NBS TECHNICAL NOTE

434

"Life Cycling" Test on Several Strain Gage Pressure Transducers

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"Life Cycling" Test on Several Strain Gage Pressure Transducers

Paul S. Lederer

This publication reports the effects of many thousands of pressure cycles on the performance characteristics of several types of strain gage pressure transducers. The results obtained indicate permanent changes in zero pressure output and sensitivity. Most of these changes tend to occur during the first few thousands of cycles. The equipment and procedures used to obtain the data are described.

Key Words: Life cycling, pressure cycling, life testing, pressure transducer, strain gage.

Introduction

The rapid increase of computer controlled processes and operations in industry, as well as the advent of space missions of long durations, places progressively more stringent requirements on the performance of the transducers used.

In these applications, deterioration of the transducer's performance characteristics with time, short of complete failure, may have a critical effect on the process or the mission. In industry, incorrect data provided by a deteriorating transducer may not only result in product waste, but may require complete shutdown to replace or recalibrate the transducer. On a space mission, malfunction of critical transducers may imperil the entire mission itself.

Sinusoidal pressure calibrators are now becoming available for the dynamic calibration of pressure transducers at frequencies up to several thousand hertz. All of these devices are designed to produce dynamic calibrations of the transducer under test with reference to a built-in "Standard" transducer which is subjected to the same pressure variations. It is apparent that in the course of determining one frequency response characteristic, both transducers may be subjected to several hundred thousand pressure cycles. Additional dynamic calibrations will impose many more pressure cycles on the reference transducer. If the performance of the reference transducer deteriorates with pressure cycling, the validity of the dynamic calibrations may be in doubt.

Relatively little effort has been expended on "life testing" of transducers to establish that time period during which transducers will continue to sense the physical quantity under test within assigned limits of precision. Most of the work done has apparently dealt primarily with the determination of "cycling life" to complete failure of potentiometers, some potentiometric transducers and strain gages.

In view of the scarcity of existing information on the subject, an experimental program was started in the Basic Instrumentation Section of the Institute for Applied Technology of the National Bureau of Standards. This work is a part of the "Interagency Telemetering Transducer Program" at the National Bureau of Standards and is currently supported by agencies of the Defense Department and NASA. The objective of the initial phase of this program was to establish test methods and develop test equipment for "life cycling" of pressure transducers. The objective of the second phase of the program was the investigation of the effects of repeated application of the physical stimulus on some of the performance characteristics. Several types of strain gage pressure transducers were tested in a normal laboratory environment.

This report describes test methods and equipment as well as the results of "life cycling" tests on several, commercial electro-mechanical pressure transducers with strain gage sensing elements. The sampling of transducers tested is insufficient to predict with validity the possible performance of all strain gage pressure transducers when subjected to pressure cycling. The test results are, however, indicative of the existence of possible deterioration of performance characteristics of some transducers and thereby serve as warning of the existence of potential problem areasin certain transducer applications. The results also serve to indicate the capabilities of the test procedure and equipment.

Related and Previous Work

An examination of the manufacturers' literature on transducers, collected during the past several years' operation of the "Interagency Transducer Program" indicates that only a relatively small number of data sheets mention anything relating to a transducer's life. The information may be given in various ways. The manufacturer of a potentiometric pressure transducer defines "life (operational)" as "minimum of 50,000 full scale cycles." A similar transducer (of different manufacture) is said to have a "life" of 25,000 cycles; life is defined in this manufacturer's catalog as "...nominal life expectancy without malfunction and can be expressed as mechanical and/or electrical life." The literature for a semiconductor strain gage pressure transducer states: "Life expectancy: indefinite. No wearing parts." A potentiometric accelerometer is said to have a life "in excess of 2,000,000 cycles without affecting performance." This last statement implies recognition of the possible effect of repeated application of the stimulus on the performance of the transducer. A data sheet for a bonded strain gage pressure transducer (dated 1952) goes further. Among the specifications for this transducer, a paragraph on "fatigue life" states "typical cells up to an including 20,000 psi have been tested to 1,000,000 cycles of pressure from 10% to 100% of rated pressure, with no change in measuring performance or reduction in bursting strength." More recent data sheets issued by the same company give no information on "life."

Additional examples can be found to confirm the following impressions:

1. Manufacturers' literature gives very little information about

the operational life of these devices.

2. In the few cases where information is given, there appears widespread disagreement as to the manner in which "life" is to be defined and reported.

3. In many of the cases where information on "life" is given, there is no indication that this denotes quantitative deterioration of performance of the device.

The "life" has assumed considerable importance in recent years. Papers have been written on life testing [1] and transducer performance [2] and, indeed, a very extensive program of reliability data exchange was conducted under sponsorship of the Bureau of Naval Weapons, the "Failure Rate Data (FARADA) Program" [3]. Information from this program, as well as in the other two references concerns total failure and may be given as a "failure rate per million operating hours" or "mean time between failures (MTBF)."

The problem of the deterioration of performance during life, before final failure occurs, has received much less attention. A search through files of federal specifications uncovered a specification on dial pressure gages [4] which specifies a "pressure whip" test: "The pressure gages shall be capable of withstanding without damage or change in accuracy of not more than 1/2 percent of full scale value from initial accuracy readings...a total of 28,800 cycles of pressure...." In these tests "cycle excursion in percent of scale range" has values of 20% to 80% for certain gages and 40% to 60% for others. More recently, several tentative recommended practices published by the Instrument Society of America have considered the problem. "Cycling Life" is defined [5] as "The specified minimum number of full range excursions or specified partial range excursions over which a transducer will operate as specified without changing its performance beyond specified tolerances." A test procedure is briefly described in another recommended practice dealing with strain gage pressure transducers. [6]

Inquries were made to the "Transducer Information Center" of Battelle Memorial Institute, Columbus, Ohio, and discussions were held with NBS staff members engaged in the investigation of strain gage characteristics. While little information appears to exist on the performance deterioration of pressure transducers, the discussions uncovered a few references describing pertinent work on strain gages. A survey of wire strain gage fatigue data [7] indicates widely varying results, with fatigue failures (at a strain level of ±.001 inch/inch) occurring after as few as 3000 cycles to not occurring after 3.4 x 10^6 cycles. Some gages showed an increase in strain sensitivity after cycling. A detailed examination of strain gage performance during "life cycling" [8] dealt with gages made from Advance (TM) foil in the as rolled (hard), heat-treated (half-hard) and annealed (soft) conditions. As rolled is said to be specified for transducer work requiring minimum hysteresis, heat-treated for temperature compensated strain gages, annealed for "post yield" gages. The tests showed a zero shift which increased with the number of strain cycles for gages prepared from the three basic batches. "As rolled" gages showed a wide spread in zero shift, ranging from about 7% of the maximum strain after about 3 x 10^5 cycles to less than 1% after 10^6 cycles. Heat treated foil gages showed much smaller zero shifts, a maximum of 2.5% of the maximum strain after 8 x 10^5 cycles. The gage factors of these two types appeared to change less than 0.5% during the entire test. One phenomenon observed was a rapid increase in sensitivity, with or without waveform distortion, which occurred in some gages during the test. This "supersensitivity" in some cases resulted in an increase in gage factor of 30%. Another study [9] of a variety of bonded foil strain gages using different adhesives concluded that "...gage factor and thermal coefficient of resistivity were negligibly affected by cyclic strain regardless of the adhesive or cure used. Zero shift was the one gage characteristic significantly affected." In all cases, zero shift was most rapid initially, generally reaching a value close to the final one for 10^6 cycles after about 2 x 10^5 cycles. Maximum zero shift observed was equivalent to about 10% of the maximum strain applied. Some tests carried to 10^7 cycles showed little additional zero shift beyond that found after 10^6 cycles. Data given in above cases, (8) (9) were obtained at a cycling rate of 30 times per second.

Published information on semiconductor strain gages (10) indicates fatigue life "in excess of 5 x 10^6 cycles without failure at 500, 1000, and 1500 microstrain levels." No indication of changes in performance characteristics is given.

A manufacturer of load cells ran some tests to determine the useful dynamic load capacity of some load cells (11). The "useful fatigue life" or "endurance limit" was defined as "The maximum cyclic strain at which the changes in no-load output and sensitivity (gage factor) will not exceed 1% of full scale and 0.25%, respectively, for at least 10^7 cycles." Large changes in sensitivity (supersensitivity) were also found during some of these tests and zero shifts up to 9% before failure occurred. These results were obtained at a rate of 11.1 hertz.

One might expect the effects of "life cycling" on pressure transducers to be somewhat different from those of the strain gages alone, since such transducers are complex devices incorporating a number of elastic components and materials. Full scale design strain levels for strain gage pressure transducers are believed to be about .0015 inch/inch. Based only on the reported results on strain gages, however, "life cycling" might be expected to have the following effects on the performance characteristics of strain gage pressure transducers.

1. A maximum zero shift of up to several percent of the full scale range, changing most rapidly during the first 2 x 10^5 cycles and then increasing much more slowly.

2. A slight change in the sensitivity during cycling. The percentage change in sensitivity should generally be a fraction of the per-

centage zero shift for the same number of cycles.

3. Relatively unpredictable fatigue failures for some of the transducers, particularly under conditions of moderate overloads.

Test Equipment

The equipment required for the "Life Cycling" tests was assembled and mounted on standard relay rack panels. A photograph of the equipment is shown in Fig. 1. The picture shows two set-ups on two separate panels. The upper one, labeled "panel #1," is the prototype and was built and used first. The bottom panel contains the modified (final) version of the test equipment. The modifications are slight, but this set-up is smaller and more versatile as will be made apparent later.

Fig. 2 is a schematic drawing of the modified (final) test equipment. A synchronous motor drives a cam operated switch which energizes a three-way solenoid valve. When energized, the valve connects the transducer under test to a source of pressure. When the power is interrupted the valve vents the transducer to the atmosphere again. An electromechanical event counter totalizes the number of times that the valve is energized (the number of times pressure is applied to the transducer). The pressure is obtained either from the laboratory compressed-air line (for pressures below about 100 psi) or from a tank of compressed air for the higher pressures. A pressure regulator is used to set the pressure to the desired value as indicated on the dial gage mounted in the panel. The solenoid valve is a commercial ac-operated "quick dump" valve. To avoid shock excitation of the transducer by the rapid pressure changes (the valve is capable of opening or closing in less than 10 milliseconds), a rise time control valve, between solenoid valve and transducer, restricts the flow and hence the rate of pressure change seen by the transducer. During testing, the transducer output is monitored on an oscilloscope whose sweep is synchronized by a small transformer also energized by the motor driven switch. For each transducer to be tested, the rise time control valve is adjusted until the oscilloscope indicates a rise time of the order of 80 to 120 milliseconds with no overshoot or "ringing." Fig. 3, the response of a transducer during a typical test, shows the pressure rise taking about 100 milliseconds followed by a plateau at full pressure of about 560 milliseconds and a fall time of about 140 milliseconds.

Additional features of the modified system include a pulse damping valve for protection of the dial gage against the pressure fluctuations, pilot lights, two additional valves which permit connection of an air piston gage for static calibration of the transducer without removing it from its fixture and an over-ride switch which permits continuous pressurization of the transducer.

The prototype (initial) system operates in the same manner but requires an external "rise time control valve," an external transducer fixture and had no provisions for dial gage protection or piston gage connection. Its synchronous motor operated at 30 rpm, thereby applying a pressure pulse to the transducer every two seconds. While this appeared adequately fast initially, "life cycling" to 10^6 cycles became too time consuming. The final, improved, set-up uses a 50-rpm synchronous motor, which permits application of 72,000 cycles per day. In order to preserve adequately long rise and fall time (to prevent shock excited "ringing") as well as a reasonable amount of time at peak pressure, it does not seem desirable to reduce the total open time of the valve to less than about 250 milliseconds.

The rate used in these tests was selected on the basis of providing the largest number of controlled cycles in a given time with readily available components. The rate of cycling or rate of application of strain may have an effect on the "life cycling" characteristics of transducers. Investigation of this will probably require equipment capable of cycling rates several orders of magnitude greater than the test apparatus described.

Test Procedure

During the early tests, the transducer was pressure cycled during the night only. In the morning, cycling stopped and four three-point calibrations were performed at two hour intervals during the day; the first calibration one hour after cycling stopped. This procedure permitted the transducer to rest between cycling periods. The three-point calibrations include a zero pressure output reading, a full scale reading and second zero pressure reading. While this procedure produced some information on short term, recoverable changes in performance characteristics, it increased the total testing time considerably. The procedure was changed to shorten the testing time required to determine the permanent changes in performance characteristics. From the comparison of the data obtained, the variations in procedure are not believed to have had any significant effect on the test results.

The test procedure finally adopted is made up of a series of eleven-point static calibrations separated by increasingly longer intervals during which the transducer is pressure cycled. The first two static calibrations are performed about one week apart. The transducer rests during the intervening period. After the second calibration the transducer is cycled about 20,000 times, and then it is again calibrated statically. This is followed by more pressure cycling. Based on the experience in this laboratory, it appears desirable to perform the static calibrations at roughly 20,000 cycle intervals up to 100,000 cycles; then at 50,000 cycle intervals to 500,000 cycles; and finally every 100,000 cycles until one million cycles are reached. The actual intervals used may vary depending on time scheduling of the work. Since the most significant changes in performance characteristics seem to occur during the initial 200,000 cycles, it is necessary to sample this region with static calibrations at closer intervals than subsequent periods of "life cycling."

Test Results

Since the main purpose of the testing program was the identification of potential problem areas, rather than the prediction of performance characteristics, a relatively small number of transducers were tested. To keep the coverage broad, however, several types of strain gage pressure transducers were investigated. They included two transducers with unbonded wire strain gage, (A, B) (representing two manufacturers of these devices), a transducer with bonded wire strain gages (C), and one with bonded foil strain gages (D). Finally two pressure transducers with semiconductor strain gages were tested; one with the strain elements diffused into a silicon diaphragm (E), the other with conventional bonded semiconductor gages (F). The transducers were gage pressure devices with a full scale range of 0 to 50 psig with two exceptions, one with an absolute pressure range of 0 to 100 psia (D), the other with a gage pressure range of 0 to 100 psig (E).

The results of the tests, shown in Figures 4 through 9, are given according to performance characteristics in order to show the range of effects that were found in these limited tests, and to emphasize the problems that may be especially significant in the use of pressure transducers over many pressure cycles. All results are plotted with reference to the static calibration immediately preceding pressure cycling.

Zero Pressure Output Changes

Fig. 4 shows the effects of cycling as well as the effects of rest periods following periods of cycling on the zero pressure output of transducer (F). It is evident that there was a cumulative effect on zero pressure output due to the pressure cycling. The zero output shifted in a negative direction (with reference to the output for a positive going pressure applied to the input cavity) with cycling time. It is interesting to note that this shift was not permanent, but that there was a gradual shift back towards the initial zero output prior to cycling. This shift during the rest period of some eight hours showed a linear average trend. This trend was interrupted each time full scale pressure was applied for the three point calibrations. A single application of full scale pressure caused a zero shift of as much as 0.5% FS. During the rest period following this single application of pressure, the zero output drifted back in an exponential manner, rapidly at first then more slowly until the shift corresponded to the linear average rate described above. This test (and similar ones on some of the other transducers) indicated that the pressure cycling was the primary factor responsible for changes in performance characteristics. Accordingly, the test procedure was modified in latter tests so that cycling was carried on continuously, interrupted only by static calibrations at prescribed intervals. Rest periods were eliminated, except in some cases at the end of the cycling tests. Continuous cycling is also more likely to be a realistic simulation of much actual industrial transducer usage.

Fig. 5, a composite of test results on six types of pressure transducers, shows the cumulative effects on the zero pressure output resulting from pressure cycling at less than the rated capacity of the transducer (typically 80% to 90% FS). In all cases, where the zero shift was large, the major part of the shift occurred during the first 100,000 cycles. With one exception, the zero pressure output shifted in a negative direction (with reference to the positive output obtained by the application of a positive pressure to the sensing element of the transducer), with maximum values ranging from -0.3% FS to -1.3% FS. Transducer (E) exhibited a positive zero shift during cycling up to 700,000 cycles. Following a six day rest at that point, this transducer showed a rapid negative zero shift during the remainder of its test.

The zero shifts of two transducers (additional samples of types A and C) that were subjected to cyclic pressures greater than their rated ranges are shown in Fig. 7 and 8. These transducers were only subjected to about 60,000 cycles. One of the transducers (type C) failed after 63,000 cycles. The zero pressure output, as shown in Fig. 6, reached 89% FS at this time. During the subsequent static calibration, the transducer output jumped to about 3.7 volts at all applied pressures above 60% FS, indicating an open circuit in one gage and probably large resistance changes in others.

A third transducer of type (C) was cycled at 146% FS for 30,000 cycles, at this time the transducer was found to be inoperative with an open circuit in one gage.

Sensitivity Changes

Fig. 6 presents a composite picture of the cumulative sensitivity changes of six pressure transducers when cycled at less than their rated ranges. While the ultimate effect of pressure cycling observed during these tests (with one exception) was an increase in sensitivity, two of the transducers tested (types A and E) exhibited an initial decrease in sensitivity. In most cases, the largest changes in sensitivity occurred during the first 100,000 cycles as did the changes in zero pressure output. Final sensitivities at the end of cycling varied widely, ranging from -0.3% FS (transducer E), through +0.01% FS (transducers A and B) to +0.45% FS (transducer D).

Effects of cycling at pressures above rated on the sensitivity are shown in Fig. 7 and 8. Fig. 7 shows that the transducer (sample of type C) cycled at 120% FS, and which subsequently failed after 63,000 cycles, did not show any sensitivity change greater than -0.45% FS during cycling. On the other hand, the sample of type(A), when cycled at 144% FS (as shown in Fig. 8) showed a change in sensitivity of about -3.0% after 20,000 cycles.

Hysteresis and Linearity Changes

Fig. 9 shows the effects of pressure cycling on linearity and hysteresis for transducer (F). These were determined from eleven point static calibrations immediately before cycling, after 360,000 cycles and after 714,000 cycles. The results are plotted as deviations from the computed "least squares" straight line through all points of each calibration.

While there appeared to be no significant change in linearity, the maximum value of hysteresis, 0.10% FS before cycling, increased to 0.14% FS after 360,000 cycles and reached 0.34% FS after 714,000 cycles. During the tests on this instrument, it became apparent that static calibrations in 30,000 cycle increments were not necessary after the first 100,000 cycles, due to the fact that the characteristics changed at a slower rate after that point.

Results obtained with the other transducers tested indicated that linearity and hysteresis showed minor changes, frequently within limits of experimental uncertainties, with a trend toward increasing hysteresis with cycling.

Summary of Test Results

To sum up briefly, from the observed performance of the small sample of strain gage pressure transducers subjected to cyclical pressure variations at the rate of about once per second:

1. Both zero output and sensitivity changed markedly during the first 100,000 cycles and more gradually after that.
2. After about 10^6 cycles, the zero pressure output had shifted about 1% FS, the sensitivity differed by as much as 0.5% from its initial value.
3. A single application of pressure caused the zero output to change by more than 0.1% FS, with practically full recovery after about 2 or 3 hours.
4. Linearity and hysteresis changes due to cycling are minor compared to changes in zero output and sensitivity.

Test results showed somewhat smaller changes in performance characteristics than had been expected based on the reported performance characteristics of strain gages(8, 9 and 11). The latter data were obtained at cycling rates of 30, 30 and 11.1 Hz, while the transducer data reported in this paper were obtained at cycling rates of 0.5 and 0.8 Hz. Since pressure transducers in some applications may be subjected to pressure variations at rates of upwards of several hundreds of hertz, additional work is desirable on the effect of high cycling rates on the performance characteristics of pressure transducers.

Very limited cycling tests at moderate over pressures indicate drastic performance changes and radical changes in operating life under these conditions. Further tests involving "life cycling" at elevated temperatures appear desirable to assess the effects of such combined environments on these transducers.

Conclusions

The equipment described is capable of subjecting pressure transducers having ranges not exceeding 125 psi to cyclic pressures at a rate of about 1 Hz. The test procedure outlined is suitable for determining the effects of such cycling on the zero pressure output, sensitivity, linearity and hysteresis of the pressure transducers.

The results of this limited test program indicate that zero pressure output and sensitivity of resistance strain gage pressure transducers may change significantly due to pressure cycling below the rated capacity of the transducer. Drastic changes may be encountered if the transducer is subjected to cyclic pressures above its rated capacity. Hysteresis and linearity do not seem to be affected to as great an extent.

Acknowledgement

John S. Hilten assembled the test equipment and performed some of the tests; Randolph Williams performed the remainder of the tests.

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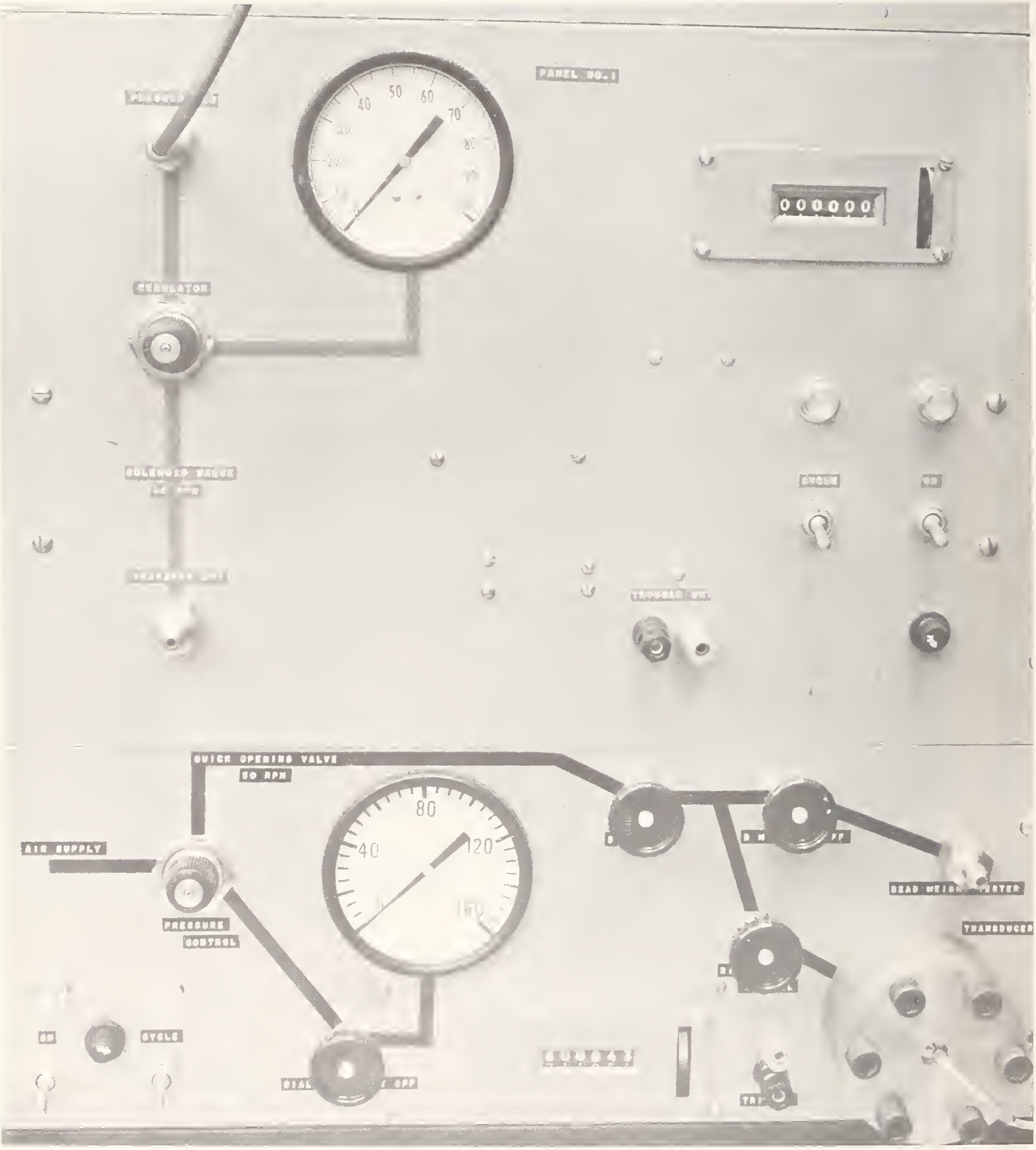

Fig. 1 VIEW OF "LIFE CYCLING" EQUIPMENT

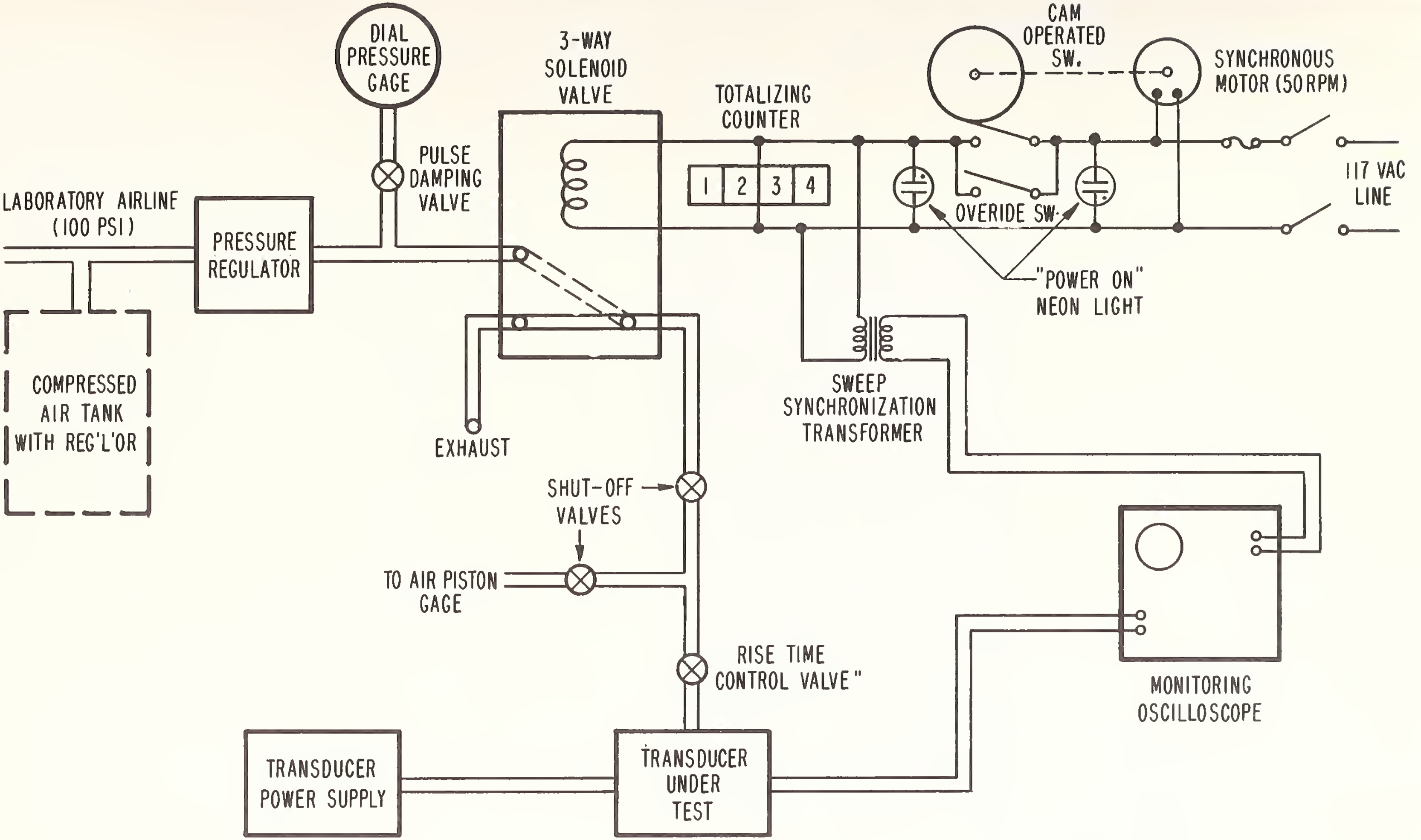

FIG. 2 SCHEMATIC OF FINAL EXPERIMENTAL SET-UP FOR "LIFE CYCLING" TESTS ON PRESSURE TRANSDUCER

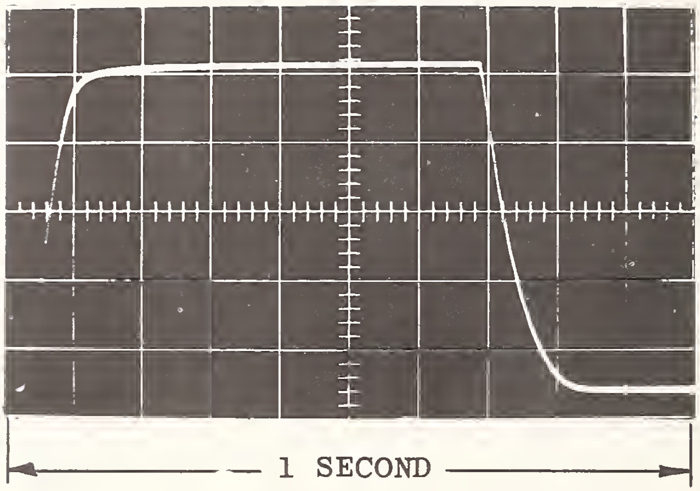

FIG. 3 RESPONSE OF UNBONDED STRAIN GAGE PRESSURE TRANSDUCER TO CYCLICAL PRESSURE OF 45 PSI

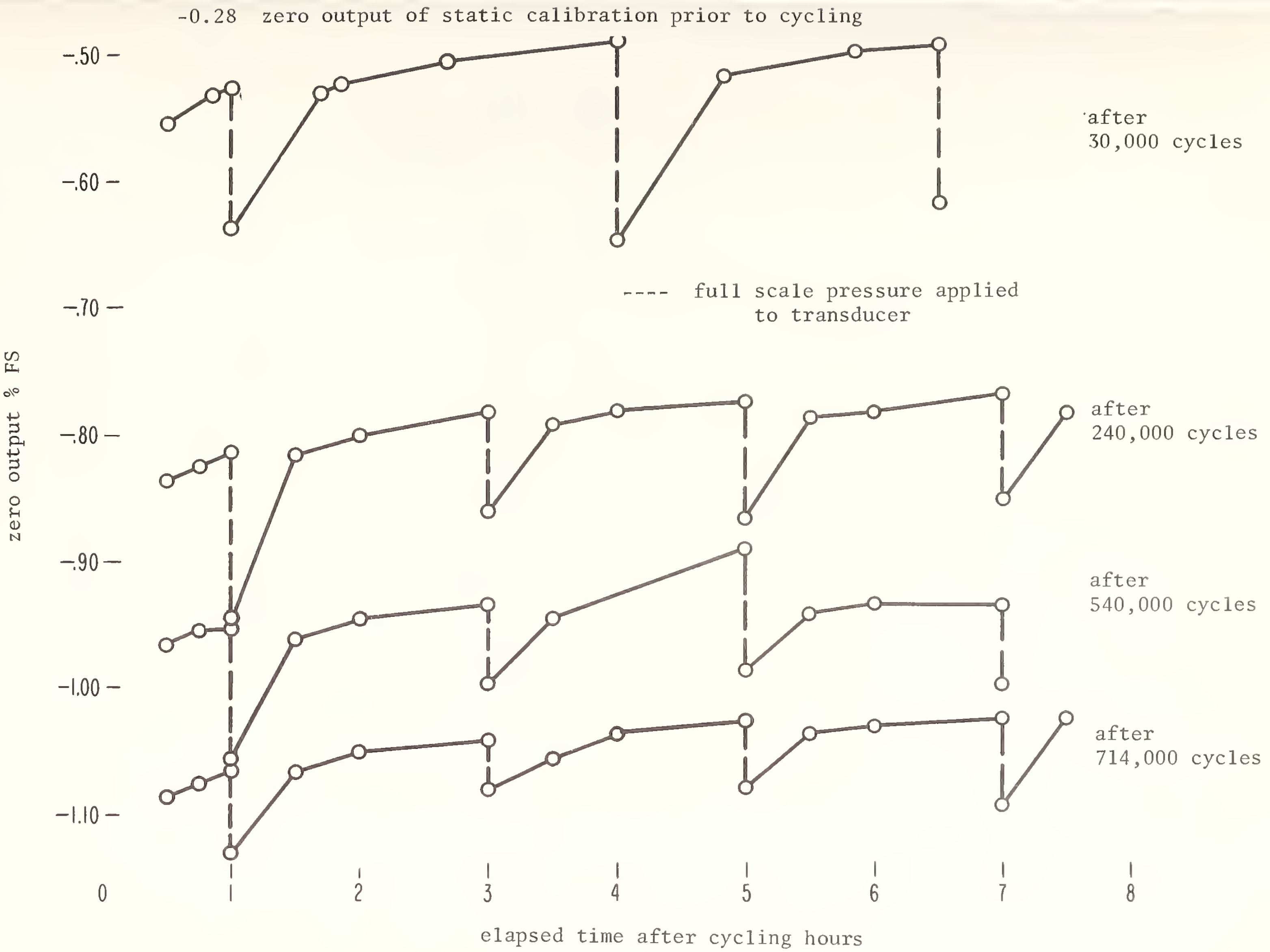

FIG. 4 EFFECT OF CYCLING AND REST ON ZERO OUTPUT OF STRAIN GAGE PRESSURE TRANSDUCER F

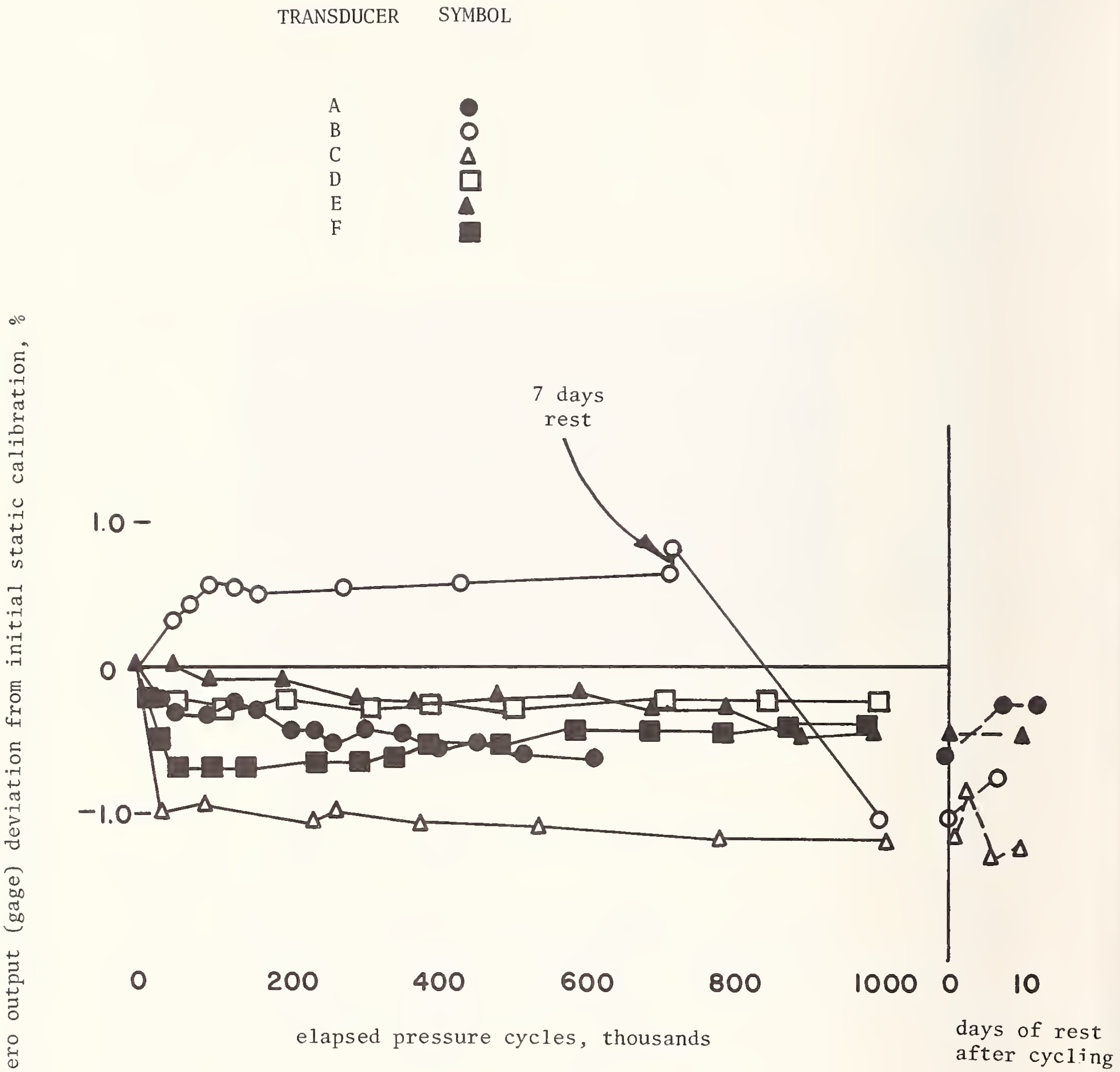

FIG. 5, EFFECT OF "LIFE CYCLING" ON ZERO PRESSURE OUTPUT OF SEVERAL STRAIN GAGE TRANSDUCERS

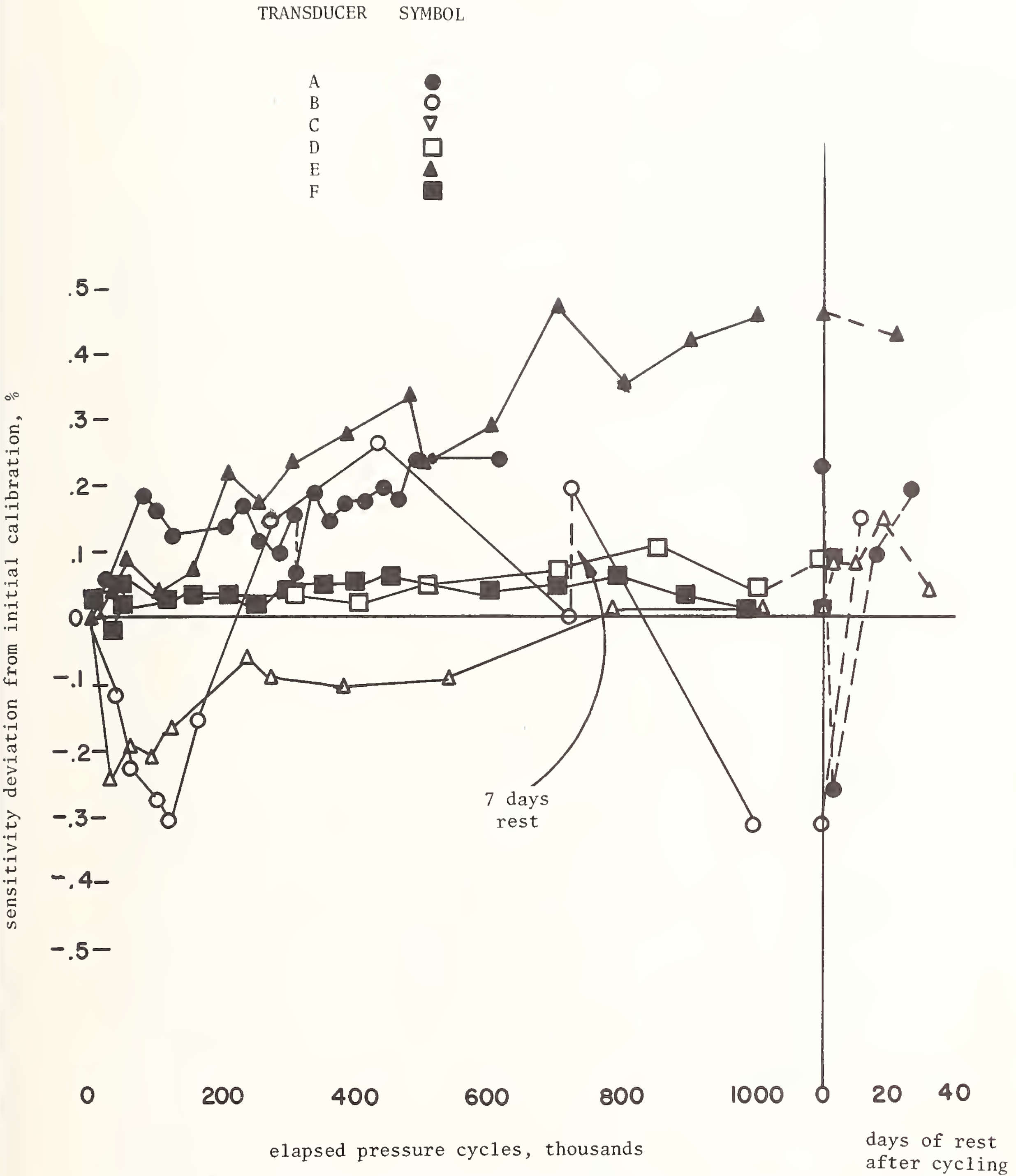

FIG. 6, EFFECT OF "LIFE CYCLING" ON SENSITIVITY OF SEVERAL STRAIN GAGE TRANSDUCERS

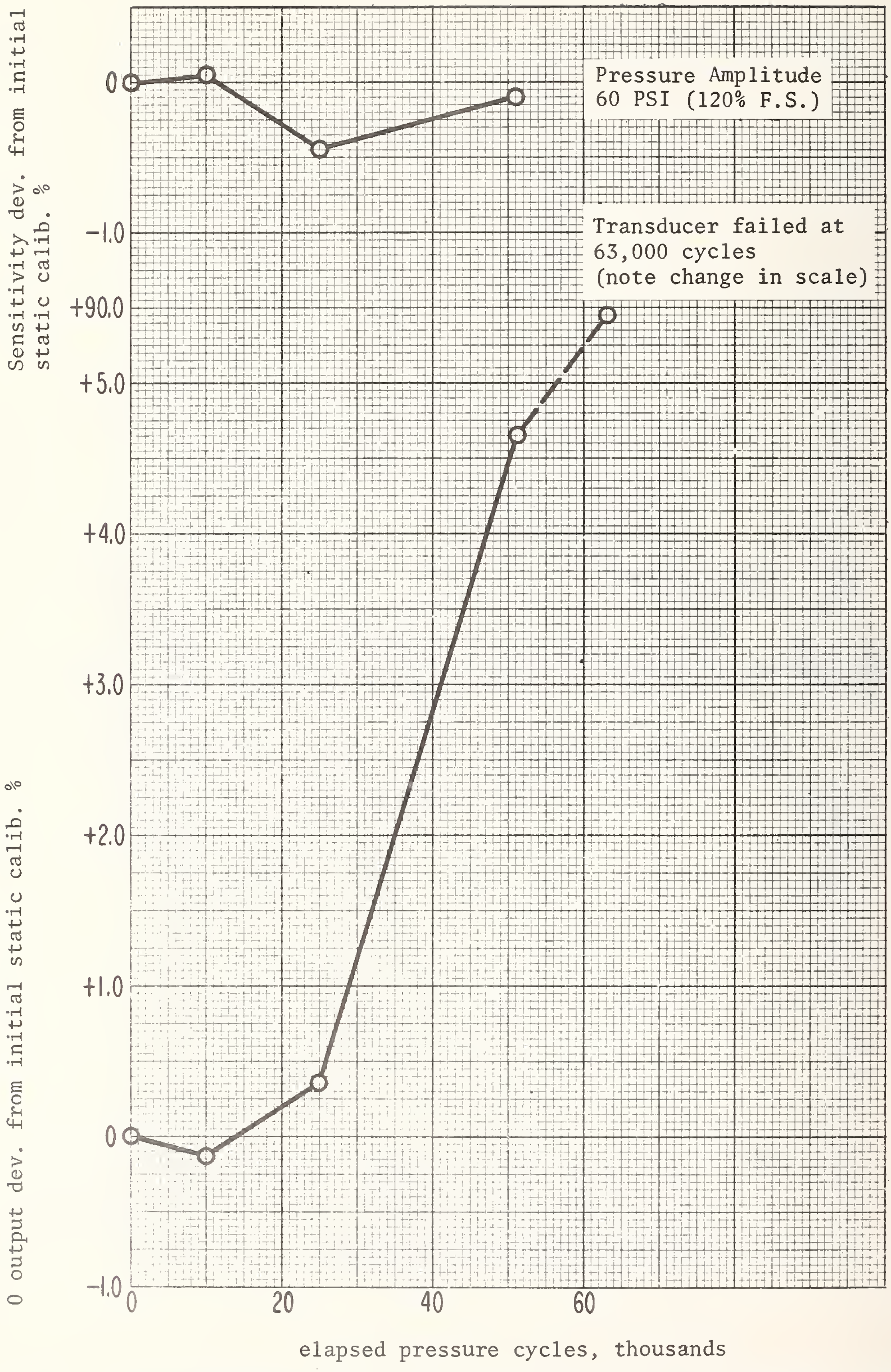

FIG. 7 OVER PRESSURE "LIFE CYCLING" CHARACTERISTICS OF PRESSURE TRANSDUCER C

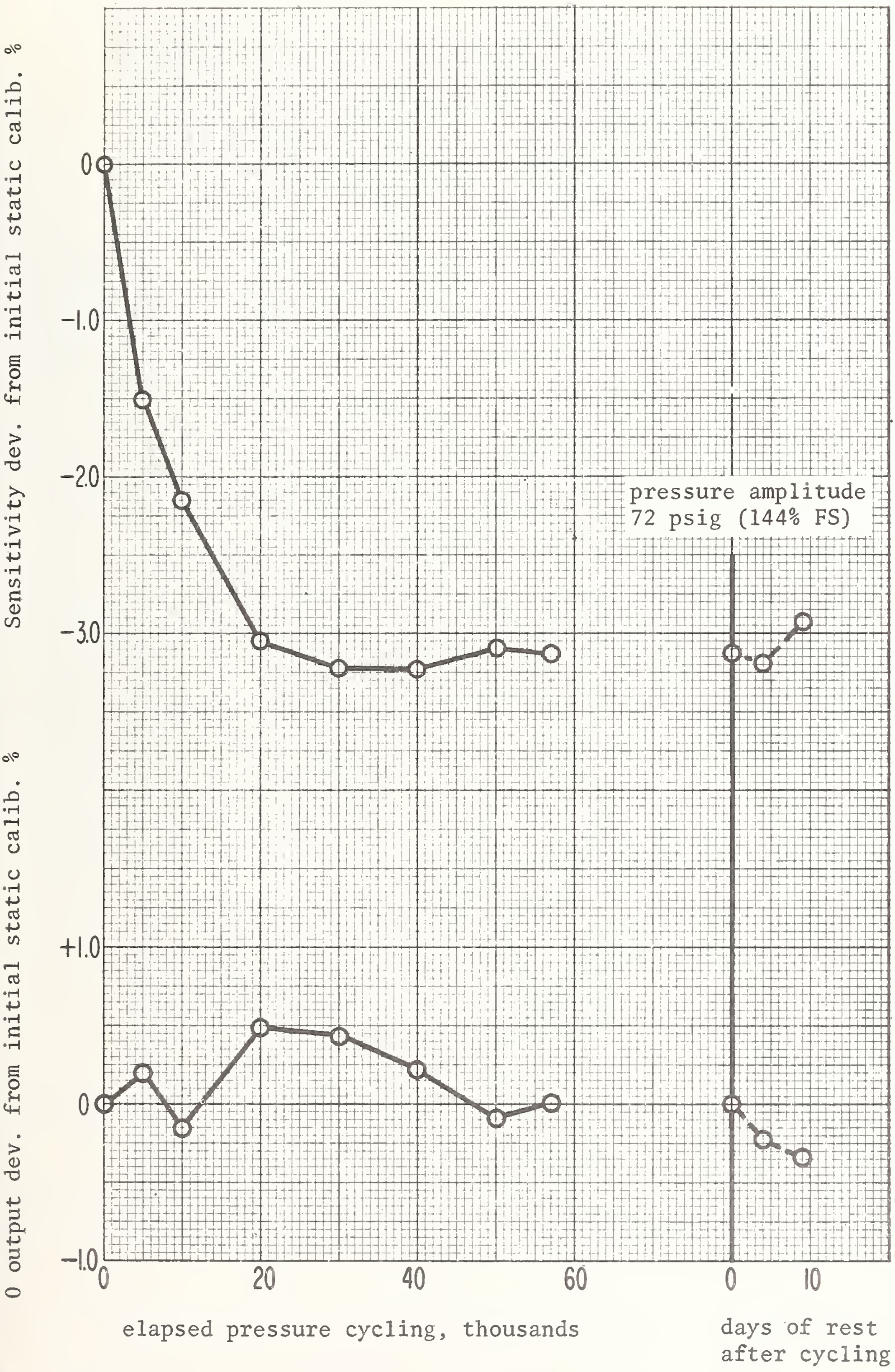

FIG. 8 OVER PRESSURE "LIFE CYCLING" CHARACTERISTICS OF PRESSURE TRANSDUCER A

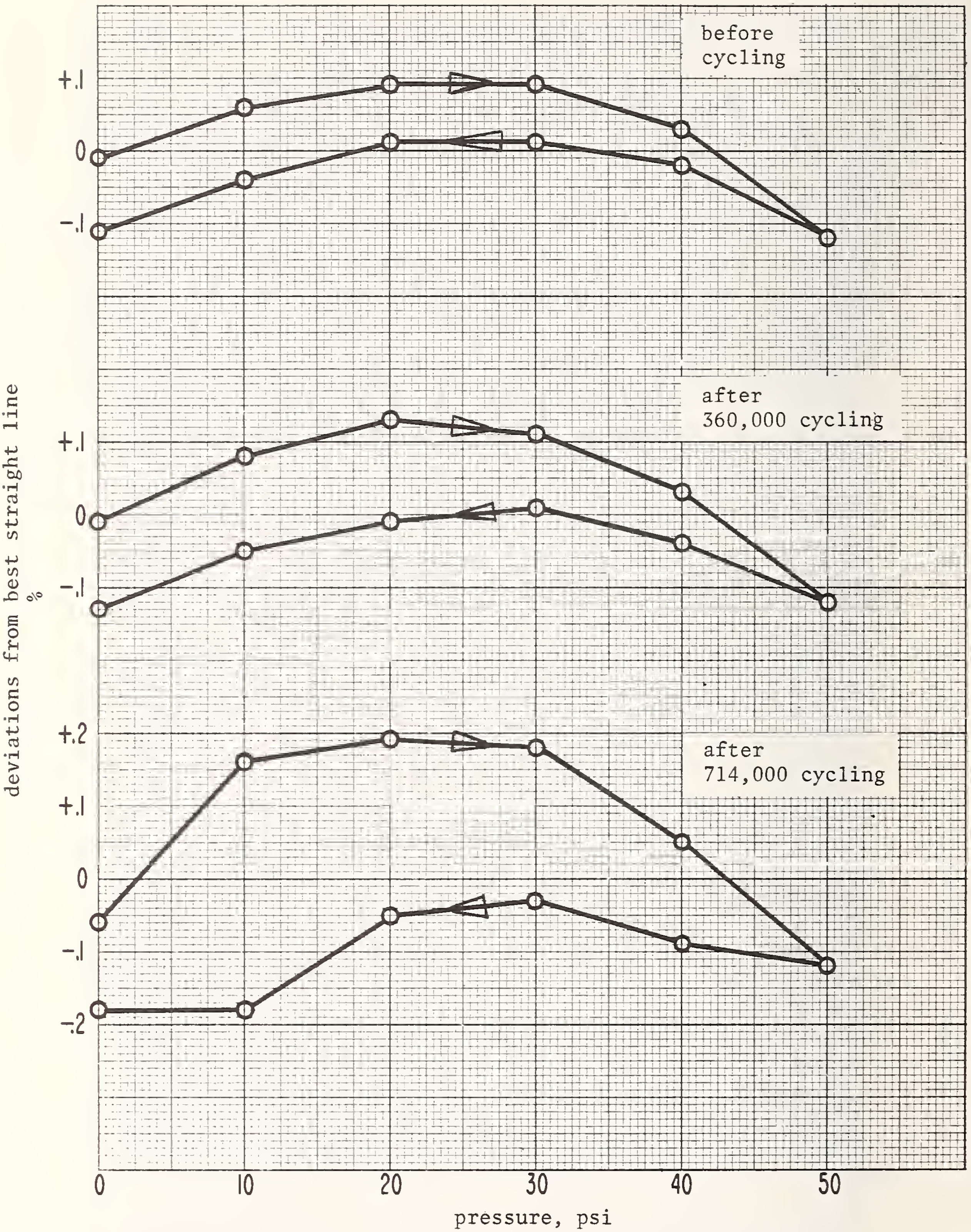

FIG. 9 EFFECT OF CYCLING ON LINEARITY AND HYSTERESIS OF TRANSDUCER F

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