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The Effects of Extended High-Temperature Storage on the Performance Characteristics of Several Strain Gage Pressure Transducers

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The Effects of Extended High-Temperature Storage on the Performance Characteristics of Several Strain Gage Pressure Transducers

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FOREWORD

The work described in this note was performed as part of a project on development of methods for evaluation of electro-mechanical transducers. The project has been jointly supported by a number of government agencies, including the Naval Air Systems Command, U. S. Navy and the Office of Advanced Research and Technology, NASA. During the period of the performance of this work, the Project Leader was Paul S. Lederer.

Joshua Stern
Chief, Section 425.03

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

The Effects of Extended High-Temperature Storage on the Performance Characteristics of Several Strain Gage Pressure Transducers

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ABSTRACT

This publication reports the results of a test program to evaluate the effects of high-temperature storage on the performance characteristics of several types of commercial strain gage pressure transducers. The results obtained indicate shifts in the zero pressure output and the sensitivity, some of which are permanent. The equipment used and the procedure followed are described.

KEY WORDS: Pressure transducer, strain gage, life testing, temperature storage, temperature cycling, sensitivity shift, zero shift.

INTRODUCTION

With the increasing use of transducers for measurement and control in industrial applications, the stability of the performance characteristics of these devices becomes very important. This is particularly important in computer-controlled industrial processes where transducers may have to operate reliably over relatively long periods of time and under adverse environmental conditions.

In a task recently completed as part of the NBS InterAgency Transducer Project, the effects of many thousands of pressure cycles on the performance characteristics of strain gage pressure transducers were investigated and reported ("Life Cycling" Test on Several Strain Gage Pressure Transducers, Technical Note No. 434). The temperature environment in which a transducer operates may also have a considerable effect on its performance. Evaluation of the temperature characteristics over a short period of time (hours) is a well established procedure. No publications have been found, however, which investigate the effect of long term storage (weeks) of transducers at elevated temperatures within the manufacturer's specified operating range. Accordingly, a test program was initiated to investigate temperature storage effects on a number of commercial strain gage pressure transducers, commonly used in aerospace technology and of particular interest to our sponsors, including types with bonded metallic wire strain gages, metallic foil strain gages, and semiconductor strain gages. The maximum specified operating temperature for eight of the transducers was 121°C (250°F). The remaining two transducers had maximum specified operating temperature of 93°C (200°F) and 343°C (650°F), respectively. Seven transducers were subjected to a temperature of about 107°C (225°F) for five weeks followed by a three week period at laboratory ambient temperature. The remaining three transducers, including the one with the maximum operating temperature of 93°C, were subjected to a maximum temperature of 91°C in the same procedure so as not to exceed the 93°C limit of that one transducer.

The terms describing the calibration of transducers in this paper conform to the definitions as given in ISA RP37.1, "Nomenclature and Specification Terminology for Aerospace Test Transducers with Electrical Outputs."

TEST EQUIPMENT

The test equipment used for transducer calibration in this laboratory is described in detail in NBS Technical Note No. 411, Method for Performance-Testing of Electromechanical Pressure Transducers. Summarizing briefly, the test set-up was composed of a dead-weight piston gage capable of generating pressures up to 500 psi with an uncertainty of less than ±0.05% and a temperature chamber with a range of -73 to 273°C and an uncertainty of ±1/2°C. For the temperature-storage evaluation, the system was modified to supply pressures of equal amplitude simultaneously to four transducers which were mounted inside of the temperature chamber. Thus static calibrations could be performed on as many as four transducers using one read-out device and a four-position switch. The pressure connection from the dead-weight piston gage to the transducers was made with copper tubing which passed through the door of the temperature chamber. The temperature of the chamber compartment was set and monitored by an externally adjustable thermostat. A wire thermocouple attached to the fixture holding the transducers was used to verify the temperature of the transducer and mounting structure. A photograph of the test set-up appears in Figure 1.

Transducer excitation voltages were supplied by commercially available semiconductor power supplied having drift characteristics specified as less than 0.2% during an eight-hour period following warm-up. A commercially available laboratory potentiometer capable of reading up to 11 volts was used to measure the excitation inputs. In cases where the excitation voltage exceeded the rating of the potentiometer, a precision voltage divider was used at the input to the potentiometer. The error in the measurement of the excitation voltage, with or without the voltage divider, was estimated to be less than ±.02%. The same laboratory potentiometer was used to measure transducer output voltage.

TEST PROCEDURE

The temperature storage tests were run in three groups, the first two groups being composed of three transducers and the last group, four.

One of three transducers of identical model number was included in each group.[1] Each run was begun by performing three successive calibrations at laboratory ambient conditions within an eight-hour period on each group of transducers to obtain information on the short term repeatability of the transducers. The static temperature characteristics of the transducers were then determined by performing eleven-point calibrations to full scale at several temperatures within operating ranges. The results of the temperature test were plotted in terms of sensitivity shift and zero shift versus temperature. The next portion of the calibration procedure consisted of high-temperature-storage evaluation. The test procedure required five consecutive days and, therefore, was begun on Monday mornings. The group of transducers was first calibrated at laboratory ambient temperature. Following the calibration the chamber temperature was set to a level near, but not exceeding, the maximum operating temperature of the transducers. After the transducer temperature had reached equilibrium, the transducers were recalibrated while at the higher temperature near the end of the first day (5-6 hours after the initial calibration) and on each of the next three days. On the fifth day the transducers were again calibrated at the higher temperature after which the chamber was brought down to ambient temperature. After adequate time was allowed for temperature equilibrium, the transducers were recalibrated. This procedure was followed for five successive weeks. During the sixth week, the transducers were held at ambient temperature and one static calibration performed daily. During the seventh week, the transducers remained at ambient temperature, but no calibrations were performed. In the eighth week, three calibrations were performed within an eight-hour period on one day. The entire test procedure was carried out on each of the three groups of transducers. At appropriate points in the procedure, the data were plotted and evaluated. The voltage excitation was continuously applied to the transducers during the entire eight weeks of the storage test period.

STATIC TEMPERATURE TEST RESULTS

All ten transducers were designed for constant voltage operation. Other pertinent transducer characteristics obtained from the manufacturers are given in Table I. As indicated in the table, the maximum operating temperature for transducer F was specified as 93°C. Thus transducer F and the two transducers tested with it, transducers A3 and G, were tested to 93°C in the static temperature test and stored at 91°C in the high-temperature procedure. The other transducers were calibrated to a maximum temperature of 117°C and stored in the extended storage

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[1]Originally, the three transducers were to be used as test monitors since these transducers were expected to have similar reaction to temperature environments. Contrary to expectation, the three transducers, A1, A2, and A3, exhibited dissimilar zero shifts in the static temperature test. See Static Temperature Test Results.

procedure at about 107°C. The results of the static temperature runs are plotted in Figure 2 for bonded and unbonded metallic-strain-gage-type transducers; in Figures 3 and 4 for the semiconductor-type transducers. The open points in Figures 3 and 4 represent calibration points within the operating range of the particular transducer but outside of the range for which temperature shift specifications are given by the manufacturer. No plot is shown for the high-temperature strain gage pressure transducer since it was not tested to its maximum operating temperature.

Six of the ten transducers were metallic-strain-gage pressure transducers designed for operation to 121°C. Transducers A1, A2, and A3 were unbonded wire-strain-gage types carrying the same model number. Each of the three test groups included one of these unbonded transducers. Transducer B was a bonded wire-strain-gage type, while transducers C and D were bonded metallic-foil-strain-gage types. The temperature-sensitivity curves for the six metallic-strain-gage pressure transducers were observed to be approximately linear with the largest thermal sensitivity being only about 0.02%/°C over the range from about -40 to 117°C. The temperature-zero pressure output curves for six transducers showed more variety than the temperature-sensitivity curves. Two unbonded strain-gage-type transducers carrying the same model number exhibited the largest positive and negative thermal zero shift of the six transducers tested. Transducer A3 had a negative thermal zero shift with a maximum change of about -2.5% FS over the temperature range from -40 to 117°C while transducer A2 had a thermal zero shift of +1.6% FS over the same range. The remaining four metallic-strain-gage pressure transducers had thermal zero shifts of less than 1% FS over the same range.

Transducer E was an unbonded high-temperature wire-strain-gage transducer designed to operate from -196 to 343°C. Static temperature tests on this transducer covered only the range from -40 to 243°C. Over this range the sensitivity of transducer E varied a maximum of 0.4% from its value at room temperature. The thermal zero shift observed for transducer E was 4.9% FS over the tested range.[2]

The semiconductor-type transducers showed more variation in sensitivity due to temperature change than the conventional strain-gage type transducers. Transducers F and G had semiconductor strain elements bonded to their diaphragms. The semiconductor element of transducer H was described as being bonded to a spring element attached to the diaphragm by a push rod. The temperature-sensitivity curves for all three

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[2]Actually, two complete static temperature calibrations were performed on transducer E. The first test indicated a thermal zero shift of about 17%/100°C over the range from -40 to 243°C. Since this shift was far beyond tolerances, the manufacturer was consulted as to the probable cause. The defect was traced to a poorly fitting mounting adapter. After the adapter was replaced transducer E was recalibrated. The results appearing in the text represent the results of this second calibration.

transducers had similar shape but different magnitudes. Within the region -18 to 54°C (0 to 130°F), transducer H had the largest thermal sensitivity shift of the three transducers. Outside of the region, the effects of temperature compensation become apparent in transducers F and H as indicated by the bends in their curves. The temperature-zero pressure output curves for the semiconductor-type transducers show that in the region -18 to 54°C, transducer F had a maximum variation of less than 1/2% FS, and transducer G had a maximum variation of about 2 1/2% FS. The temperature-zero pressure output curve obtained for transducer H formed a hysteresis loop. During the test, transducer H reacted to each temperature change as if the transducer had received a thermal shock. Because of this, the normal one-hour allowance for temperature equilibrium was extended to assure that the transducer's temperature had equalized. The approximate heating rate of the air inside the temperature chamber was about 24°C per minute.

Recalibration of transducer E with an adapter designed to alleviate case strain problems resulted in a thermal zero shift of about 4.9% FS/100°C over the same temperature range. Static temperature tests on this transducer did not cover its entire operating temperature range. The sensitivity of transducer E varied a maximum of 0.4% from its value at room temperature over the tested range.

TEMPERATURE-STORAGE TEST RESULTS

Figures 5, 6, and 7 show the trends in the ambient temperature sensitivity and values resulting from the eight week temperature test. Figure 5 represents the typical daily pattern of the shifts noticed during the extended storage procedure. Figures 6 and 7 represent the effects of the temperature storage on the weekly ambient temperature calibrations for all transducers. Zero pressure outputs and sensitivities obtained in the high-temperature storage were referred to the initial ambient temperature calibration in the first week of the extended storage test. To determine the effects of temperature storage during a given week, the sensitivity and zero pressure output obtained for the ambient temperature calibration at the end of the week and the ambient temperature calibration at the beginning of the next week were averaged. For the weeks when the transducer was stored at high temperature (the first five weeks), this average was plotted. For the weeks when the transducer was stored at ambient temperature, the weekly average was plotted.

HIGH-TEMPERATURE-STORAGE EFFECTS ON TRANSDUCER SENSITIVITY

The high-temperature-storage effects on transducer sensitivity are plotted in Figure 6. With the exception of transducers A2 and D, the conventional strain-gage-type transducers underwent maximum sensitivity shifts of less than 0.1%. Transducer A2 underwent a rapid sensitivity shift of 0.2% during the initial week; following the rest period, the sensitivity of transducer A2 recovered to within 0.1% of its initial value. Transducer D underwent an initial sensitivity shift, recovered somewhat, and then showed a gradual increase in sensitivity until the beginning of the rest period. The sensitivity of transducer D stabilized within 0.2% of its initial value during the rest period. The sensitivity did not return to its original value during the remainder of the test period.

The high-temperature strain gage pressure transducer, E, showed its largest sensitivity shift during the second week of temperature storage. Transducer sensitivity changed a maximum of about +0.4% from its initial value. The sensitivity did not recover from this shift during the remainder of the test period.

The sensitivities of the three semiconductor-type transducers, F, G, and H, showed a notable change following the first week of high-temperature storage. By the fourth week, the transducer sensitivities had reached the maximum departure from their initial values. They began to level off or recover during the fifth week. During the rest period following the fifth week, the sensitivities drifted back toward their initial value. Transducer F, which had a maximum shift of 0.4% from its initial sensitivity, recovered to within 0.14% of that sensitivity by the eighth test week. Transducer G had a maximum shift of about 0.2% and recovered to within 0.02% by the eighth week. Transducer H had a maximum shift of about 0.7% from its initial value and recovered to within 0.4% of that value by the eighth week.

HIGH-TEMPERATURE-STORAGE EFFECTS ON TRANSDUCER ZERO PRESSURE OUTPUT

The effects of temperature storage on zero pressure output are shown in Figure 7. For the wire-strain-gage pressure transducers, zero pressure output shifted markedly during the first week of storage test and more gradually afterwards. Transducers A1, A2, A3, B, and D had positive zero shifts while transducer C had a negative zero shift. The gradual zero shift continued through the entire high-temperature procedure until the transducers were stored at ambient temperature (the rest period). During the first week of the rest period, each zero pressure output stabilized at some fixed level and did not vary notably from that level through the remainder of the rest period. The following shifts were observed in the transducer zero pressure outputs following the high-temperature-storage test: transducer A1, about +3.1% FS; transducer A2, about +2.3% FS; transducer A3, about +0.9% FS; transducer B, about +3.3% FS; transducer C, about -1.4% FS; and transducer D, about +0.7% FS.

The high-temperature pressure transducer, E, also had a marked shift in zero pressure output after the first week of high-temperature storage. The zero pressure output continued to decrease until after the first week of the rest period. By the eighth week of the test period (the third week of the rest period), the zero pressure output of transducer E had stabilized at about -3.3% FS from its initial value.

The zero pressure output of the semiconductor-type pressure transducers reacted differently to the high-temperature storage. The zero pressure output of transducer F showed little change due to high-temperature storage. Its zero pressure output had a maximum shift of about +0.15% FS during the first five weeks of test and had recovered to within +.05% FS at the end of the test period. Transducer G had a gradual zero output shift of about +4.3% FS during the first five weeks and leveled off at about +4.4% FS at the end of the test period. The zero pressure output of transducer H decreased irregularly (following a slight initial increase), reaching about -0.9% FS at the end of the fifth week of the test period. During the first week at ambient temperature, however, it recovered to within -0.3% FS from its initial value, where it remained throughout the remainder of the test period.

HIGH-TEMPERATURE-STORAGE EFFECTS ON LINEARITY AND HYSTERESIS

Linearity is herein defined as the maximum deviation from the best-fit straight line as determined by least squares through all calibration points. Hysteresis is herein defined as "the maximum different in output at any given measurand value when that value is approached first with increasing and then decreasing measurand." (ISA RP37.1) Figure 8 shows the linearity and hysteresis curve for three ambient temperature calibrations of transducer A3; the initial ambient, the ambient beginning the fifth week, and the final ambient of the eighth week. This transducer had the largest change in linearity and hysteresis during the extended temperature storage tests. From the graphs of Figure 7 and similar graphs for the other nine transducers, it appears that the extended high temperature storage had no significant effect on the ambient temperature linearity and hysteresis values.

SUMMARY OF TEST RESULTS

Briefly, the following information has been obtained from observation of the ten commercial transducers tested:

1. The five week high-temperature-storage program produced sensitivity shifts ranging from -0.7% to +0.3%, and zero shifts ranging from -2.5% full scale to +4.5% full scale.

2. Apparent permanent changes at the end of the entire eight week stroage and rest program ranged from -0.4% to +0.4% for sensitivity, and from -3.0% full scale to +4.5% full scale for zero output.

3. Extended storage of a transducer at temperatures near its maximum operating temperature can result in permanent changes in the transducer performance characteristics.

4. Conventional metallic-strain-gage pressure transducers as well as semiconductor-strain-gage pressure transducers are

susceptible to high-temperature-storage effects with the zero pressure output being more susceptible to permanent change than the sensitivity.

5. High-temperature-storage effects are apparently not prevented nor reduced by temperature compensation. Although a transducer may be compensated over a temperature range, extended storage within that range can still cause performance changes.

6. The change in performance characteristics due to high temperature storage appears to be not only a function of transducer design but also of the quality of assembly of the particular transducer. Thus storage effects observed in one transducer of a particular model may differ from that of another transducer of the same model.

CONCLUSION

The results of this 5-week test program indicate that changes in the sensitivity and zero characteristics of electromechanical pressure transducers can occur as a result of storage at temperature above ambient laboratory conditions. In some cases these performance changes are permanent. High-temperature soaking of some transducers before putting them into service at elevated temperature may reduce performance changes during their operation since some transducers were observed to have their most drastic changes during the early portion of this temperature-storage test.

To assure reliable performance of pressure transducers operated at elevated temperatures for extended periods of time, the effects of the environment on the particular transducer must be investigated, since zero shifts up to 4.5% FS were observed in this program in which the pressure transducers were subject to the elevated temperatures for only 5 weeks. Some applications of transducers require that the transducer operate reliably in elevated temperature environments for much longer periods.

ACKNOWLEDGEMENT

The technical assistance of John H. Pinkard, Jr. is gratefully acknowledged for his aid in compiling the data for this report.

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TABLE I

Transducer Specifications
(Furnished by the Manufacturers)

Identification	Type	Pressure Range psi	Operating Range °F	Sensitivity Shift %/°F	Zero Shift % FS/°F	Manufacturers Error Band % FS
Metallic Strain Gage						
A1	Unbonded wire strain gage	0-50	-65 to 250	.02	.03	.5
A2	Unbonded wire strain gage	0-50	-65 to 250	.02	.03	.5
A3	Unbonded wire strain gage	0-50	-65 to 250	.02	.03	.5
B	Bonded wire strain gage	0-50	-65 to 250	.01	.01	.25
C	Bonded foil strain gage	0-50	-100 to 250	.03	.03	.1
D	Bonded foil strain gage	0-50	-100 to 250	.02	.03	--
High-Temperature Metallic Strain Gage						
E	Wire strain gage	0-50	-320 to 650	.01	.02	.5
Semiconductor Strain Gage						
F	Silicon strain gage	0-50	-40 to 200	.01	.01	.5
G	Bonded semiconductor strain gage	0-50	-65 to 250	*	*	.75
H	Semiconductor strain gage	0-50	-20 to 250	.01	.01	.5

*Specified as "within 2% over compensated range"

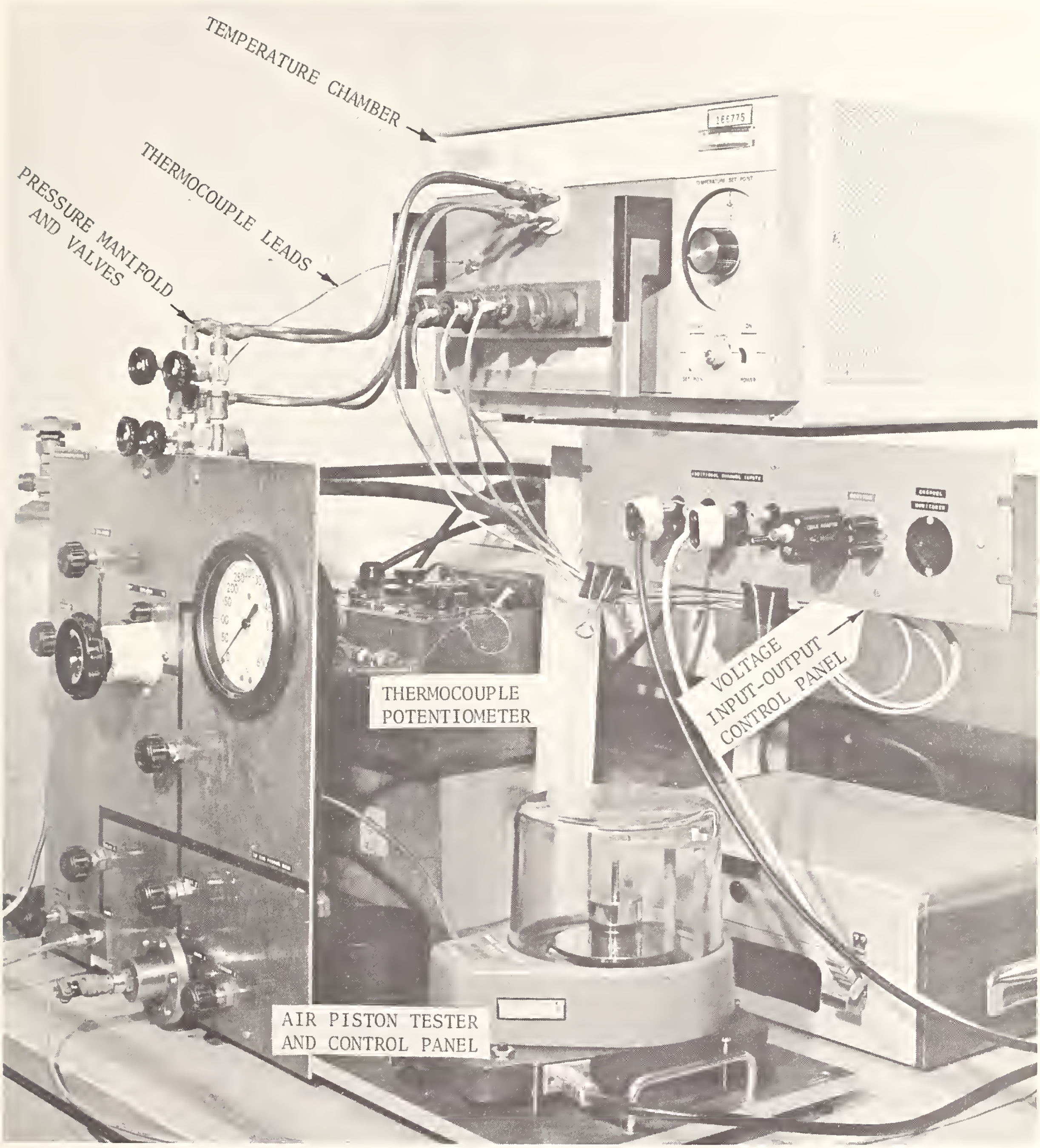

Figure 1: Extended High-Temperature-Storage Test Equipment

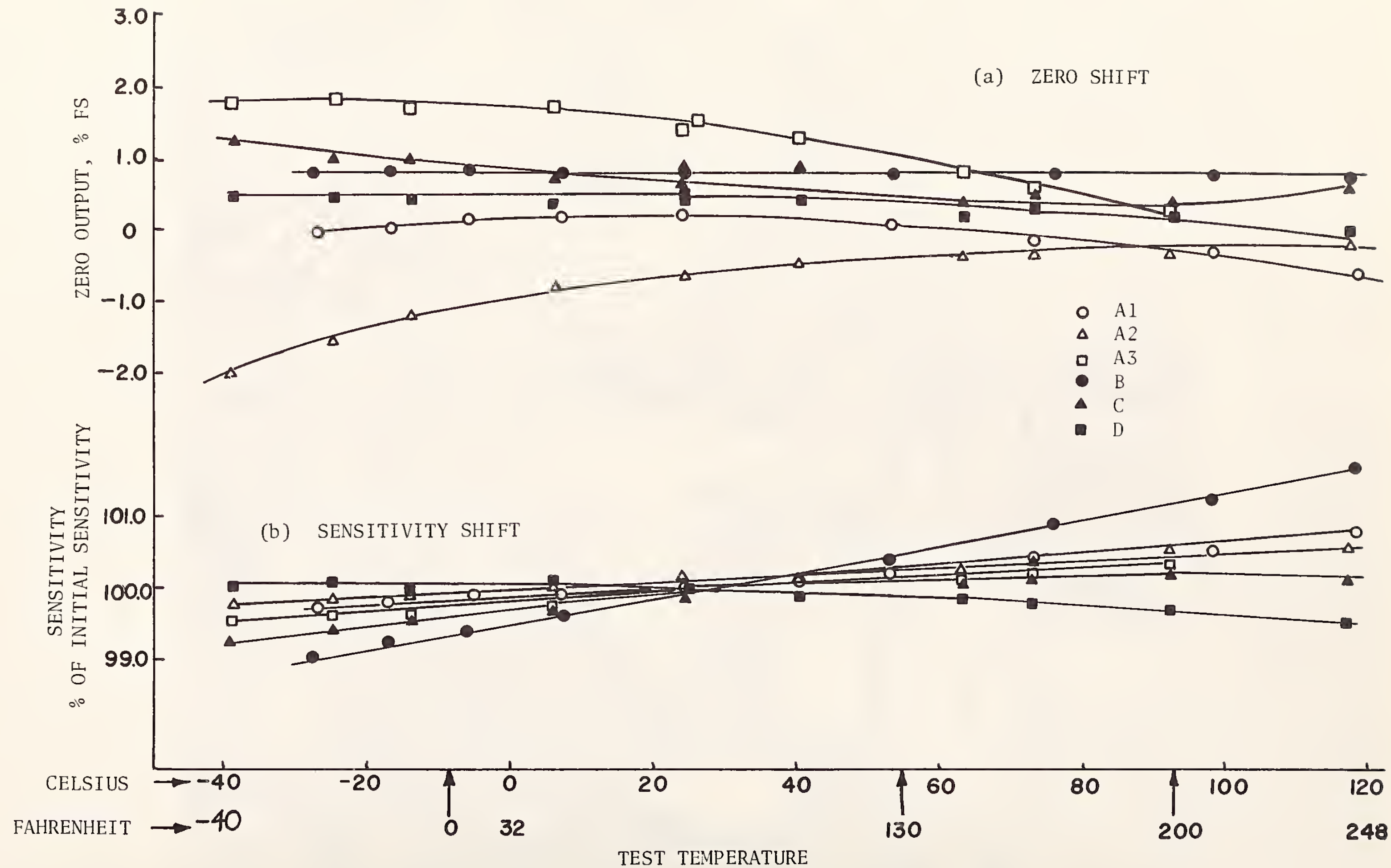

Figure 2: Constant Voltage Static Temperature Test - Metallic Strain Gage Pressure Transducers

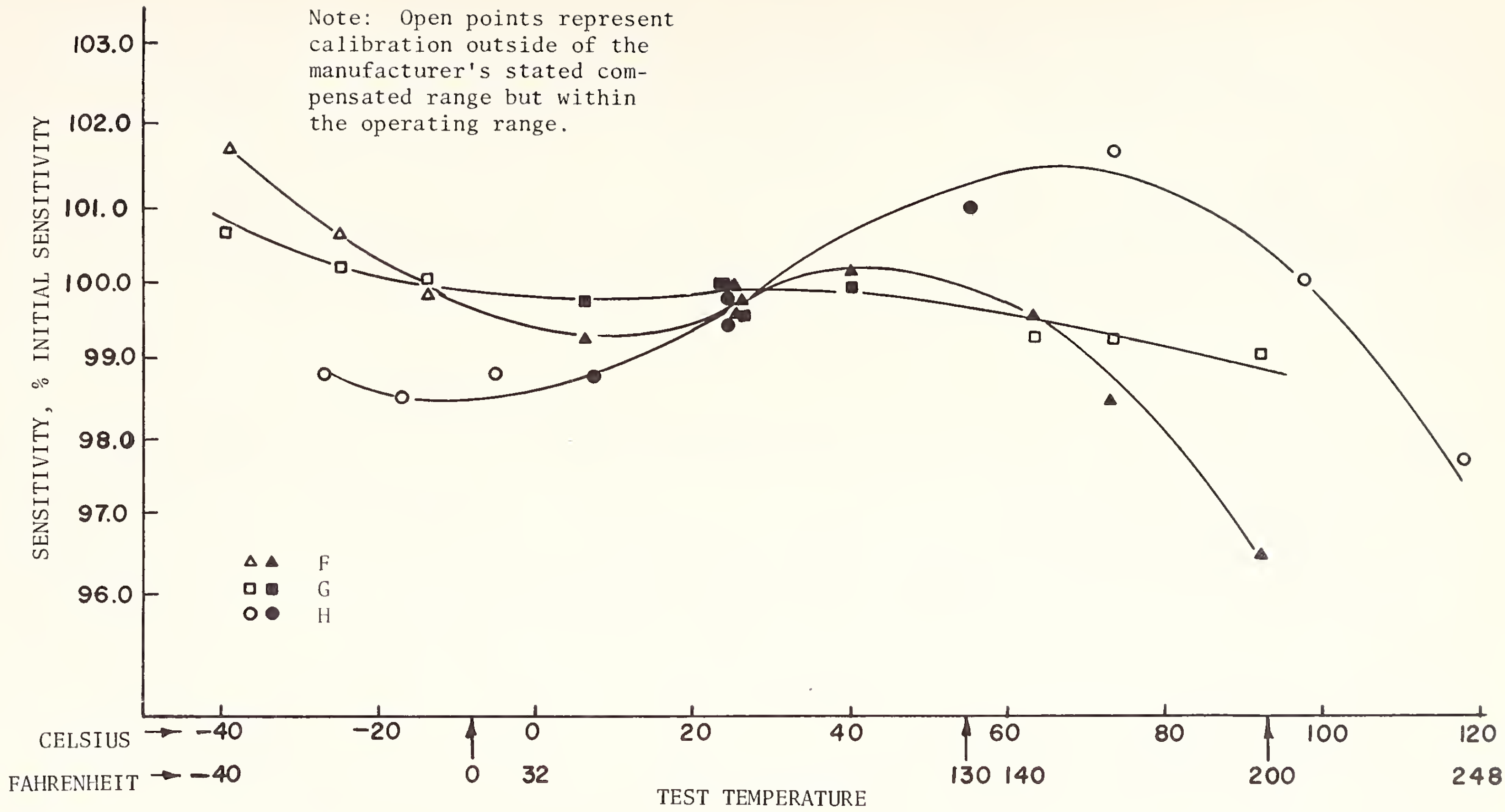

Figure 3: Constant Voltage Static Temperature Test - Semiconductor Pressure Transducers, Effect of Temperature on Transducer Sensitivity

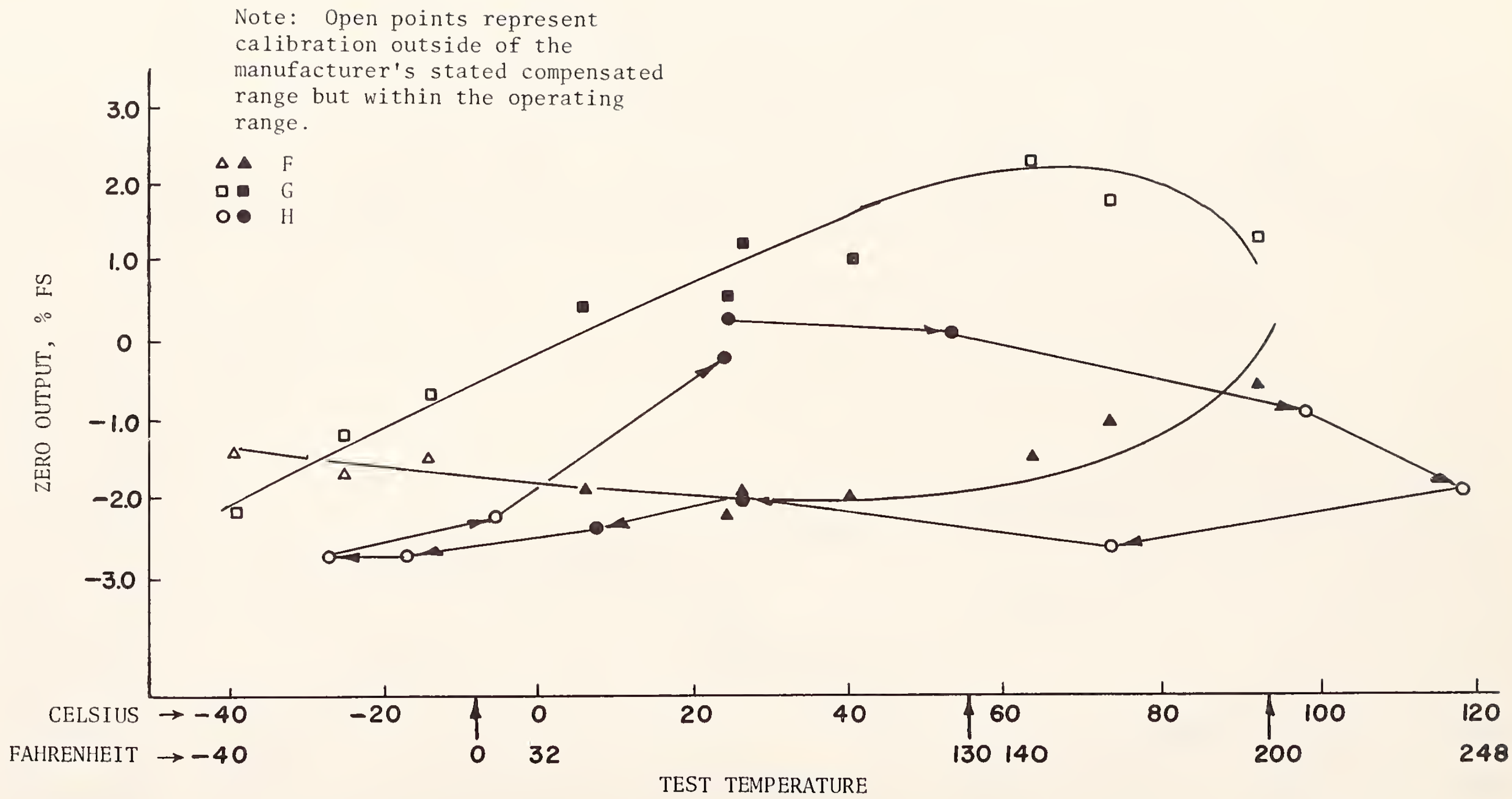

Figure 4: Constant Voltage Static Temperature Test - Semiconductor Pressure Transducers, Effect of Temperature on Transducer Zero Value

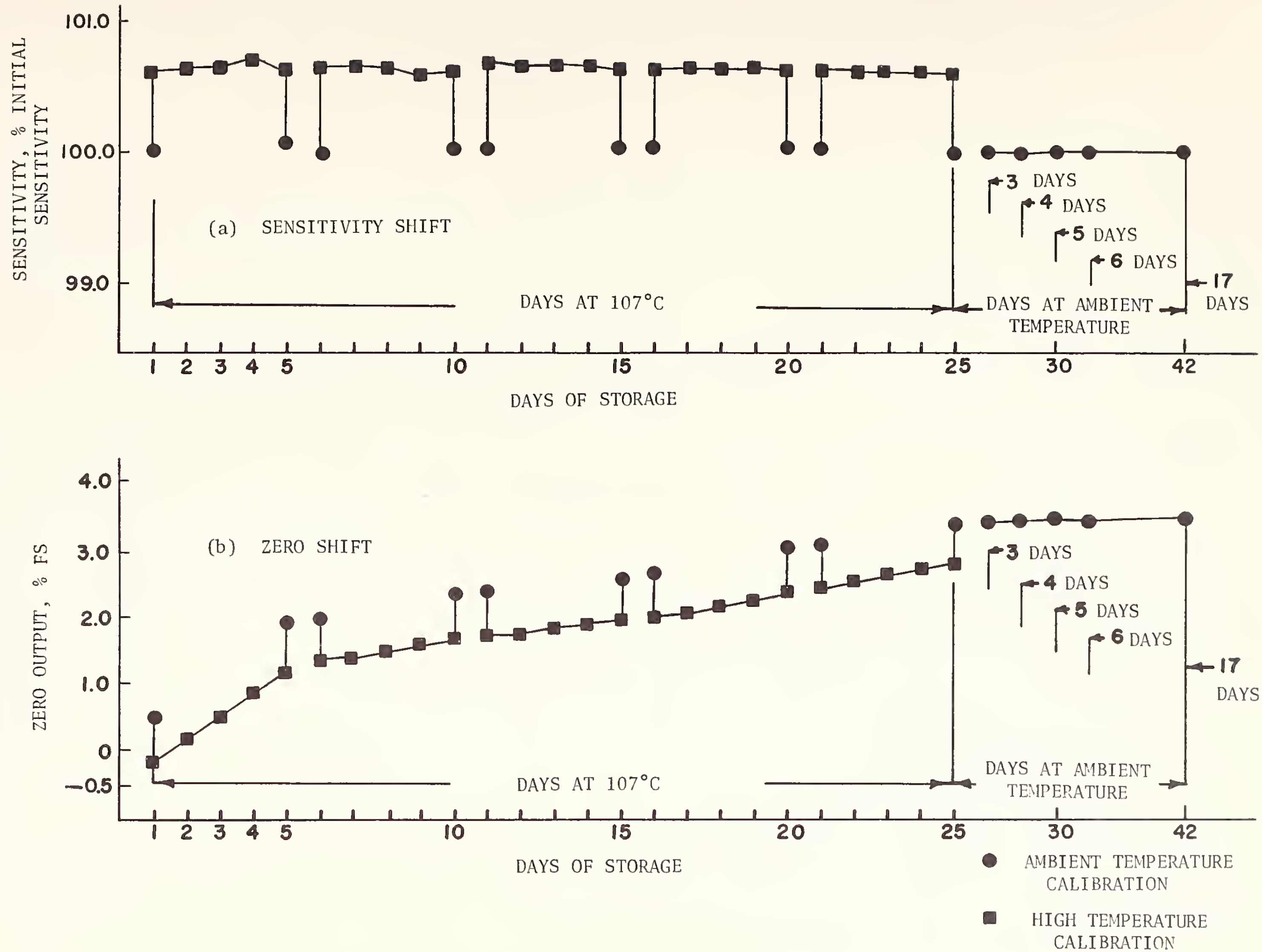

Figure 5: Typical Daily Trend During High-Temperature Storage-Unbonded Metallic-Strain-Gage Pressure Transducer Al

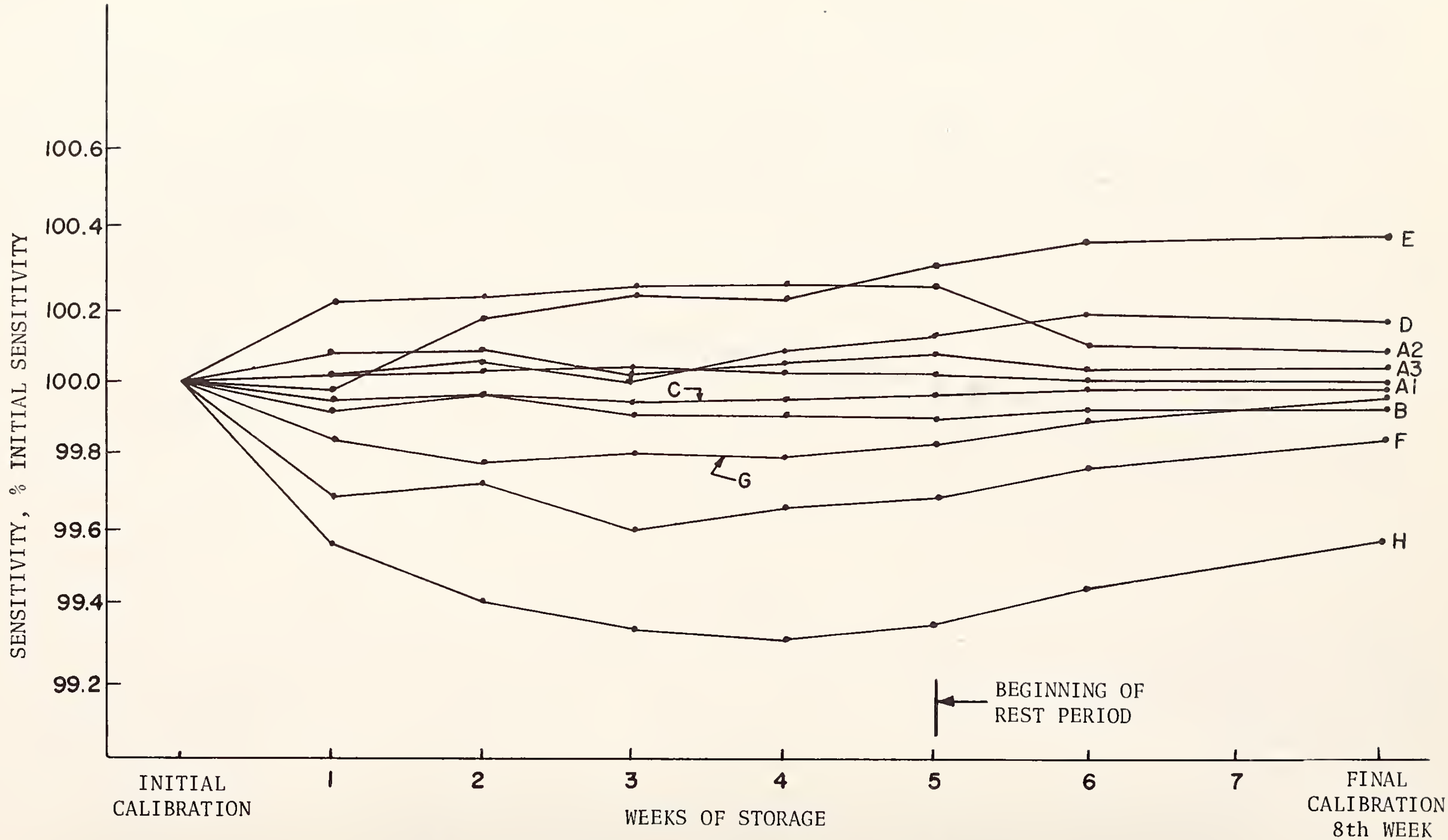

Figure 6: Sensitivity Shift During High-Temperature-Storage Test

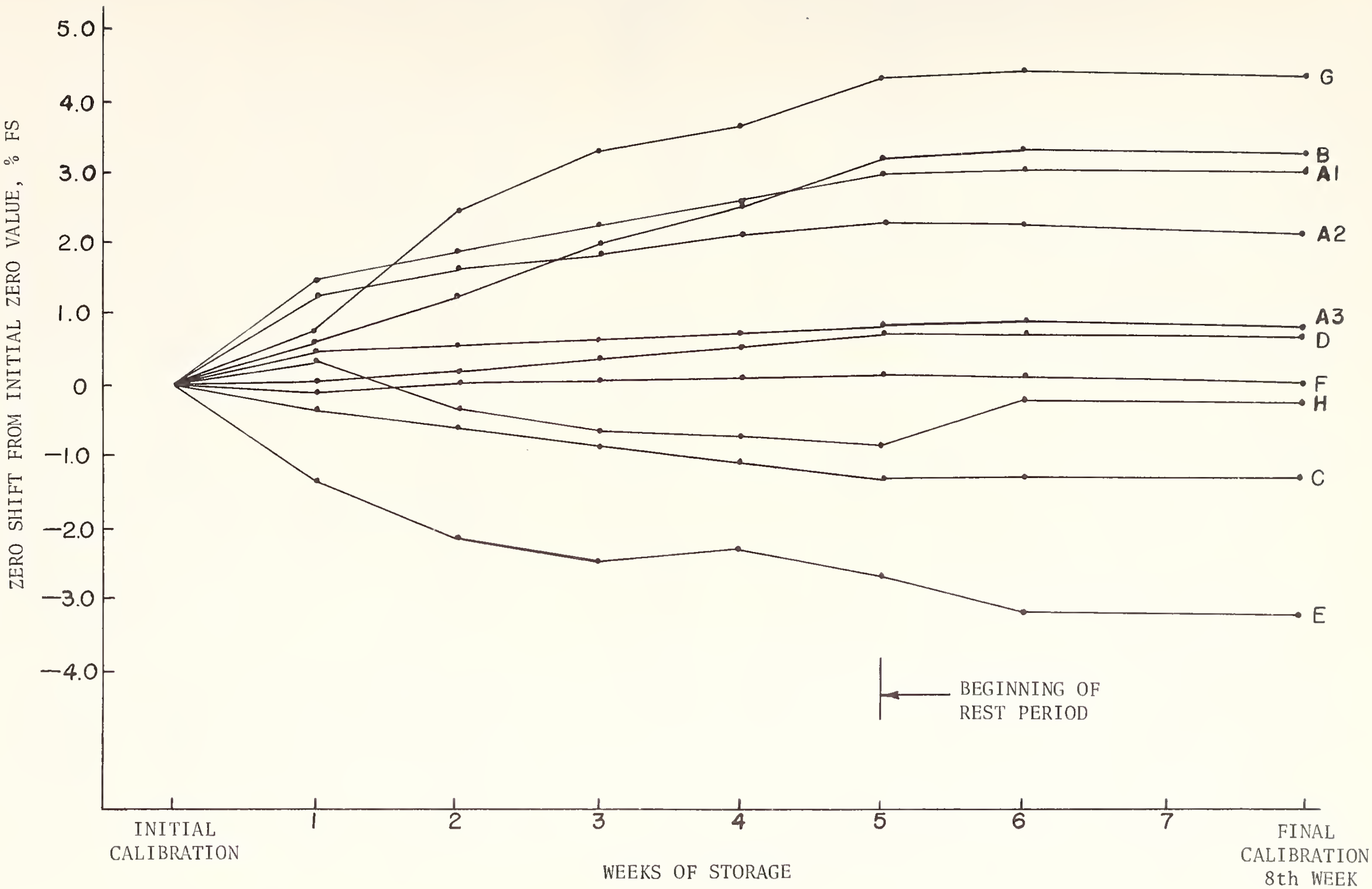

Figure 7: Zero Shift During High-Temperature-Storage Test

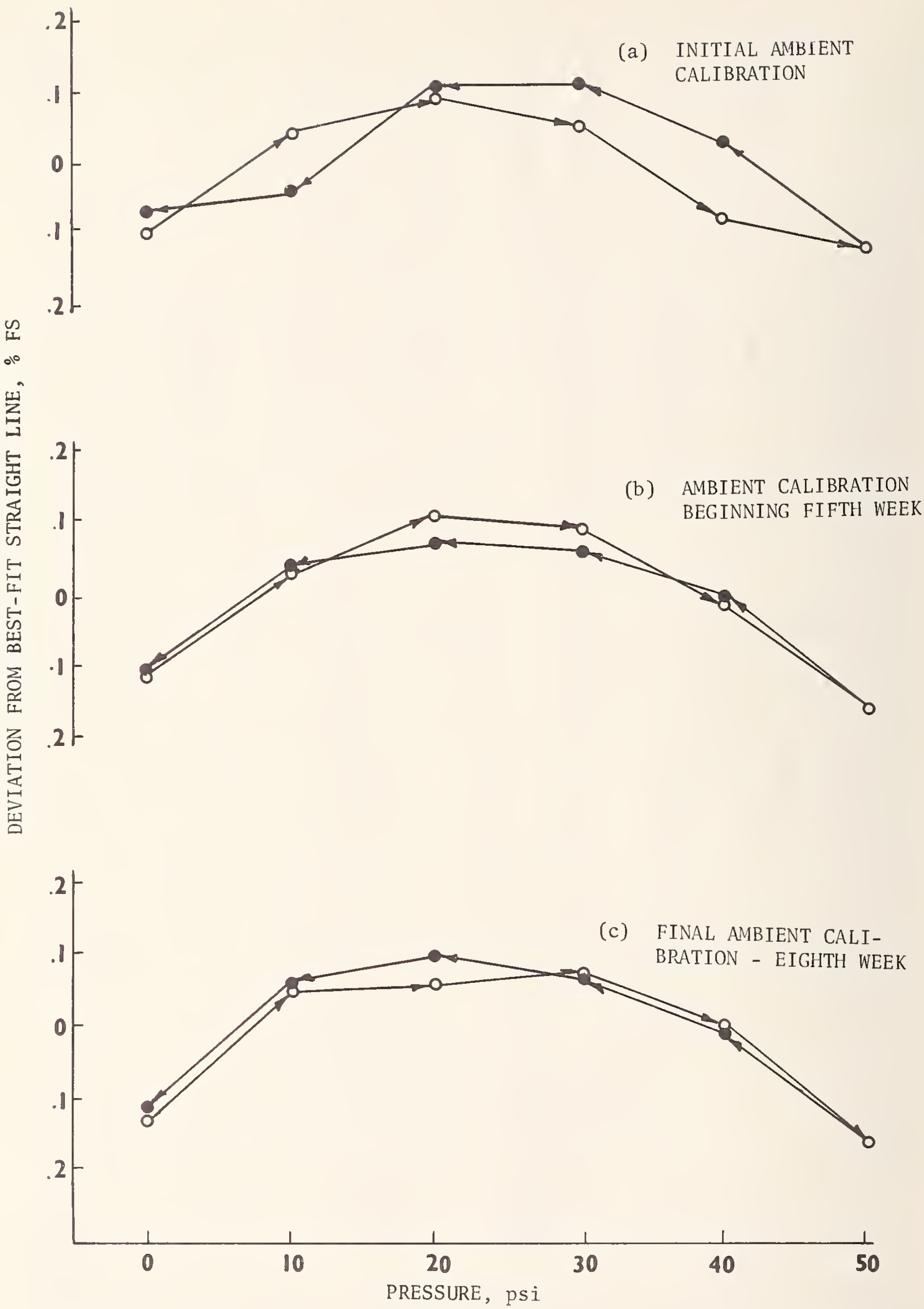

Figure 8: Effect of Temperature Storage on Linearity and Hysteresis - Transducer A3

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JULY 1969

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