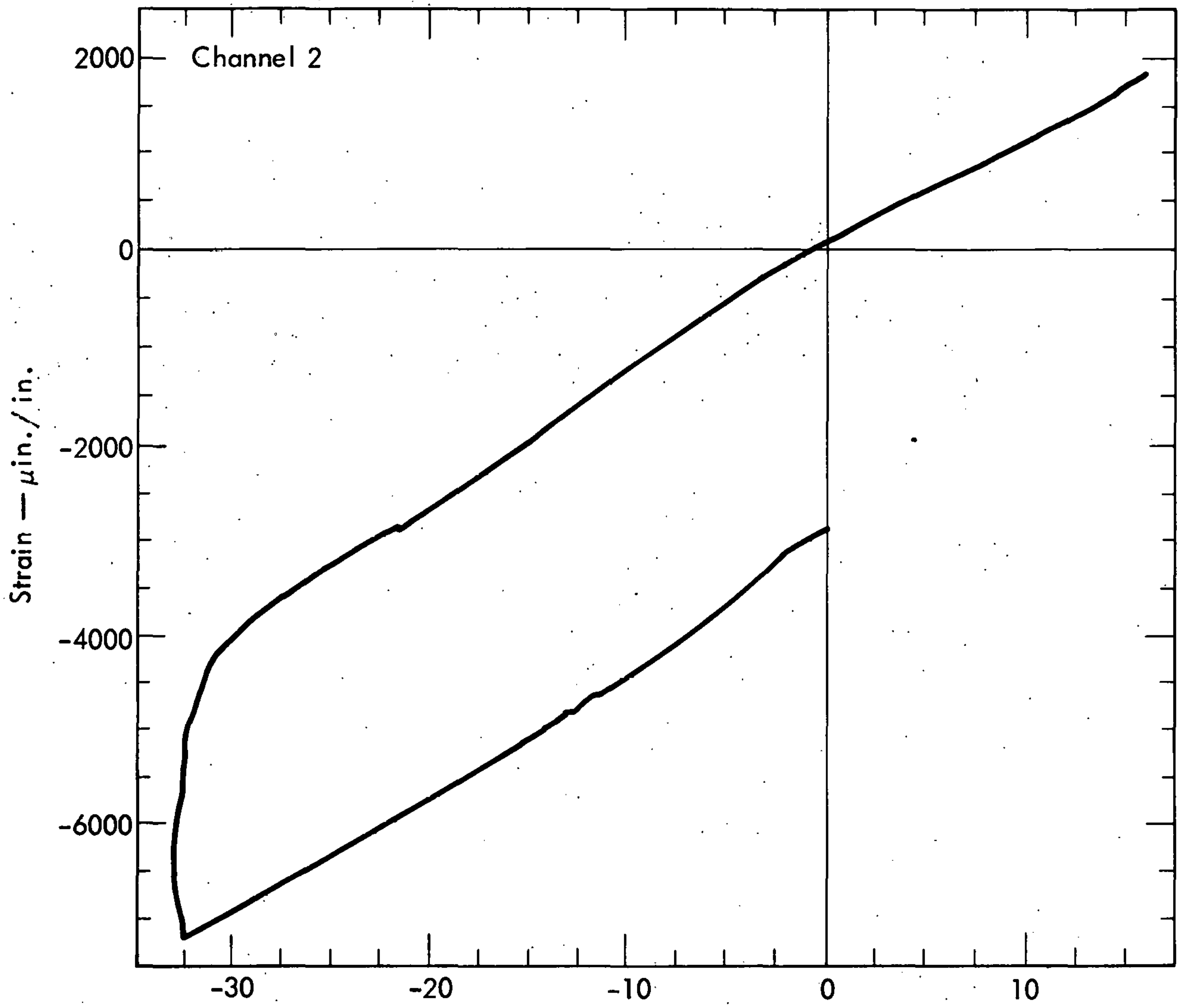


Fig. 4. Tension and compression plot of metal foil strain gage No. 3.

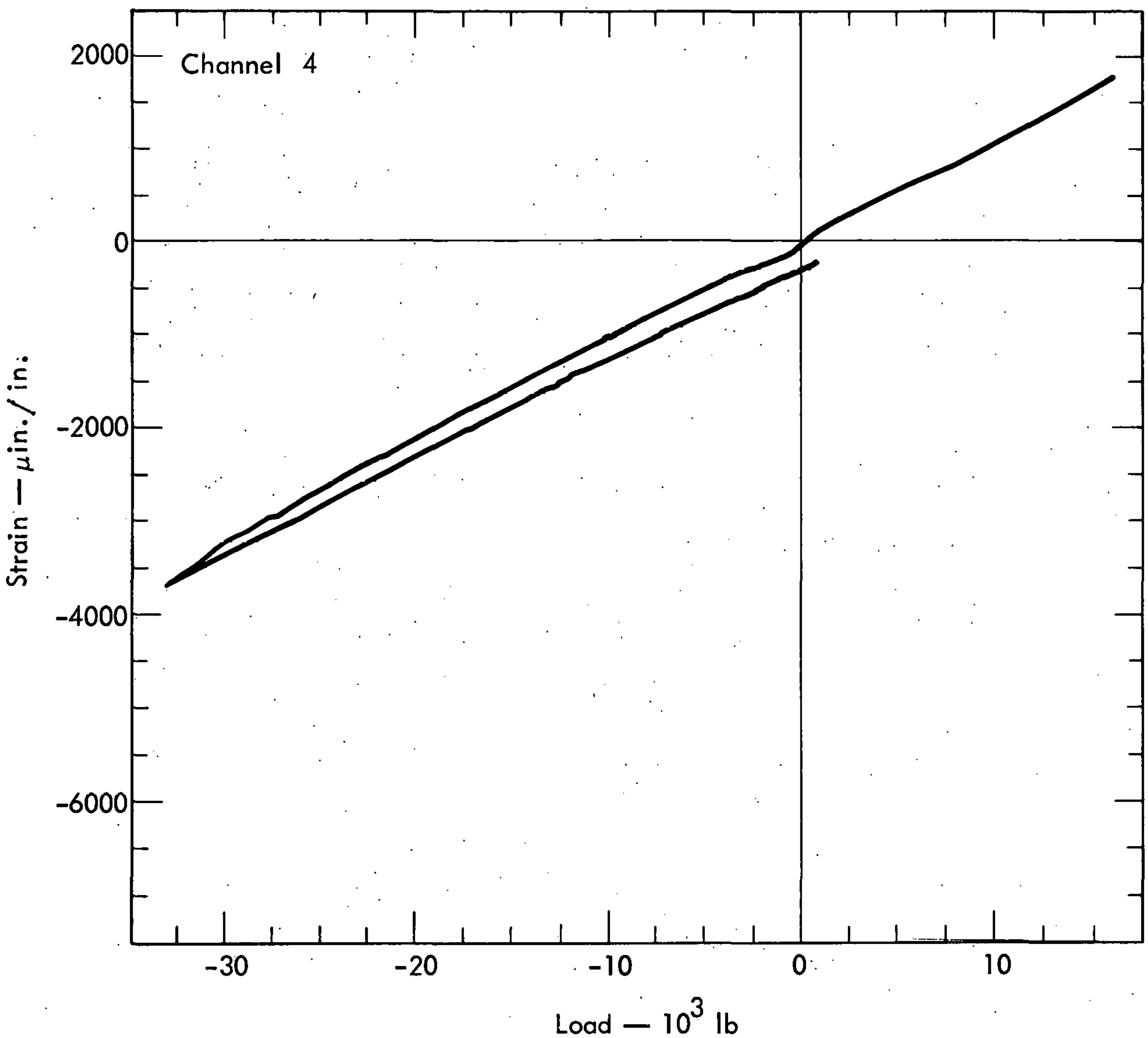


Fig. 5. Tension and compression plot of metal foil strain gage No. 4.

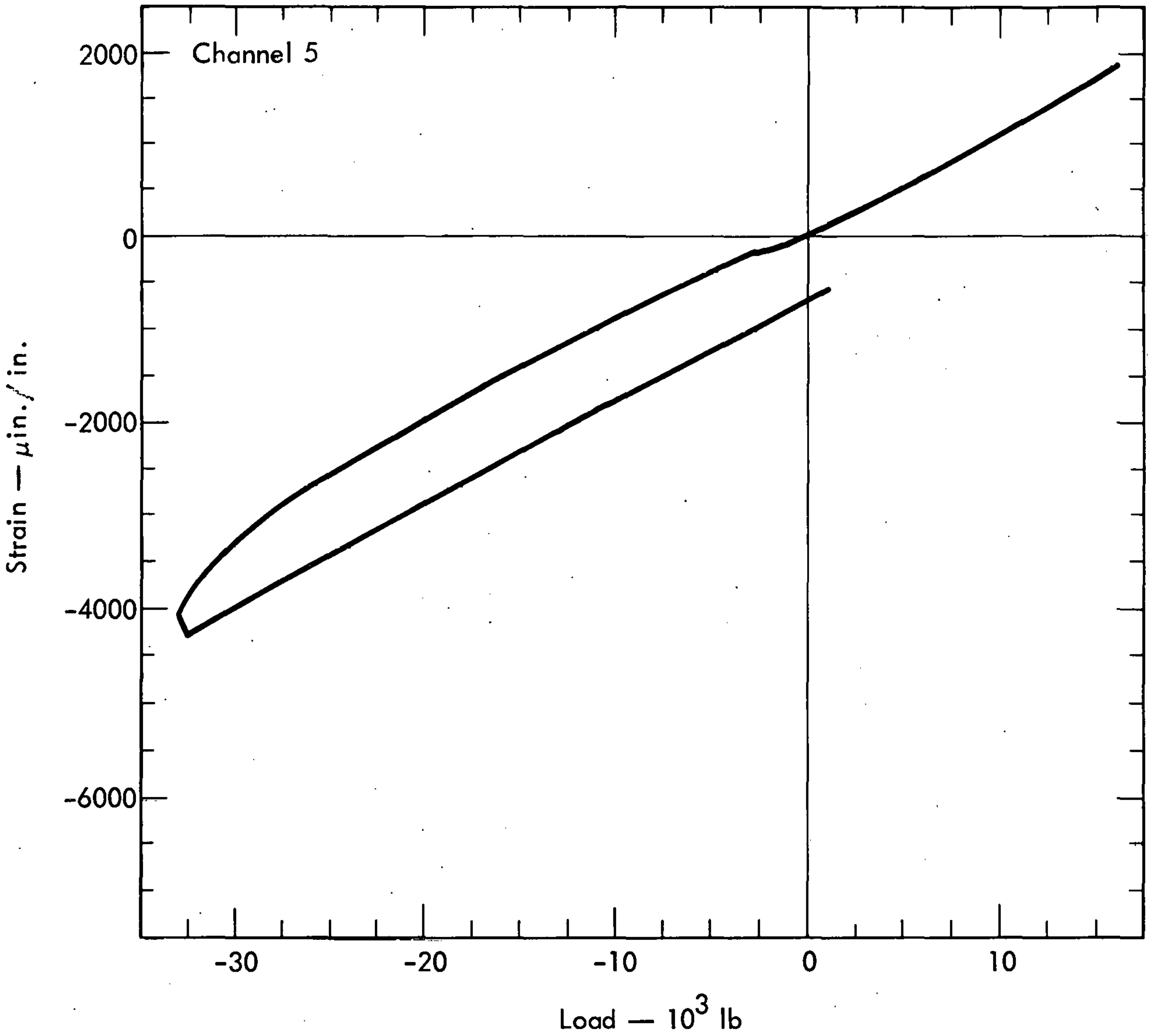


Fig. 6. Tension and compression plot of metal foil strain gage No. 5.

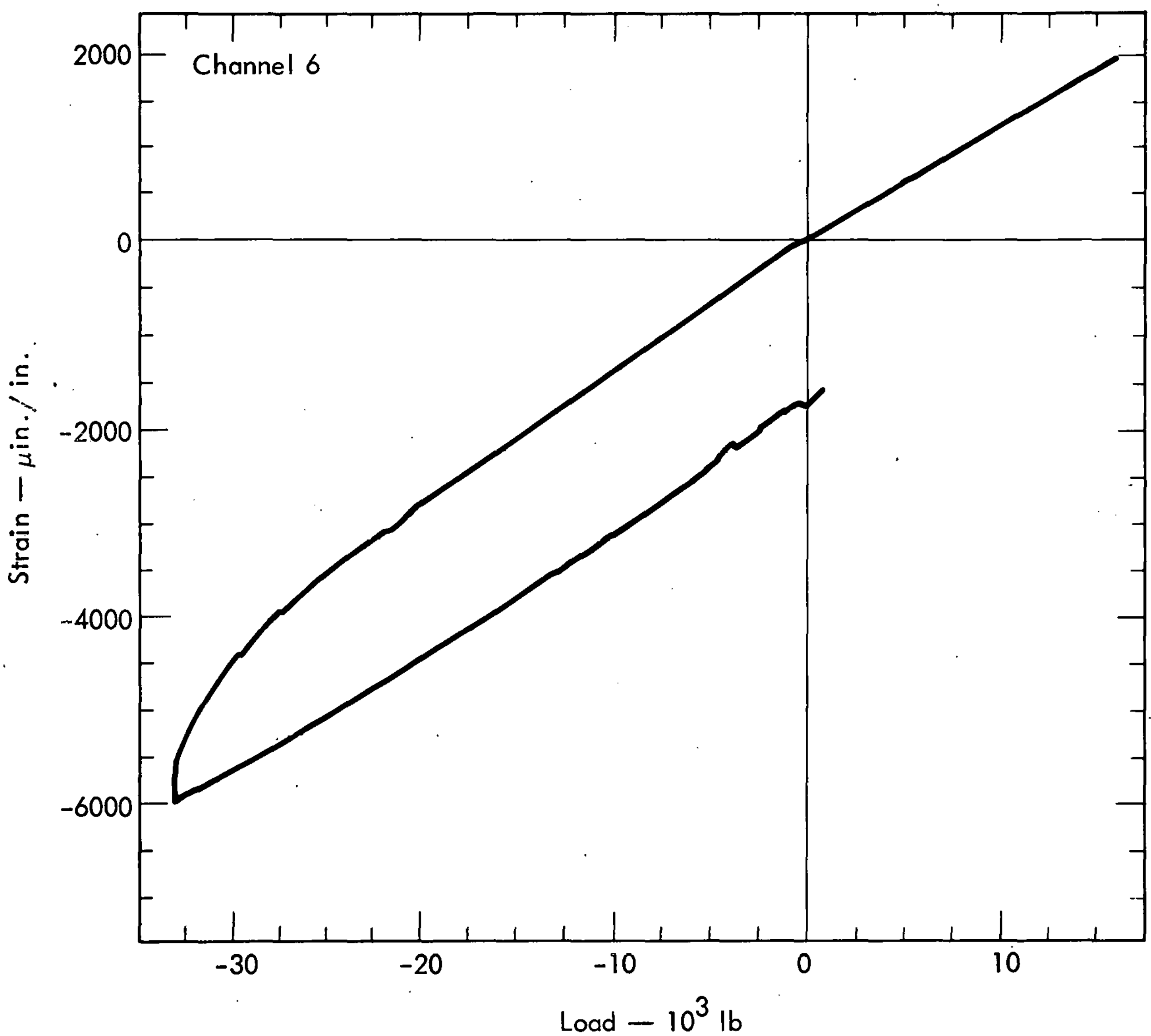


Fig. 7. Tension and compression plot of metal foil strain gage No. 6.

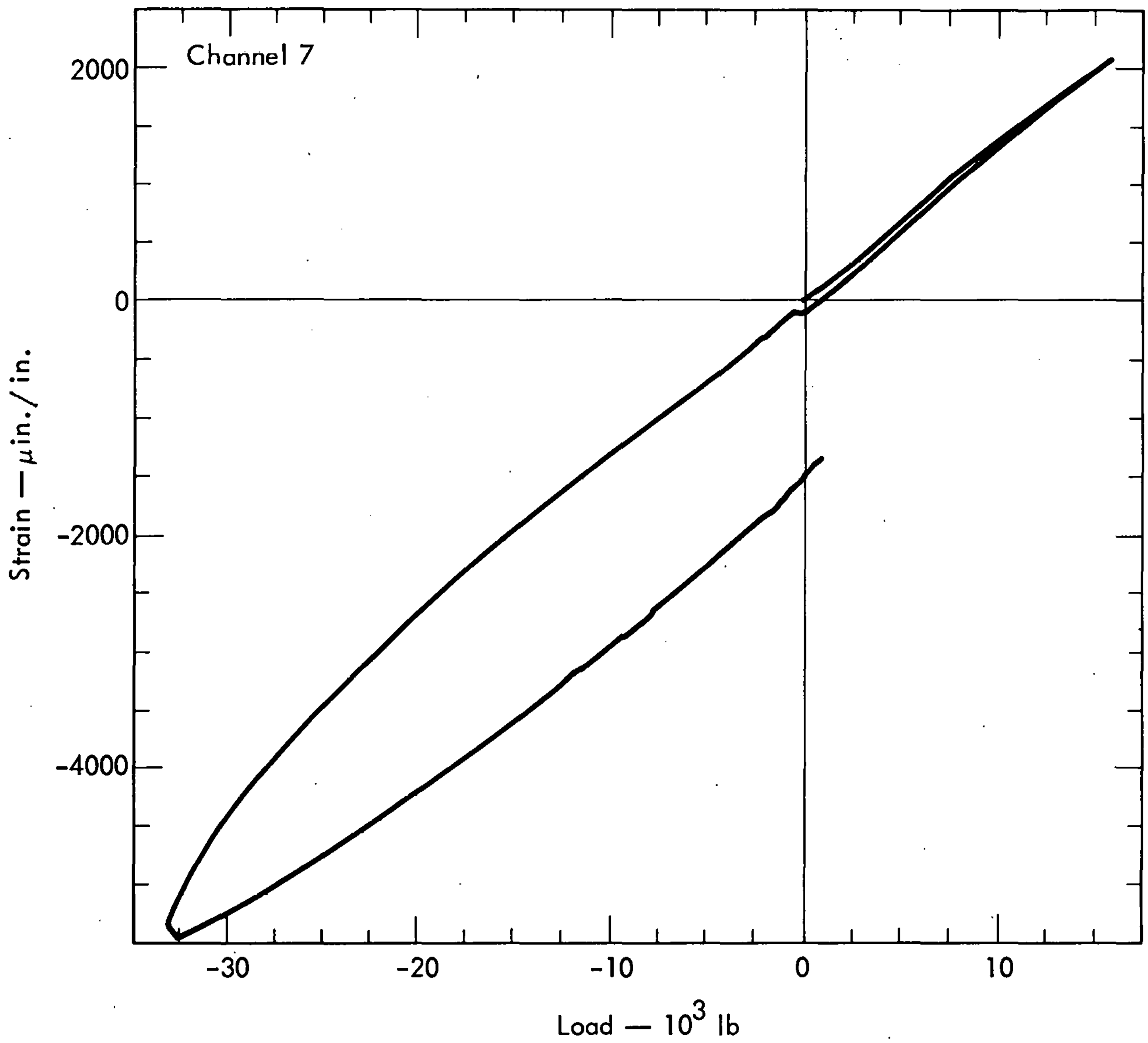


Fig. 8. Tension and compression plot of weldable Kulite gage No. 7.

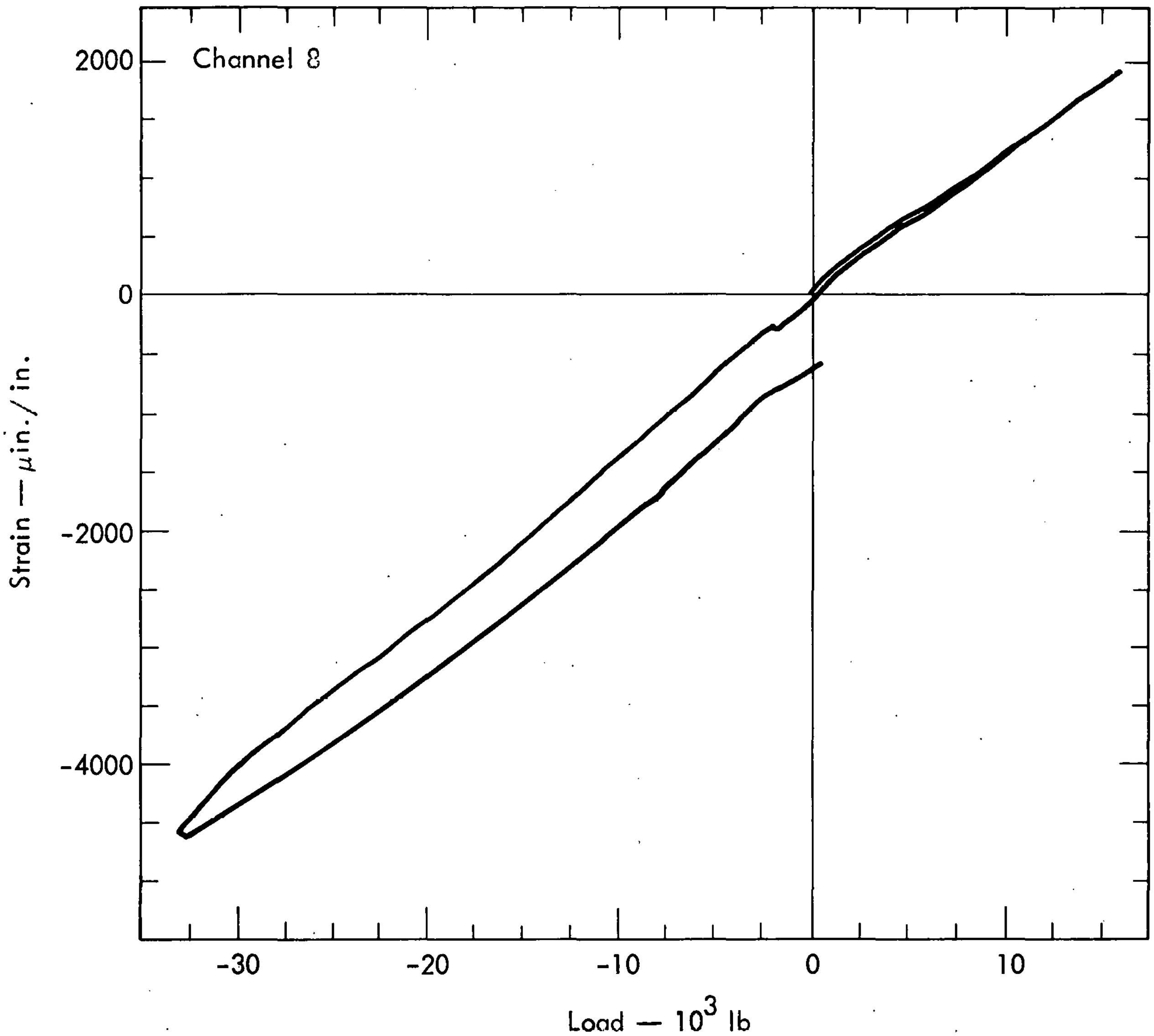


Fig. 9. Tension and compression plot of weldable Kulite gage No. 8.

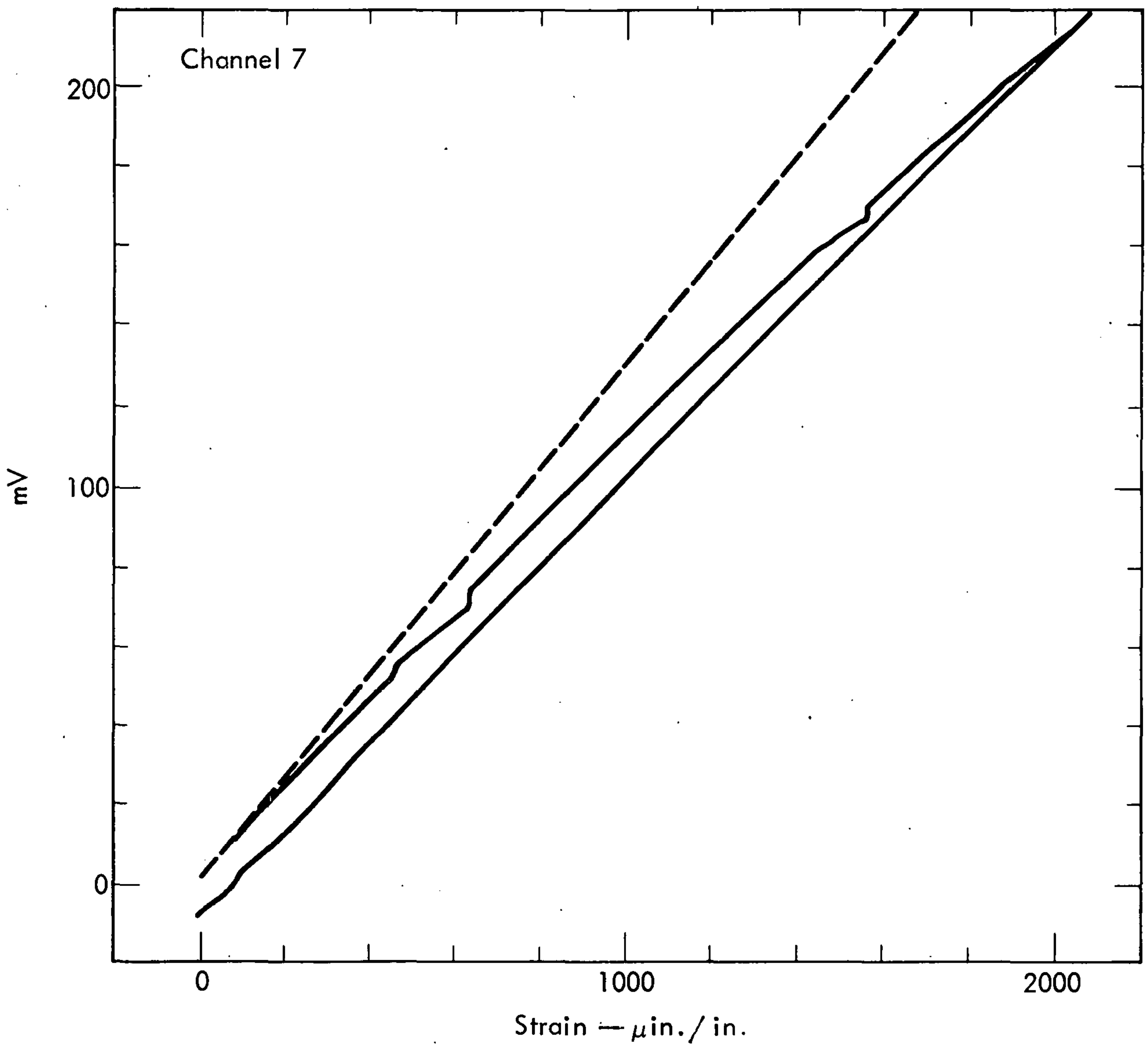


Fig. 10. Linear approximation (dashed line) derived from the Kulite-specified gage factor compared to the actual tension data for weldable Kulite gage 7.

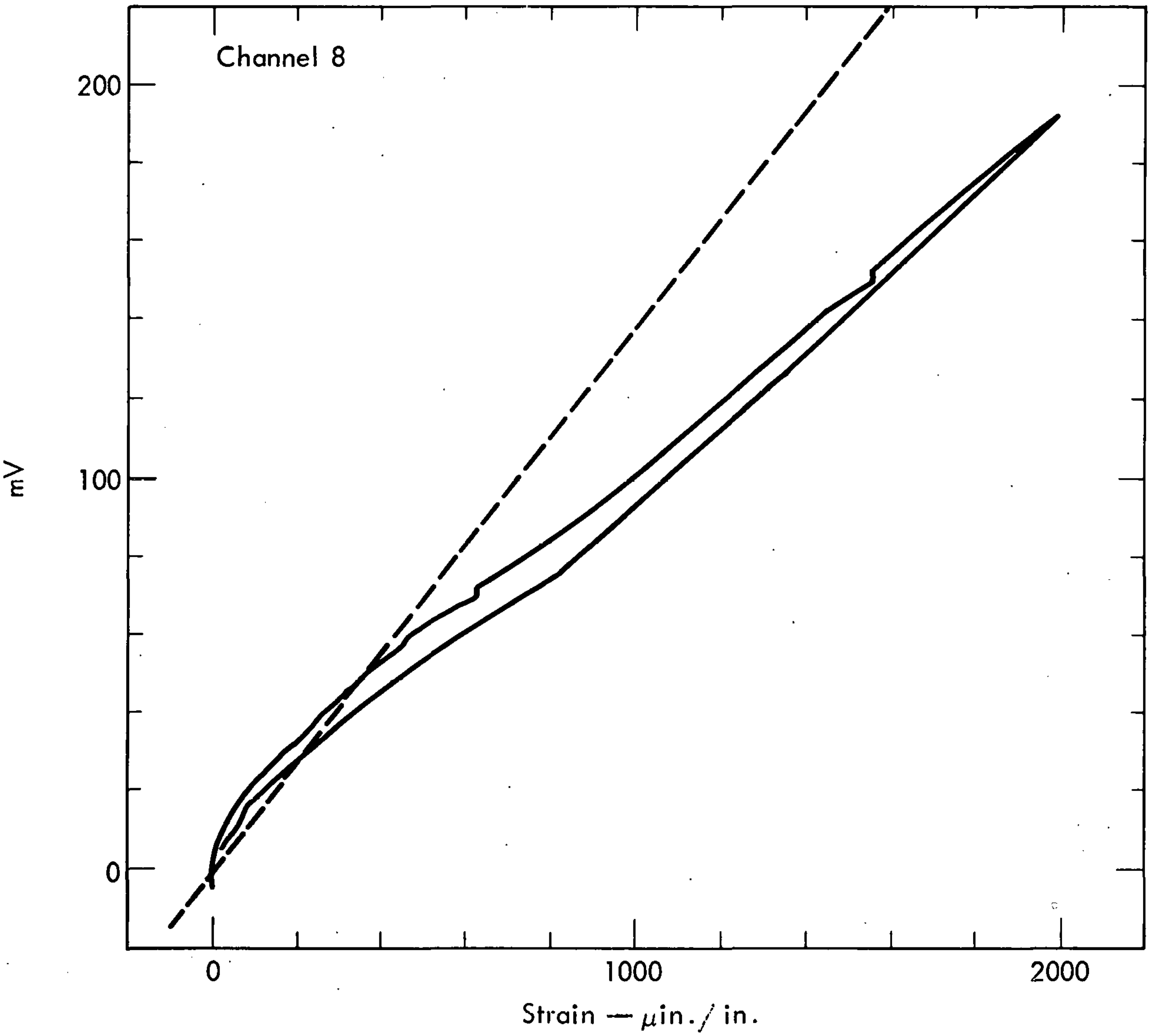


Fig. 11. Linear approximation (dashed line) derived from the Kulite-specified gage factor compared to the actual tension data for weldable Kulite gage 8.

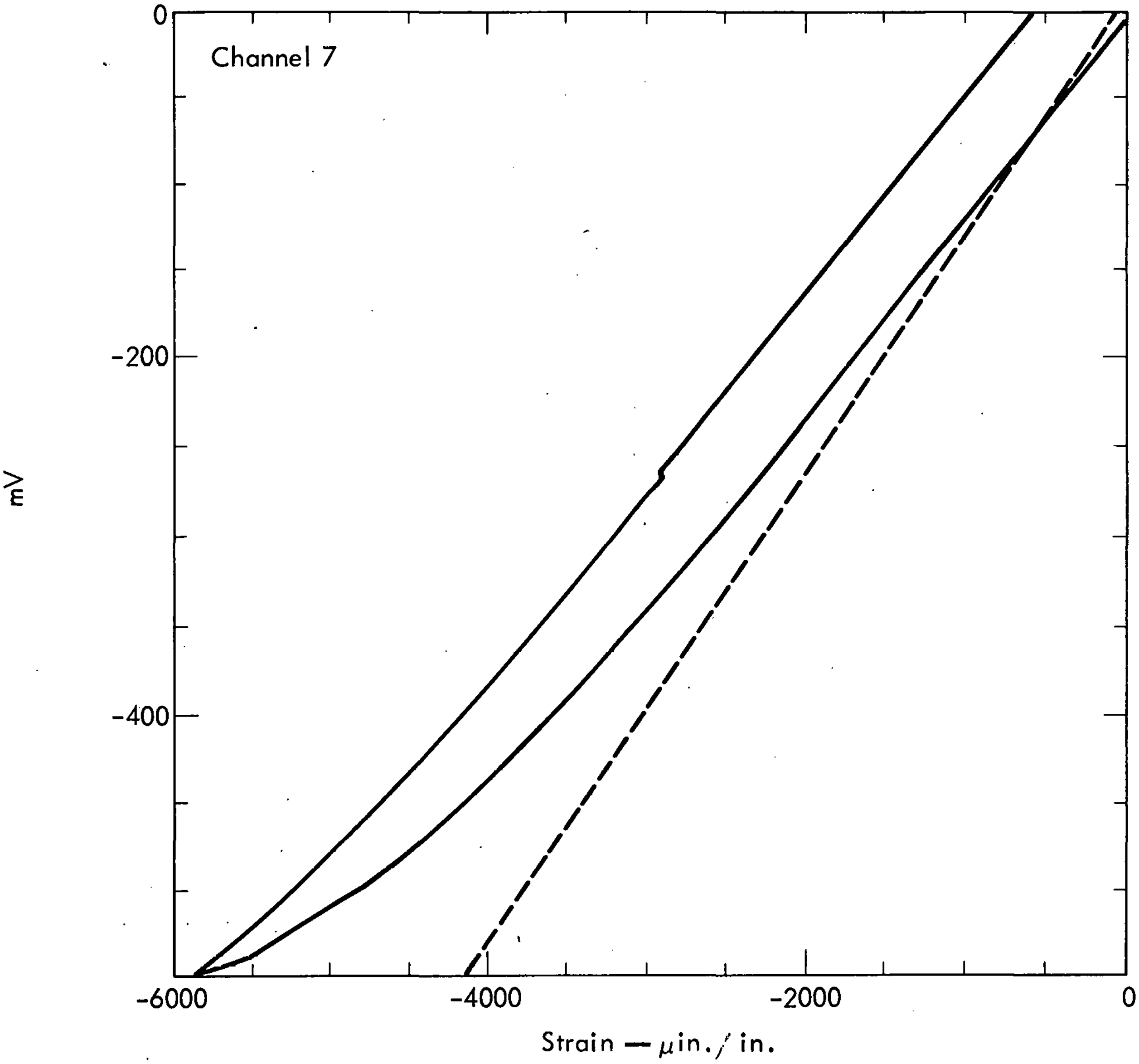


Fig. 12. Linear approximation (dashed line) derived from the Kulite-specified gage factor compared to the actual compression data for weldable Kulite gage 7.

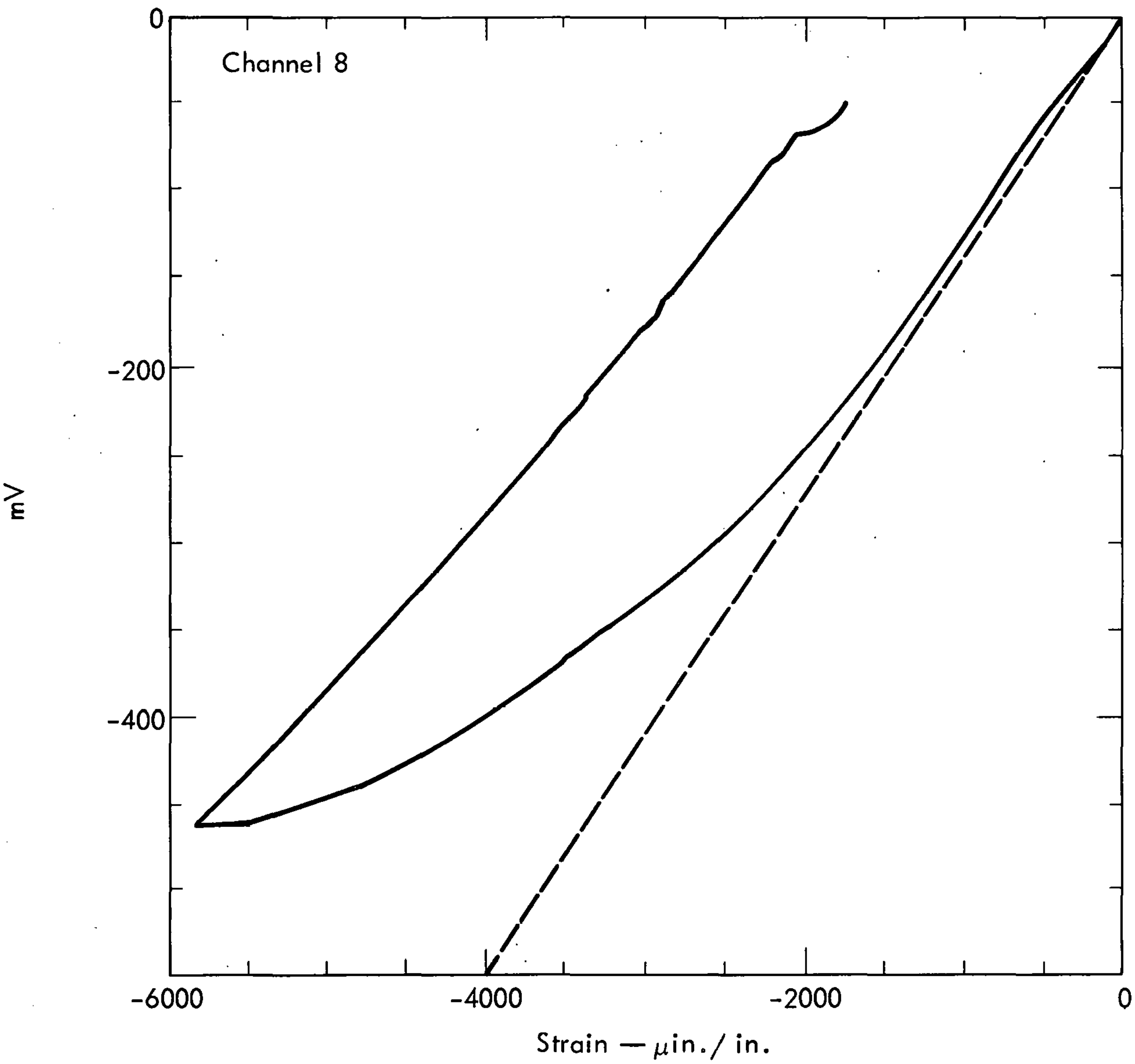


Fig. 13. Linear approximation (dashed line) derived from the Kulite-specified gage factor compared to the actual compression data for weldable Kulite gage 8.

of the Kulite gages were linear within 100 microstrain. The two Kulite strain gages exhibited large differences in their output voltages below -3000 microstrain. Refer to Fig. 14, which shows the compression data for both Kulite gages plotted on the same scale.

CONCLUSIONS

The operating range of the weldable Kulite model M(6)-EP-120-500W is limited practically to +2000 microstrain tension followed by -2500 microstrain compression. The Kulite gage outputs appeared to be reasonably linear between +2000 and -2500 microstrain. Below -2500 microstrain both gages zero-shifted by such large and differing amounts that pipe forces cannot be reliably calculated. We believe that the strain gage spot welds began to fail at -2500 microstrain.

Between +2000 and -2500 microstrain, the measured gage factor for Kulite gage 7 was 177 at +2000 microstrain and 194 at -2500 microstrain. For Kulite gage 8, it was 154 at +2000 microstrain and 190 at -2500 microstrain. These gage factors are 12 to 30% less than the Kulite-specified gage factor of 220 microstrain. The Kulite-supplied gage factor, therefore, is not correct.

RECOMMENDATIONS

Because of different gage factors in tension and compression, zero shifts due to yielding spotwelds, and nonlinearity, the Kulite gage should be limited to 2500 microstrain in either tension or compression. This strain corresponds to 78 000 psi stress in P-110 pipe material.

There is no need to use either semiconductor or weldable strain gages, with their inherent problems, for measuring the high strains in field test applications. A conventional adhesive-bonded metal foil strain gage is recommended because of its constant gage factor, negligible hysteresis and zero shift, and its high accuracy.

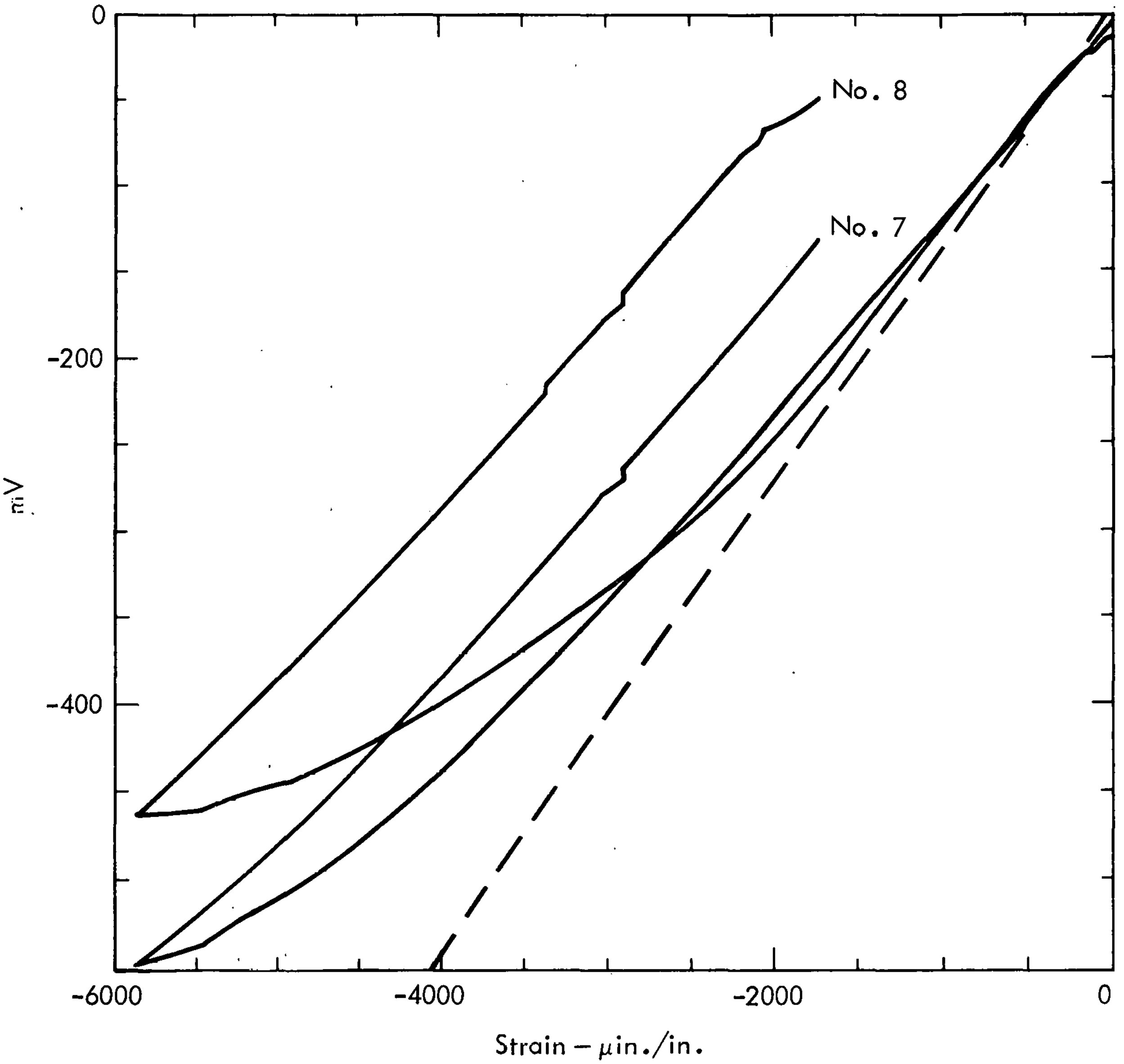


Fig. 14. Comparison of the actual superimposed compression data for weldable Kulite gages 7 and 8 to the linear approximation (dashed line) derived from the Kulite-specified gage factor.

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