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NATIONAL BUREAU OF STANDARDS REPORT

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DURABILITY INVESTIGATION OF A GROUP OF STRAIN GAGE PRESSURE TRANSDUCERS

Prepared for

National Aeronautics and Space Administration
NASA Lewis Research Center
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NBS

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

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DURABILITY INVESTIGATION OF A GROUP OF STRAIN GAGE PRESSURE TRANSDUCERS

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Prepared for
National Aeronautics and Space Administration
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16. Abstract
A durability investigation was conducted on a group of eighteen bonded-wire strain gage pressure transducers with ranges of 0 to 15 psig (0 to 1.03×10^5 Pa) and 0 to 100 psig (0 to 6.89×10^5 Pa) using an improved version of a previously developed technique. Some of the transducers were subjected to 40×10^6 pressure cycles at a 5-Hz rate at laboratory ambient conditions, others were cycled at a temperature of 150°F (65.6°C). The largest change in sensitivity observed was 0.22% for a 100-psig transducer subjected to 40×10^6 pressure cycles at 150°F. The largest change in zero pressure output observed was 0.91% FS for the same transducer. None of the transducers failed completely as a result of cycling at or below full scale pressure.

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A durability investigation was conducted on a group of eighteen bonded-wire strain gage pressure transducers with ranges of 0 to 15 psig (0 to 1.03×10^5 Pa) and 0 to 100 psig (0 to 6.89×10^5 Pa) using an improved version of a previously developed technique. Some of the transducers were subjected to 40×10^6 pressure cycles at a 5-Hz rate at laboratory ambient conditions, others were cycled at a temperature of 150°F (65.6°C). The largest change in sensitivity observed was 0.22% for a 100-psig transducer subjected to 40×10^6 pressure cycles at 150°F. The largest change in zero pressure output observed was 0.91% FS for the same transducer. None of the transducers failed completely as a result of cycling at or below full scale pressure.

1. INTRODUCTION

The increasing use of pressure transducers for measurement and control, in applications ranging from laboratory research to industrial process control, has been accompanied by increased demands on the measuring accuracy and durability of these devices over extended periods of time.

At the request of the NASA Lewis Research Center, the Instrumentation Applications Section of the National Bureau of Standards undertook to investigate the durability of pressure transducers subjected to long-term pressure cycling at laboratory ambient and at elevated temperatures. This task, described in this report, has two major objectives: (a) The development of the optimum evaluation techniques for assessing the durability characteristics of pressure transducers, and, (b) the actual determination of these characteristics for a number of selected pressure transducers of the type currently used in engine-test facilities at the Research Center. The results of this work are expected to provide the desired performance characteristic information on the particular transducers tested, and to lead to the development of evaluation techniques of general benefit to users and to manufacturers of pressure transducers.

1.1 Related and Previous Work

The NBS InterAgency Transducer Project, a part of the program of the Instrumentation Applications Section of NBS, had previously completed two tasks dealing with transducer durability. In the first task [1][1] six different, commercial, pressure transducers were cycled at a rate of fifty times per minute from zero gage pressure to about 90% of the full scale range (FS) of the transducers. Cycling was interrupted at increasing time intervals for static calibration of the transducers. The tests were

[1]Figures in brackets indicate the literature references at the end of the paper.

performed at laboratory ambient temperature and continued until 10^6 pressure cycles had been applied to the transducers. A summary of test results from this investigation follows:

1. Both zero pressure output and sensitivity changed significantly during the first 100,000 cycles and more gradually after that.

2. After about 10^6 cycles, the zero pressure output had shifted a maximum of about 1% FS, while the sensitivity had changed a maximum of 0.5%.

3. Linearity and hysteresis changes due to cycling were small compared to changes in zero output and sensitivity.

4. Very limited testing at moderate overpressure produced drastic performance changes and radical changes in operating life under these conditions [1].

In the second task, [2] ten different, commercial, strain gage pressure transducers were subjected to an elevated temperature (slightly below the maximum recommended operating temperature) for 5 days. This was followed by returning the transducers to laboratory ambient conditions over the weekend. During the following week the transducers were subjected to the elevated temperature again for five days. Two days at ambient conditions followed. This procedure was continued for five weeks, after which the transducers were kept at ambient conditions for three more weeks. Static calibrations were performed at regular intervals throughout the entire period. Test results can be summarized as follows:

1. Sensitivity changed progressively in a few cases during the test period, and zero output changed in more cases. Most of the changes occurred during the first three weeks of the test.

2. Storage of the transducers at the elevated temperatures resulted in permanent changes in practically all cases,with observed maxima at the end of the total eight-week period ranging from -0.4% to +0.4% for sensitivity, and from -3.0% FS to +4.5% FS for zero pressure output.

3. Although the sampling was too small for rigorous conclusions, semiconductor strain gage devices appeared to show greater permanent changes in characteristics than metallic strain gage devices.

4. Three presumably identical samples (same model and range, purchased at the same time) showed significant variations in behavior, suggesting that transducers even from the same batch do not behave in the same manner [2].

Since both investigations disclosed that substantial changes in performance characteristics occur as a result of pressure cycling and of storage at elevated temperatures, we felt it desirable to investigate the effects of a combination of these test conditions. Such a combination of environments is not unlikely in an actual application situation, and indeed is precisely the situation in the engine-test laboratory at the NASA Lewis Research Center. Since the completion of the two earlier tasks we had acquired improved laboratory equipment which would enable us to carry out an investigation of the effects of combined environments more effectively. Accordingly we undertook, at the request of the Lewis Research Center, the task described in this report.

1.2. Task Outline

The task proposed for investigating the durability of pressure transducers encompassed the following tests on a group of bonded-wire strain gage transducers of two different ranges 0 to 15 psig (0 to 1.03×10^5 Pa) and 0 to 100 psig (0 to 6.89×10^5 Pa). The transducers were to be pressure cycled to 40×10^6 cycles at the rate of 5 Hz at laboratory ambient conditions and at 150°F (65.6°C). In addition, some of the transducers were to be cycled at pressures greater than the full scale range. It was also planned to investigate briefly the feasibility of pressure cycling at higher rates, possibly as high as 100 Hz. In each of these investigations we proposed using four transducers, two to serve as controls while the other two were undergoing the tests. Throughout the tests, all transducers were to be calibrated statically at specific intervals.

2. TEST EQUIPMENT

2.1. Test Setup

The test setup is shown in Figures 1 and 2. It consists of the test and calibration console, and oscilloscope for monitoring pressure wave shape, and two transducer test stations.

The console contains the static calibration equipment and the cycling control setup. The static calibration equipment contains a set of pressure regulators, solenoid control valves, a pushbutton assembly for actuating the solenoid valves, and a constant-voltage power supply for each of the two ranges of pressure transducers. A schematic of the calibration setup is shown in Figure 3. A precision quartz Bourdon tube pressure indicator and a precision, five-digit, integrating voltmeter are also in the calibration console and serve both pressure ranges of test transducers. In addition, an electrical patch panel for each pressure range permits selective measurement of the power supply voltage and the output voltage of each of the four pressure transducers in each test group. Further, each patch panel also contains the switches and the electromechanical totalizing counter required for each of the two pressure cycling arrangements. Pressure cycling is controlled by a motor driven cam operating a switch which energizes a three-way solenoid valve at the rate of 5 Hz at each test station. A schematic of a patch panel is shown in Figure 4.

The quartz Bourdon tube pressure indicator has a full scale range of 100 psig to facilitate the calibration of transducers of both ranges. Since the pressure transducers furnished by NASA for the tests have full scale ranges expressed in psig and the precision quartz Bourdon tube pressure indicator and the air piston deadweight tester used to calibrate the latter are also calibrated in terms of psig, these units are used in this report. For conversion purposes, it should be noted that 1 pound per square inch gage (psig) is equivalent to 6894.7 pascals (newtons per square meter) in the SI system.

The test stations, shown in Figure 2, were built into the removable doors of two temperature chambers. This was done to facilitate tests at elevated temperatures which are accomplished by inserting the door with the attached components into the chamber. For laboratory ambient tests, the test station was simply left exposed on the laboratory bench. Each test station has its own pressure regulator to set the cycling pressure amplitude, a dial gage to indicate its value, and a solenoid valve which does the actual cycling. A series of valves at each station permits rapid switching from the cycling mode (during which the control transducers are isolated from the fluctuating pressures) to the calibration mode in which all four transducers can be calibrated statically. Flexible pressure hoses with quick-connect features and some additional valves in the calibration console enable the change from cycling mode to calibration mode to be made in about thirty seconds.

2.2. Test Equipment Failures

A number of test equipment components failed during the test period. The electrical power for the cycling valves was controlled by a snap-action switch which was actuated by a five-lobe cam rotated by a motor at one rotation per second. Switch failures were initially handled by simple switch replacement, although the actual positioning of the body of the switch with respect to the cam was quite critical. Subsequently we learned that in several cases, with proper switch positioning for the desired valve actuation time, the timing motor had to exert excessive torque during certain portions of the cycle. This was true despite the use of rollers at the end of the switch leaf. We believe several failures of the timing motors resulted from the large mechanical resistance of the switch leaf causing damage to the teeth of the reduction gears in the timing motors.

We experienced a high failure rate of the electromechanical counters used to keep track of the elapsed number of cycles. Again, the failures appeared to result from wear on mechanical components. At those times when both cycling setups were in use, if one counter failed (say during a weekend) it was possible to calculate the number of cycles applied by that setup, provided the other counter had accumulated the expected count. Conversely, if one timing motor failed, we accepted the final indicated count as correct, provided the counter continued to function properly after the timing motor or switch had been replaced. There was no instance in which the timing motor, switch and counter failed during the same unattended time interval. The counters had been purchased as new surplus with a life rating to 200 x 10^6 cycles. The failures occurred after 1, 4, and 10 x 10^6 cycles respectively. The defective counters were returned to the dealer for repair or for replacement, and one of the replacements also failed. Spares of a different model were finally procured as back-up, but did not have to be used.

One solenoid valve failed after about 39 x 10^6 operations, a second one, although still operating, was replaced when one test station was modified for over-pressure testing.

To avoid the timing-motor switch failures, we assembled a new switching system. It consists of a heavy duty one-rotation-per-second motor driving a round disc of mild steel with five circular holes equally spaced around a circle concentric with the shaft. Two permanent magnets are mounted on a framework on one side of the disc, two glass enclosed magnetic reed switches are mounted on an insulated plate on the opposite side of the disc and facing the magnet. The reed switches are alternately subjected to the magnetic field, or shielded from it by the rotating disc at the rate of 5 Hz. This system has proved to be more reliable than that previously used. The reed switches are easily replaced should this become necessary.

3. TEST PROCEDURES

3.1. Static Calibrations

Early in September 1971, upon receipt of the twenty pressure transducers, we calibrated each of them statically three times, consecutively. We selected four transducers of each of the two pressure ranges for the first series of cycling tests at laboratory ambient conditions. The choice was based on the following criteria: minimum deviation from linearity, minimum hysteresis, minimum spread among zero pressure output values, and smallest standard deviation (minimum scatter). The two transducers which most nearly met all of these criteria were selected for cycling, the next best two were used as controls. The latter were not subjected to pressure cycling, but were calibrated statically at the same time as the cycled ones.

From the 15-psig group, we selected #41929 and #41932 for cycling, and #41931 and #41919 as controls. From the 100-psig transducers, we chose #41921 and #41933 for cycling, and #41923 and #41927 as controls.

Our calibration and cycling setup accomodates four transducers of each pressure range at one time. We followed a standardized procedure, developed during the previous investigation, by carrying out an eleven-point static calibration on each transducer. We used the same procedure for all subsequent static calibrations of the transducers during, and after, the cycling tests.

One hour prior to calibration, the quartz Bourdon tube pressure standard and the digital voltmeter were turned on to assure their thermal stability during calibration. The transducer excitation supply was always kept on, even during equipment down-times. A test on the quartz Bourdon tube thermal stabilization system indicated that a stable temperature was attained in the laboratory one half hour after the power was turned on.

The calibration procedure consisted of an initial reading of the transducer temperature (room temperature was used for ambient temperature tests, whereas the transducer case temperature was used for the elevated temperature tests) followed by measurement of the transducer excitation voltage (nominally 10 volts), and measurement of the zero output voltage of each instrument with zero pressure on the transducers. The voltage measurements performed were "open circuit" ones; the input resistance of the digital voltmeter was 10^{10} ohms.

After recording these values, the push button was activated which energized a solenoid valve applying the pressure from the first regulator to the four transducers. This first regulator was set to about 20% of the full-scale range (FS) of the instruments tested. After system pressure had stabilized (about 15 seconds) the output voltages of the first two transducers were read. Then the applied pressure was read from the digital indicator of the Bourdon tube reference, followed by output voltage readings of the remaining two transducers. The same procedure was followed for all remaining calibration points up to full scale and back down to zero pressure. At the conclusion of the calibration final temperature and power supply readings were taken. This entire procedure required about ten minutes for the four transducers, a significant improvement over our previously used calibration procedures. In all cases, the calibration sequence was: control, control, cycled, cycled, transducer. The possible small amount of bias introduced by this fixed procedure is far outweighed by the ease of keeping track of the calibration data for each transducer.

Calibration data were punched into data cards along with a power supply value averaged from the two measured values. The data were reduced by a "least squares best straight line" computer program, which also corrected input pressure dial readings to true pressure values. The print-out shows sensitivity (slope) in terms of (mV/V)psi, as well as deviations from the line (linearity), hysteresis, initial and final zero outputs, and standard deviation (a measure of the scatter of all calibration points).

3.2. Tests at Laboratory Ambient Conditions

The first series of tests involved the cycling of the pressure transducers of both ranges at laboratory ambient conditions. As explained in 3.1 above, two transducers of each range were selected for cycling, the other two were used as controls. All four were calibrated statically at selected intervals during the test period, following the procedure described above.

On the basis of the pressure cycling results obtained from the previous task, [1], we decided to calibrate after the following numbers of pressure cycles: 5×10^4, 10^5, 2×10^5, 5×10^5, 10^6, 2×10^6, 4×10^6, 6×10^6, 8×10^6, 10×10^6, 15×10^6, 20×10^6, 25×10^6, 30×10^6, 35×10^6, 40×10^6. We did not in fact follow this pattern after about 2×10^6 cycles, primarily because of the constraints of working time limitations. As noted on the graphs, the calibration intervals were on the order of 3×10^6 cycles. The established routine was to interrupt cycling each Friday morning, calibrate the transducers statically, and then resume the cycling. Equipment failures and holidays also contributed to minor irregularities in the cycling program. Immediately after 40×10^6 cycles had been reached, a static calibration was run, followed by a final one four to seven days later. This was done to assess the permanent changes in performance characteristics caused by the cycling.

The actual cycling pressure was kept below the full scale range of the transducers to avoid any possible overload due to line pressure or regulator variations. The amplitudes were set at 13.5 psig (90% FS) for the 15-psig instruments and at 95 psig (95% FS) for the 100-psig ones. In view of the number of static calibrations required during the early stages of the test, we started the cycling procedure with only the 15 psig transducers. After they had been tested for three weeks, we began testing on the 100-psig transducers.

As described in the next section, when the 100 psig transducers were cycled at laboratory ambient conditions, the inside of the instruments actually reached a temperature close to the 150°F (65.6°C) level. To be able to test at room temperature and at the 5 Hz rate, we experimented with various cooling schemes near the end of the test series and finally found one that worked satisfactorily. It uses a coil of copper tubing wound around the transducer case, perforated at 90° intervals and fed directly from the laboratory 110-psig air line. With this cooling system, the cycling of the 100-psig transducers was then carried out at essentially laboratory ambient conditions. The temperature of the cases of the two cycled instruments was monitored by a thermocouple throughout the tests. In view of time and funding limitations we carried these tests only to 10×10^6 cycles. Some adiabatic heating also occurred in the 15-psig transducers. This, combined with the internal electrical dissipation, resulted in a transducer case temperature after cycling of about 86°F (30.0°C) at an ambient temperature of about 75°F (23.9°C). Consequently, tests at "laboratory ambient conditions" actually represent a case temperature of 86°F (30.0°C) for the 15-psig transducers.

3.3. Tests at Elevated Temperatures

It was the original intention to test the transducers first at laboratory ambient conditions, (see 3.2 above) and then to test another group of four transducers in a temperature chamber at 150°F (65.6°C). This was the procedure followed with the 15-psig transducers. The test station shown in Figure 2 was placed in a temperature test chamber which was set to operate at the desired temperature level. The actual transducer temperature was monitored by chromel-alumel thermocouples: one attached to the case of a cycled transducer, the second one to the case of a control, and then the third one to monitor the test chamber air temperature.

Again as in the laboratory ambient tests, static calibrations were made after the number of pressure cycles outlined in 3.2 had been performed. Calibrations of the transducers which were subjected to adiabatic heating were started not more than two minutes after cycling had stopped. The calibration procedure described in 3.1 was followed with the addition of the measurement of the three temperatures before and after the calibration.

The initial static calibration was actually at about 86°F (30.0°C) case temperature due to internal power dissipation: following this the temperature in the chamber was raised in steps to 100°F (37.8°C), 125°F (51.6°C) and 150°F (65.6°C). The transducers were allowed to stabilize at each of these temperatures for one hour prior to a static calibration at that temperature. When the 150°F level was reached, the temperature was kept at this level for the remainder of the tests on the

15-psig transducers.

About the time that testing all the 100-psig transducers at laboratory ambient conditions had reached 10 x 10^6 cycles, we noted that these transducers seemed hot. A thermometer placed against the case of one of the cycled transducers indicated 130°F (54.4°C). It seemed likely that the diaphragm and strain gages would be at an even higher temperature as a result of the adiabatic temperature rise of the gas during cycling; probably close to the desired 150°F (65.6°C) level. Accordingly, we continued this test series without any changes in setup until the 40 x 10^6 cycle point was reached and considered this experiment as the high cycle temperature test for this transducer range. Subsequently, we checked our assumption more closely by taking apart one of the 100-psig transducers that had survived 40 x 10^6 cycles and mounting thermocouples at various locations. We cycled the re-assembled transducer for one hour until the temperature of its components had stabilized. The data resulting from this experiment are shown in Figure 6. Tests other than those reported in Figure 6 indicated a temperature rise of about 5°F (2.8°C) during the second hour. Within about two minutes after cessation of cycling, the diaphragm temperature drops essentially to the case temperature . That temperature then further decays exponentially, reaching the starting temperature about one hour later. The temperature drops from about 147°F (63.9°C) two minutes after cycling shut-off to 126°F (52.2°C) ten minutes later (the time period normally required for the after-cycling static calibrations). The static calibrations of the 100-psig transducers following cycling were thus conducted at an average transducer temperature of about 137°F (58.3°C) while the cycling temperature as measured at the strain gages was about 162°F (72.2°C). A brief theoretical investigation, assuming adiabatic charging and discharging of pressure vessels [3] (neglecting the possible loss of heat to the walls of the transducer), indicated a value of average gas temperature in the transducer of roughly 208°F (97.7°C), is undoubtedly a loss of heat to the walls, thus lowering the actual gas temperature (and therefore temperature of the thin diaphragm). This computed value supports the assumption that the measured diaphragm temperature is quite close to the actual temperature.

3.4. Artificial Cooling of 100-psig Transducers

As indicated earlier, we were able to perform cycling tests on the 100-psig transducers at laboratory ambient conditions at the 5-Hz rate with the aid of a cooling jacket consisting of a perforated copper tube wrapped around each cycled transducer case and using the laboratory air line to supply cooling air. A series of tests was run on the previously used 100-psig transducer instrumented with three thermocouples. The results are shown in Figure 6. In the first test without the cooling, jacket temperatures continued to rise slightly after one hour. The three temperature curves (diaphragm, strain gage beam, and case) nearly coincide within two minutes after cycling shut-off. Using the cooling jacket supplied with compressed air at 100 psig from the laboratory air line, another test was run. The results are also shown in Figure 6. It can be seen that after one hour of cycling, the component temperatures are stable: the diaphragm at about 104°F (40.0°C) the strain gage beam at 86°F (30.0°C) and the case at 81°F (27.2°C). Within two minutes after cycling ended (but with air cooling continued) all three temperature curves merged into that of the case, which had dropped to approximately 78°F (25.6°C). This was considered close enough to the laboratory ambient temperature so that cycling tests performed with this additional cooling were truly laboratoy ambient tests.

3.5. Over-Pressure Tests

With the agreement of the sponsor, two of the 15-psig transducers were subjected to cycling at laboratory ambient conditions at pressure amplitudes greater than the full-scale range. The first one was pressure cycled at 30 psig (2.04×10^5 Pa) (200% FS) and failed before reaching 35,000 cycles; the second was subjected to about 22 psig (1.50×10^5 Pa) (147% FS) following essentially the same calibration-cycling-calibration sequence used during the test procedures outlined in 3.1. and 3.2., but terminating after about 4.5×10^6 cycles. In our judgement, a transducer in measurement use is highly unlikely to be exposed to such an over - pressure for even this number of cycles.

4. TEST RESULTS

4.1. Experimental Uncertainty Considerations

As indicated previously, the pressure applied to the transducers during static calibration was measured with a quartz Bourdon tube pressure gage reference. By using a Bourdon tube element with a range of 0 to 100 psig, we were able to calibrate pressure transducers of both ranges without changing elements. This saved a considerable amount of time since the warm-up time for another element was eliminated. The measurement accuracy was compromised only to a very minor degree for almost all calibrations, as will be apparent from the estimated uncertainties for static calibrations of the transducers at 15 psig and 100 psig during the cycling procedure shown in Tables I and II.

The calibration chart which gives values of true pressure versus dial reading of the quartz Bourdon tube gage is described by the manufacturer as being accurate within ±0.015% of the reading. We calibrated the gage against a dead weight air piston gage pressure reference which its manufacturer indicates as having an accuracy of ±0.015% of the reading. Both instruments are described as having been calibrated against NBS traceable standards. The results of two calibrations which we performed, about five weeks apart at 7.5, 15, 50, and 100 psig, showed a maximum deviation between the corrected values of pressure for both devices of 0.011% of the reading, and an average deviation of 0.007% of the reading.

The tables show a detailed listing of the sources of error in the static calibration after cycling and their estimated magnitudes. The estimated error of the measured value of the excitation voltage, the pressure reference and the digital voltmeter are treated as systematic error (bias). The estimated effect of adiabatic expansion of the gas, in view of its small magnitude, is treated as a random error. Both systematic and random errors are summed into respective totals as the square root of the sum of the squares of the values [4]. The systematic error may be ignored for those tests where changes in the characteristics of the full-scale range of the transducer were investigated.

The sum of the estimated systematic errors is ±0.040% of the reading at 15 psig and 100 psig full-scale pressure. The sum of estimated random errors is ±0.021% of the reading at 15 psig, and ±0.026% of the reading at 100 psig. The estimated total error, obtained by adding three times the summed random error to the summed systematic errors is ±0.103% at 15 psig and ±0.118% at 100 psig.

These values should apply to all calibrations following cycling for the 15-psig transducers. They should apply as well to the initial static calibrations and the ones at 150°F (65.6°C) for these transducers since in all cases the estimated variations in transducer temperature are within ±2°F. The estimated values for the 100-psig transducers should apply to the calibrations following cycling without cooling. For the initial calibrations, and those with additional cooling, the estimated random error in transducer temperature probably do not exceed ±5°F rather than the ±10°F estimated in Table II, thereby reducing the estimated random error total to ±0.015% for the 100-psig transducers.

The computer program used for reduction of the calibration data furnishes a print-out of the computed standard error based on ten degrees of freedom (eleven calibration points). In addition one obtains values of hysteresis and of the deviations of the experimental points from the computed best-fit straight line. All of these experimentally derived values are shown in Tables VII-XIV. Table IV lists the computed values of the standard error from all static calibrations, expressed as a percentage of the sensitivity of the transducer. It will be noted that most of these values are considerably larger than the estimated values in Tables I and II. The reason is that these computed values (deviations from the "best-fit straight" line) include the effects of transducer linearity and hysteresis, which are not included in the estimated values.

4.2. General Considerations of Plotted Data

The data obtained from the tests are plotted in two general type of graphs. The first type (Figures 7-13) shows the changes in sensitivity or in zero-pressure output for the four transducers in a test group as a function of test duration. In the case of the cycled transducers, the test duration scale is "cycles x 10^6", for the control transducers the test duration scale is "days since start of test". The two scales are given at the bottom and top of the graph, respectively. The latter scale is not completely linear, because of various amounts of downtime during these tests and because the cycle scale was linearized for plotting purposes as the more important one. The scale from 0 to 2 x 10^6 cycles is expanded to show early cycling results. In some graphs a final point, taken following a four-to seven-day rest after cycling, is indicated by a square. It represents the total permanent effects of the test procedure on the transducer. The vertical scale is given in terms of the change in sensitivity (%) or zero-pressure output (% FS) from the first static calibration immediately prior to cycling.

The second type of graph (Figures 14-21) shows the effects of the test procedure on linearity and hysteresis. In this case, the deviations from the computed least squares straight line are plotted as a function of the full scale range of the transducer. For the cycled transducer the curves are plotted for the initial static calibration (immediately prior to cycling) and for the final calibration after the cycling procedure had been completed. For the control transducers, the curves are also shown for the first and final calibrations. The vertical scale of these graphs is percent of full scale (% FS).

4.3. Sensitivity Changes

The changes in transducer sensitivity during the test procedure are plotted in Figures 7, 8, 9, 10. The sensitivity characteristics of the 15-psig transducers are shown in Figures 7, and 8. Differences among the eight curves (four controls and four cycled transducers) are not clearly significant, although it appears that the sensitivities of the two transducers cycled at 150°F may show slightly greater excursions and slightly greater slopes than any others plotted. An attempt was made to establish trends by determining the slope of the computed least-squares straight line through all sensitivity values for all transducers tested (and subsequently through the zero pressure output values also). These data are contained in Table III. To provide comparison between control and cycled transducers, the equivalent number of cycles from the graphs were substituted for the number of elapsed days for the control transducers.

From the data in this table, computed over a testing span of 40×10^6 cycles, it can be seen that for the 15-psig transducers:

A. The sensitivity decreases by an average of 0.010% for three of the four 15-psig transducers (controls and cycled) tested at laboratory ambient conditions.

B. The sensitivity increases by an average of 0.025% for three of the four 15-psig transducers tested at 150°F (65.6°C).

C. On the basis of these observations, it appears that there is no change in sensitivity that can be unambigiously attributed to the cycling itself.

For the 100-psig transducers (Figures 9 and 10) extrapolating to 40×10^6 cycles the data from the laboratory ambient cycling tests which lasted for 10^6 cycles, it can be seen that:

A. The sensitivity decreases by an average of 0.11% for the four transducers (controls and cycled) tested at laboratory ambient conditions.

B. The sensitivity increases by an average of 0.30% for the two transducers cycled at 150°F (65.6°C).

C. The tests at laboratory ambient conditions indicate that there may be an effect of cycling on sensitivity, although the scatter of values is too great to confirm this. It was not possible to corroborate this at 150°F (65.6°C) since no 100-psig controls were tested at that temperature.

On examining Figures 7 and 8, it can be seen that the random variation in characteristics are slightly larger than the random error values estimated in Table I. This is undoubtedly due to some random variation in properties of the transducer, which, of course, are not included in the estimates in that table. There are also some observable changes in apparent characteristics of all transducers tested at the same time and in the same directions. These are thought to result from small variations in the systematic errors of the calibration system, and are well within the limits estimated for these errors.

It can also be seen in Figure 9, that transducer #41921 (100-psig cycled, 150°F) is more erratic in behavior than the other transducers, and exhibited a permanent change in sensitivity of about 0.20% at laboratory ambient temperature at the conclusion of the tests.

4.4. Zero-Pressure Output Changes

The changes in zero pressure output during the test procedure are plotted in Figures 10, 11, 12, 13. The slopes of the least squares straight lines through the zero output values are compiled in Table III. From the data in this table (and computed over a testing span of 40×10^6 cycles) it can be seen that for the 15-psig transducers:

A. The zero pressure output decreases with cycling an average of 0.084% FS at laboratory ambient conditions and an average of 0.33% FS at 150°F (65.6°C).

B. The zero pressure output of three of the transducers shows no significant common trend either at laboratory ambient conditions or at 150°F (65.6°C), although individual transducers show variations. The fourth transducer, #41919, shows a drift much larger than the estimated total error.

For the 100-psig transducers (data from the laboratory ambient tests were extrapolated to 40×10^6 cycles), it can be seen that:

C. The zero pressure output decreases for all transducers tested. For the control transducer (all four at laboratory ambient conditions) the average change was 0.12% FS. For the two transducers cycled at laboratory ambient conditions, the average change was 0.45 % FS, and for the two transducers cycled at 150°F (65.6°C) the average change was 0.60% FS.

Figure 10 shows somewhat erratic excursions for transducers #41925 (control) and #41924 (cycled) at laboratory ambient conditions. Figure 11 shows the large drift and erratic behavior of the zero pressure output of transducer #41919 (which had originally been selected as control on the basis of the results of the initial set of three static calibrations). Figure 13 shows some erratic excursions of the zero pressure output of transducers #41921 and #41933 while cycled at 150°F. After 6×10^6 cycles these transducers appear to settle down, however.

4.5. Linearity and Hysteresis Characteristics

The effects of the test procedures on the linearity and hysteresis characteristics are shown in Figures 14-21. In each case the data are shown for the initial static calibration (prior to cycling of the cycled transducer) and calibration after all cycling had been completed. For the 15-psig transducers:

A. The maximum hysteresis is slightly smaller at the end of the test period for the controls than at the beginning. This applies to laboratory ambient as well as elevated temperature tests.

B. The maximum hysteresis is slightly larger at the end of the test period for the cycled transducers at both test temperatures.

C. Maximum hysteresis values range from about 0.25% FS (#41931, control, laboratory ambient) to 0.10% FS (#41918, cycled, 150°F).

D. There is no discernable change in linearity.

For the 100-psig transducers:

A. The maximum hysteresis is slightly smaller at the end of the test period for three of the four control transducers at laboratory ambient conditions.

B. The maximum hysteresis is essentially unchanged at the end of the test period for the four cycled transducers (150°F, and air cooled to laboratory ambient conditions).

C. The maximum hysteresis values range from about 0.01% FS (#41920, control, laboratory ambient) to 0.03% FS (#41928, cycled, air cooled to laboratory ambient).

D. The two transducers cycled at elevated temperature showed only a small change in linearity (Figure 19).

The experimentally obtained values of hysteresis did not exceed the manufacturers' specification of 0.1% FS. The combined linearity and hysteresis values did not exceed manufacturers' specifications ±0.25% FS (15-psig) and ±0.2% FS (100-psig).

4.6. Mounting and Temperature Effects

Prior to cycling the 15-psig transducer at the elevated test temperature, the temperature of the environmental chamber was raised in three steps. At each step a stabilization time of one hour was allowed before a static calibration was performed. The data from these calibration and data from static calibration performed after 10^6 cycles and 40 x 10^6 cycles are plotted in Figure 22. These transducers had been calibrated upon receipt (as were all others) after which they were removed from the test setup and later reconnected for the cycling tests. The data from the calibration (upon receipt) are also plotted, and it can be seen that for three of the four transducers the change in sensitivity between the two static calibrations (before and after remounting) is greater than any subsequent change due to cycling or storage at the elevated temperature. Zero output pressure changes before and after remounting are also significant, relative to the somewhat greater changes due to the test procedure. We decided to investigate briefly the possibility that the torque with which the pressure line was attached to the transducer caused changes in transducer characteristics. Accordingly, the four 15-psig transducers previously tested at 150°F (65.6°C) controls, #41914 and #41916; and cycled, #41915 and #41918 were re-calibrated at laboratory ambient conditions after they had been disconnected from the test setup and then reconnected. The first test used a torque on the pressure fitting of roughly 6 lb -ft. (8.2N-m), just enough to prevent a leak at pressure. The second test used a torque of about 17 lb -ft. (23N-m) close to the point of deforming the brass pressure fitting. Eleven-point static calibrations were performed at each value of torque and the data were reduced and compared to the final static calibration following rest after cycling. The maximum change in sensitivity observed for any transducer was 0.03%, the maximum zero shift 0.09% FS. No correlation between torque and change in characteristics was found. It appears likely then that the changes observed (see Figure 22) between acceptance calibration and the first test calibration 133 days later may be attributed to the passage of time rather than mounting torque.

The results of the static temperature tests are shown in Figure 22 as seen from the graphs, the sensitivity of all transducers decreases with increasing temperature, at rates from 0.12% to 0.26% per 100°F (essentially within the manufacturers specifications of ±0.25%). Zero shifts with temperature showed a variation ranging from ±0.10% FS to ±0.20% FS. The observed results do not include the effects of cycling or timelapse.

4.7. Over-pressure Cycling Effects

Two 15-psig transducers were subjected to pressure cycling at amplitudes greater than the full scale range. One transducer was run at 200% FS and failed sometime after 14 x 10^3 cycles and before reaching 35 x 10^3 cycles. Since none of the other transducers had exhibited any problems as a result of cycling up to 40 x 10^6 cycles, we did not monitor the test closely enough to establish the exact time of failure, which manifested itself as an open arm in the strain gage bridge.

A second transducer, #41917, was pressure cycled (laboratory ambient conditions) at a nominal pressure of 22 psig (about 147% FS). The results are shown in Figure 23 which also shows the characteristics of #41931 (control) over a period of 26 days. Testing continued until almost 4.6 x 10^6 cycles had been reached. The sensitivity of the cycled transducer showed an initial drop of about 0.12% during the initial 4 x 10^5 cycles, followed by a gradual rise in sensitivity at the rate of 0.018%/10^6 cycles. This rate is considerably greater than that obtained during tests of the other transducers, as summarized in Table III.

The zero pressure output of this transducer shows an initial drop of about 0.35% FS during the initial 4 x 10^5 cycles. This was followed by a gradual but continuing drop at a rate of about 0.015% FS/10^6 cycles. The total change in zero pressure output during this test is also considerably greater than that observed in the other transducers tested (compiled in Table III). Only transducer #41919 in this table shows unstable zero-pressure output from the beginning of the tests.

4.8. Increased Cycling Rate

A brief investigation of the experimental feasibility of cycling rates greater than 5 Hz was carried out. A large ten-lobe cam was attached to the shaft of a motor rotating at 1 rps. A cam operated snap-action switch was used to operate the same type of solenoid valve used in the 5-Hz test setup. A 100-psig test transducer was connected to the valve with a three-inch length of tubing. Operation of this system showed that 10-Hz operation is feasible, although careful design of such a cam (or of a magnetic reed switch cycling system) is necessary to allow adequate time for the pressure in the transducer to reach its full value. Similarly, care must be taken to insure complete discharge of the transducer pressure during each cycle. The test transducer got hot very quickly due to adiabatic compression, and if this cycling rate were to be used, artificial cooling of the transducer would undoubtedly be necessary. In view of the minimum practical length of connecting tube used for this experiment and the limitations imposed by solenoid valve and transducer internal volumes, it does not appear practical to attain cycling rates of greater than 10 Hz for this type of transducer.

5. CONCLUSIONS

From the test results summarized in Sections 4.3. - 4.7., certain conclusions may be drawn for the particular type of transducer tested. Their application to other types of pressure transducers may not be valid, nor is the sample size used here adequate to permit predicting the characteristics of other individual devices of this type.

A. The sensitivities of some of these transducers tested at laboratory ambient conditions <u>decrease</u> with <u>cycling</u> as well as time. This appears to rule out work hardening of the elastic members as a cause.

B. The sensitivities <u>increase</u> for most transducers tested at elevated temperatures. Thus, it is not possible to clearly attribute any change in sensitivity to the cycling (for nominal full scale pressure amplitudes).

C. Changes in sensitivity are smaller numerically than changes in zero pressure output.

D. The zero pressure output <u>decreases</u> with <u>cycling</u> for the 15-psig transducers, and for the 100-psig transducers with <u>cycling</u> and <u>time</u>. In all cases, the quantitative changes were larger with cycling, and at elevated temperatures.

E. Changes in hysteresis and linearity with cycling or time are small compared to the values of these characteristics themselves. (Hysteresis, itself, did not exceed 0.1% FS in the worst case.)

F. In the case of some transducers, somewhat larger changes in characteristics may be expected during the first 10^5 cycles than during later testing. In addition, some of the control transducers showed such changes during the first three or four days of testing.

G. Over-pressure cycling produces characteristics similar to those observed during earlier work (See Reference [1]): Sensitivity and zero pressure output change significantly during the first 10^5 cycles, and more gradually after that.

H. In general, the 15-psig transducers show smaller changes in performance characteristics during the entire test procedure than the 100-psig units.

6. RECOMMENDATIONS

To obtain the desired accuracy of pressure measurement over a long period of time by the use of this type of transducer several considerations should be observed:

A. It is desirable to keep the transducers at a stable temperature as close to laboratory ambient conditions as possible within system operating constraints.

B. In view of some observed characteristic changes during early cycling and aging, it may be desirable to age the transducers after the first static calibration, and to perform another static calibration after this. Immediately following, the transducers should be cycled 10^5 times, and again calibrated. Cycling should preferably be at lower rate than 5 Hz or should involve cooling, to avoid the stress of elevated temperature cycling. The results from the three calibrations should be within the manufacturers specified limits of repeatability to furnish a reasonable assurance of the desired measurement performance.

C. Although the transducers sampled did not show any apparent mounting torque or aging effects on characteristics, all transducers should be calibrated statically after assembly into the final measurement system.

7. REFERENCES

1. "Life Cycling Test on Several Strain Gage Pressure Transducers" NBS Technical Note #434, October 1967.
2. "The Effects of Extended High-Temperature Storage on the Performance Characteristics of Several Strain Gage Pressure Transducers" NBS Technical Note #497, October 1969.
3. "Compressed Gas Handbook" J. S. Kunkly, S. D. Wilson and R. A. Cota, NASA SP-3045, 1969.
4. "Precision Measurement and Calibration" NBS Special Publication 300, Volume 1, February 1969.

TABLE I

Estimated Calibration Uncertainties

15 psig Transducers at 15-psig
(after cycling)

Source of Error	Systematic Error, Percentage of Reading	Random Error Percentage of Reading
<u>Excitation Voltage</u>		
Estimated error of measured value, 10 V	±0.010	-------
Estimated variation during calibration, ±0.5 mV		±0.005
<u>Applied Pressure</u>		
Accuracy of calibration (manuf. value)	±0.015	-------
Repeatability, resolution, ± dial division		±0.007
Quartz Bourdon tube stability; 0.002% FS (manuf. value)		±0.013
Estimated effect of adiabatic expansion of gas, ±2 dial divisions		±0.013
<u>Output Voltage</u> Approximately 36 mV		
Accuracy of calibration: ±(0.008% reading +0.01% range) (manuf. value)	±0.036	-------
Resolution ±1 digit		±0.003
<u>Transducer Temperature</u>		
Average temperature during calibration after cycling 86°F (29.8°C), variations during calibration estimated at ±2°F; transducer temperature effect, 0.25% FS/100°F (manuf. value)		±0.005

Estimated Total Systematic Error, RMS = ±0.040%

Estimated Total Random Error, RMS = ±0.021%

Estimated Total Error (S.E. +3 R.E.) = ±0.103%

TABLE II

Estimated Calibration Uncertainties

100 psig Transducers at 100 psig
(after cycling)

Source of Error	Systematic Error Percentage of Reading	Random Error Percentage of Reading
Excitation Voltage		
Estimated error of measured value, 10 V	±0.010	--------
Estimated variation during calibration, ±0.5 mV		±0.005
Applied Pressure		
Accuracy of calibration (manuf. value)	±0.015	-------
Repeatability, resolution, ±1 dial division		±0.001
Quartz Bourdon tube stability, 0.002% FS (manuf. value)		±0.002
Estimated effect of adiabatic expansion of gas ±5 dial divisions		±0.005
Output Voltage Approximately 36 mV		
Accuracy of calibration, (manuf. value): ±(0.008% reading +0.01% range)	±0.036	-------
Resolution, ±1 digit		±0.003
Transducer Temperature		
Average temperature during calibration after cycling at 137°F (58°C); variations during calibration estimated at ±10°F; transducer temperature effect, 0.25% FS/100°F (manuf. value)		±0.025

Estimated Total Systematic Error, RMS= ±0.040%

Estimated Total Random Error, RMS = ±0.026

Estimated Total Error (S.E. +3 R.E.) = ±0.118%

TABLE III

Slopes of Straight Lines Through Experimental Sensitivity and Zero Pressure Output Values

Transducer Number	Range psig	Test Condition		Sensitivity Slope		Zero Output Slope	
				%/10^6 cycles	%/40 x 10^6 cycles	%FS/10^6 cycles	%FS/40 x 10^6 cycles
41919	15	Control Lab. Amb.		-0.00011	-0.0046	0.013	0.53
41931	15	Control Lab. Amb.		-0.00029	-0.012	0.00016	0.006
41929	15	Cycled Lab. Amb.		0.00072	0.029	-0.0027	-0.11
41932	15	Cycled Lab. Amb.		-0.00036	-0.015	-0.0015	-0.058
41923	100	Control Lab. Amb.		0.00004	0.0017	-0.0024	-0.098
41927	100	Control Lab. Amb.		0.00057	0.023	-0.0010	-0.040
41921	100	Cycled 150°F	See	0.0077	0.31	-0.013	-0.53
41933	100	Cycled 150°F	3.3.	0.0074	0.30	-0.017	-0.67
41914	15	Control 150°F		0.00047	0.019	-0.0024	-0.097
41916	15	Control 150°F		0.00062	0.025	0.0016	0.062
41915	15	Cycled 150°F		0.00077	0.031	-0.0054	-0.22
41918	15	Cycled 150°F		-0.00005	-0.0021	-0.011	-0.43
41920	100	Control Lab. Amb.		-0.0013	-0.052*	-0.00042	-0.017*
41925	100	Control Lab. Amb.		-0.0023	-0.091*	-0.0083	-0.33 *
41924	100	Cycled Lab. Amb.*+		-0.0043	-0.17 *	-0.0067	-0.27 *
41928	100	Cycled Lab. Amb.*+		-0.0034	-0.13 *	-0.016	-0.64 *

* Extrapolated from test data obtained up to 10 x 10^6 cycles.
*+ Using artificial cooling

TABLE IV

Values of Standard Deviation
Computed as a Percentage of the Sensitivity
from Static Calibration Data in Tables VII-XV

Transducer	Test Conditions	Initial	Final	Smallest	Largest
41919	15 psig control ambient	.0468	.0418	.0413	.0470
41931	15 psig control ambient	.0470	.0485	.0462	.0533
41929	15 psig cycled ambient	.0470	.0501	.0420	.0504
41932	15 psig cycled ambient	.0500	.0537	.0495	.0575
41923	100 psig control ambient	.0150	.0245	.0150	.0253
41927	100 psig control ambient	.0300	.0277	.0263	.0300
41921	100 psig cycled 150°F	.0297	.0252	.0169	.0311
41933	100 psig cycled 150°F	.0531	.0554	.0364	.0565
41914	15 psig control 150°F	.0611	.0594	.0555	.0625
41916	15 psig control 150°F	.0577	.0563	.0552	.0613
41915	15 psig cycled 150°F	.0761	.0777	.0700	.0834
41918	15 psig cycled 150°F	.0598	.0754	.0598	.0805
41920	100 psig control ambient	.0446	.0416	.0416	.0446
41925	100 psig control ambient	.0326	.0390	.0324	.0393
41924	100 psig cycled cooled	.0339	.0334	.0334	.0406
41928	100 psig cycled cooled	.0271	.0282	.0271	.0332
41931	15 psig control ambient	.0519	.0476	.0454	.0527
41917	15 psig cycled overpress	.0644	.0647	.0582	.0671

Note: Sensitivity Values in Tables VII-XV are given in terms of (mV/V)/psig, and are converted to full scale output values in before dividing into standard deviation values in to obtain final results in this Table.

TABLE V

Effect of Durability Tests on Sensitivity and Zero-Pressure Output

Number	Status		Test Condition	Test Duration	Initial Sensit. (mV/V)/psi	Final Sensit. (mV/V)/psi	% Change	Initial Zero % FS	Final Zero % FS	Change % FS
41919	Control	15	Lab. Amb.	109 days	0.24376	0.24376	0.000	-0.683	0.088	0.771
41931	Control	15	Lab. Amb.	109 days	0.23521	0.23520	-0.0042	0.267	0.278	0.011
41929	Cycled	15	Lab. Amb.	40.5×10^6	0.23670	0.23674	0.017	0.652	0.485	-0.167
41932	Cycled	15	Lab. Amb.	40.5×10^6	0.24115	0.24106	-0.037	0.430	0.376	-0.054
41914	Control	15	150°F	108 days	0.23826	0.23826	0.000	-0.532	-0.677	-0.145
41916	Control	15	150°F	108 days	0.24294	0.24297	0.012	0.426	0.472	0.046
41915	Cycled	15	150°F	40.9×10^6	0.24316	0.24323	0.029	0.579	0.335	-0.244
41918	Cycled	15	150°F	40.9×10^6	0.24786	0.24783	-0.012	0.283	-0.153	-0.436
41923	Control	100	Lab. Amb.	108 days	0.035984	0.035984	0.000	-0.592	-0.734	-0.142
41927	Control	100	Lab. Amb.	108 days	0.036046	0.036051	0.014	-0.619	-0.688	-0.069
41921	Cycled	100	150°F	40.1×10^6	0.036033	0.03608	0.15	-0.108	-0.738	-0.630
41933	Cycled	100	150°F	40.1×10^6	0.035457	0.035534	0.22	-0.0874	-0.997	-0.910
41920	Control	100	Lab. Amb.	36 days	0.036098	0.0360	-0.0083	0.553	0.542	-0.011
41925	Control	100	Lab. Amb.	36 days	0.036157	0.036150	-0.019	0.508	0.538	0.030
41924	Cycled	100	Air Cooled	10.9×10^6	0.035973	0.035956	-0.047	-0.558	-0.544	0.014
41928	Cycled	100	Air Cooled	10.9×10^6	0.036180	0.036172	-0.022	0.100	-0.0361	-0.136
41931	Control	15	Lab. Amb.	26 days	0.23510	0.23507	-0.017	0.309	0.321	0.012
41917	Over Pressure	22½	Lab. Amb.	4.5×10^6	0.24648	0.24637	-0.044	-0.217	-0.623	-0.406

TABLE VI

SUMMARY OF TESTS

Serial	15 psig Range				100 psig Range				Over Pressure Tests 15 psig Range		
	Room Temperature		150° F		Room Temperature		150° F		Room Temperature		
	Control	Cycle	Control	Cycle	Control	Cycle	Control	Cycle	Control	Cycle 50% Overrange	Cycle 100% Overrange
41919	X										
41931	X								X		
41929		40×10^6									
41932		40×10^6									
41914			X								
41916			X								
41915				40×10^6							
41918				40×10^6							
41920					X						
41925					X						
41924						10×10^6					
41928						10×10^6					
41923					X						
41927					X						
41921								40×10^6 (A)			
41933								40×10^6			
41917										4.5×10^6	14×10^3
41930											
41922										not tested	
41926										not tested	

(A) Heating as a result of pressure & cycling rate
(B) Failed from 100% overpressure tests between 14×10^3 and 34×10^3 cycles

TABLE VII

STATIC CALIBRATION DATA

#41919, CONTROL, 15 PSIG						#41931, CONTROL, 15 PSIG								
Sensi-tivity	Line-arity	Hys-teresis	First Zero	Ending Zero	Standard Deviation	Sensi-tivity	Line-arity	Hys-teresis	First Zero	Ending Zero	Standard Deviation	Date	Test Days	Calibration Number
.243290	.079	.049	-.4839	-.4730	.00164	.234384	.072	.022	.1676	.1761	.00168	9/20		26 & 13
.243286	.083	.039	-.4785	-.4676	.00165	.234365	.079	.030	.1676	.1762	.00167	9/20		28 & 17
.243318	.089	.044	-.4702	-.4647	.00179	.234377	.074	.021	.1705	.1790	.00168	9/20		30 & 21
Transducers Remounted														
.243763	.082	.042	-.6827	-.6607	.00171	.235211	.074	.025	.2671	.2756	.00166	10/4	0	61 & 62
.243723	.085	.041	-.4166	-.3974	.00169	.235183	.074	.035	.2840	.2926	.00177	10/4	0	65 & 66
.243752	.081	.037	-.0630	-.0548	.00170	.235171	.083	.035	.2898	.2983	.00188	10/8	4	77 & 78
.243737	.079	.035	-.1508	-.1426	.00168	.235200	.080	.033	.2784	.2926	.00180	10/15	11	83 & 84
.243740	.084	.041	-.1289	-.1124	.00169	.235202	.072	.041	.2728	.2898	.00179	10/22	18	87 & 88
.243759	.084	.030	-.1424	-.1342	.00164	.235217	.072	.029	.2952	.2980	.00169	10/29	25	91 & 92
.243728	.070	.027	.0630	.0739	.00158	.235167	.082	.036	.2867	.2980	.00181	11/5	32	117 & 118
.243752	.080	.033	.0793	.0875	.00156	.235196	.077	.041	.2863	.2977	.00170	11/12	39	127 & 128
.243715	.071	.034	-.0328	-.0164	.00151	.235133	.072	.027	.2807	.2949	.00164	11/22	49	131 & 132
.243666	.076	.035	.1013	.1067	.00157	.235107	.071	.027	.2950	.2978	.00172	11/26	53	139 & 140
.243717	.080	.044	.1176	.1231	.00163	.235165	.077	.040	.2864	.2977	.00176	12/3	60	151 & 152
.243726	.073	.024	-.0055	.0000	.00160	.235183	.082	.028	.2892	.2977	.00178	12/10	67	159 & 160
.243730	.081	.026	+.0547	+.0629	.00155	.235185	.075	.030	.2863	.2977	.00164	12/17	74	167 & 168
.243770	.079	.030	.1286	.1422	.00158	.235209	.080	.029	.2778	.2892	.00170	12/23	80	175 & 176
.243746	.075	.036	.1204	.1341	.00152	.235166	.079	.036	.3063	.3205	.00163	12/30	87	183 & 184
.243724	.081	.043	.1368	.1505	.00172	.235166	.084	.037	.2723	.2836	.00179	1/7	95	191 & 192
.243736	.077	.039	.1888	.2025	.00167	.235163	.087	.039	.2836	.2978	.00181	1/17	105	199 & 200
.243763	.073	.029	.0876	.0958	.00153	.235202	.075	.027	.2779	.2921	.00171	1/21	109	207 & 208

TABLE VIII

STATIC CALIBRATION DATA

Cycles x 10^3	#41929, CYCLED, 15 PSIG Sensitivity	Linearity	Hysteresis	First Zero	Ending Zero	Standard Deviation	#41932, CYCLED, 15 PSIG Sensitivity	Linearity	Hysteresis	First Zero	Ending Zero	Standard Deviation	Date	Test Days	Calibration Number
0	.236725	.088	.027	.5817	.5873	.00141	.241182	.087	.041	.4130	.4185	.00177	9/20		1 & 3
0	.236707	.085	.025	.5901	.5901	.00138	.241156	.083	.042	.4157	.4213	.00175	9/20		5 & 7
0	.236691	.089	.019	.5873	.5930	.00147	.241144	.082	.041	.4185	.4240	.00179	9/20		9 & 11
						Transducers	Remounted								
0	.236698	.102	.040	.6522	.6579	.00147	.241148	.091	.041	.4296	.4351	.00181	10/4	0	63 & 64
50	.236711	.095	.051	.6011	.5983	.00166	.241135	.089	.066	.4211	.4266	.00198	10/4	0	67 & 68
100	.236705	.095	.041	.5675	.5704	.00160	.241131	.094	.051	.4241	.4296	.00193	10/5	1	69 & 70
200	.236702	.096	.031	.5589	.5617	.00157	.241101	.087	.047	.4018	.4101	.00179	10/5	1	71 & 72
500	.236747	.096	.037	.5420	.5420	.00159	.241138	.092	.053	.3825	.3936	.00184	10/6	2	73 & 74
1,000	.236693	.089	.036	.5251	.5279	.00149	.241114	.092	.057	.3991	.4046	.00188	10/7	3	75 & 76
1,400	.236724	.101	.043	.5278	.5306	.00167	.241146	.091	.056	.3657	.3768	.00190	10/8	4	79 & 80
2,950	.236745	.093	.029	.5250	.5250	.00149	.241130	.089	.060	.3686	.3825	.00186	10/12	8	81 & 82
4,210	.236747	.098	.039	.5222	.5222	.00162	.241141	.090	.058	.3769	.3852	.00189	10/15	11	85 & 86
7,200	.236756	.099	.045	.5081	.5166	.00160	.241138	.095	.060	.3520	.3741	.00188	10/22	18	89 & 90
10,190	.236803	.103	.044	.5272	.5243	.00165	.241178	.098	.064	.3598	.3709	.00195	10/29	25	93 & 94
12,800	.236713	.095	.048	.4879	.4879	.00159	.241057	.097	.061	.3821	.3877	.00196	11/5	32	119 & 120
15,374	.236780	.107	.053	.4844	.4844	.00173	.241119	.103	.070	.3540	.3650	.00198	11/12	39	129 & 130
18,400	.236679	.097	.045	.5466	.5466	.00159	.241036	.091	.058	.4011	.4094	.00185	11/22	49	133 & 134
20,090	.236718	.109	.045	.4930	.4873	.00178	.241062	.110	.059	.3541	.3596	.00208	11/26	53	141 & 142
23,030	.236735	.103	.062	.4816	.4816	.00169	.241089	.098	.073	.3540	.3595	.00191	12/3	60	153 & 154
25,189	.236770	.103	.057	.4900	.4928	.00177	.241106	.095	.072	.3539	.3622	.00207	12/10	67	161 & 162
28,095	.236778	.109	.049	.4844	.4872	.00179	.241112	.101	.070	.3706	.3789	.00197	12/17	74	169 & 170
30,635	.236807	.110	.047	.4674	.4674	.00177	.241144	.101	.052	.3484	.3595	.00191	12/23	80	177 & 178
33,638	.236764	.106	.051	.4732	.4788	.00175	.241081	.096	.067	.3541	.3596	.00185	12/30	87	185 & 186
36,240	.236778	.105	.045	.4591	.4619	.00174	.241118	.100	.061	.3458	.3568	.00200	1/7	95	193 & 194
40,533	.236794	.102	.051	.4591	.4619	.00174	.241113	.094	.070	.3319	.3402	.00200	1/17	105	201 & 202
4 days rest	.236740	.112	.048	.4846	.4931	.00178	.241062	.099	.060	.3763	.3846	.00194	1/21	109	209 & 210

TABLE IX

STATIC CALIBRATION DATA

	#41914, CONTROL, 15 PSIG, 150°F (66°C)						#41916, CONTROL, 15 PSIG, 150°F (66°C)								
	Sensitivity	Linearity	Hysteresis	First Zero	Ending Zero	Standard Deviation	Sensitivity	Linearity	Hysteresis	First Zero	Ending Zero	Standard Deviation	Date	Test Days	Calibration Number
(85° F)	.238287	.092	.041	-.5429	-.5261	.00207	.242964	.118	.041	.4144	.4282	.00210	1/28	0	215 & 216
(85° F)	.238260	.081	.031	-.5318	-.5178	.00199	.242943	.118	.035	.4255	.4337	.00206	1/31	0	219 & 220
(100° F)	.238120	.086	.031	-.5824	-.5656	.00201	.242792	.120	.043	.5026	.5108	.00208	1/31	0	223 & 224
(125° F)	.237980	.093	.042	-.6108	-.5940	.00206	.242634	.117	.035	.5304	.5386	.00206	1/31	0	227 & 228
(150° F)	.237863	.097	.039	-.6110	-.5914	.00218	.242551	.122	.042	.5223	.5278	.00210	1/31	0	231 & 232
	.237894	.091	.040	-.5635	-.5467	.00215	.242619	.122	.037	.4536	.4618	.00215	2/1	0	235 & 236
	.237871	.093	.028	-.5551	-.5410	.00212	.242587	.122	.035	.4508	.4536	.00218	2/4	3	251 & 252
	.237860	.096	.037	-.5608	-.5496	.00223	.242603	.120	.043	.4508	.4563	.00223	2/11	10	261 & 262
	.237846	.090	.029	-.5749	-.5580	.00213	.242593	.113	.035	.4509	.4591	.00205	2/18	17	269 & 270
	.237881	.089	.032	-.5749	-.5609	.00211	.242618	.116	.036	.4619	.4674	.00208	2/25	24	273 & 274
	.237926	.096	.039	-.5860	-.5719	.00223	.242676	.122	.048	.4728	.4810	.00220	3/3	31	277 & 278
	.237879	.095	.031	-.5749	-.5608	.00214	.242634	.120	.041	.4729	.4839	.00211	3/9	37	281 & 282
	.237893	.092	.033	-.6000	-.5859	.00214	.242635	.116	.038	.4865	.4920	.00210	3/17	45	285 & 286
	.237876	.091	.034	-.5915	-.5775	.00212	.242612	.114	.040	.4810	.4892	.00206	3/24	52	289 & 290
	.237909	.095	.037	-.6027	-.5887	.00204	.242665	.115	.038	.4892	.4947	.00202	3/31	59	311 & 312
	.237916	.095	.051	-.6111	-.5943	.00209	.242674	.122	.056	.4837	.4919	.00218	4/10	69	315 & 316
	.237917	.097	.040	-.6364	-.6280	.00209	.242662	.123	.049	.4948	.4975	.00215	4/14	73	326 & 327
	.237913	.094	.038	-.6364	-.6224	.00216	.242657	.121	.043	.4865	.4920	.00218	4/21	80	342 & 343
	.237933	.085	.031	-.6222	-.6110	.00198	.242683	.114	.037	.5111	.5166	.00201	4/28	87	356 & 357
	.237898	.088	.033	-.6506	-.6366	.00212	.242644	.116	.044	.5059	.5141	.00212	5/5	94	364 & 365
	.237944	.096	.030	-.6448	-.6335	.00210	.242688	.126	.045	.5085	.5140	.00221	5/11	100	372 & 373
	.237875	.090	.032	-.6673	-.6589	.00212	.242622	.113	.040	.5168	.5223	.00205	5/15	104	376 & 377
(85° F)	.238262	.095	.045	-.6774	-.6606	.00208	.242970	.116	.044	.4721	.4886	.00213	5/19	108	384 & 385

TABLE X

STATIC CALIBRATION DATA

	#41915, CYCLED, 15 PSIG, 150°F (66°C)						#41918, CYCLES, 15 PSIG, 150°F (66°C)								
Cycles x 10^3	Sensi-tivity	Line-arity	Hys-teresis	First Zero	Ending Zero	Standard Deviation	Sensi-tivity	Line-arity	Hys-teresis	First Zero	Ending Zero	Standard Deviation	Date	Test Days	Calibration Number
0	.243169	.168	.049	.5704	.5786	.00271	.247850	.132	.080	.2798	.2852	.00234	1/28	0	217 & 218
0	.243156	.176	.046	.5787	.5869	.00277	.247855	.139	.069	.2825	.2933	.00239	1/31	0	221 & 222
0	.243028	.174	.042	.6091	.6173	.00269	.247805	.133	.063	.2745	.2798	.00223	1/31	0	225 & 226
0	.242881	.178	.047	.6533	.6643	.00280	.247716	.128	.073	.2772	.2880	.00223	1/31	0	229 & 230
0	.242770	.180	.045	.7003	.7085	.00277	.247659	.128	.078	.2827	.2934	.00222	1/31	0	233 & 234
0	.242790	.180	.043	.6977	.7087	.00279	.247710	.131	.072	.2719	.2773	.00229	2/1	0	237 & 238
50	.242814	.171	.019	.7057	.7139	.00264	.247706	.140	.069	.2799	.2880	.00244	2/1	0	239 & 240
100	.242789	.175	.036	.7058	.7140	.00272	.247672	.146	.066	.2854	.2961	.00252	2/1	0	241 & 242
200	.242825	.173	.023	.6947	.7085	.00268	.247699	.146	.059	.2746	.2880	.00247	2/2	1	243 & 244
537	.242837	.164	.029	.6921	.7003	.00255	.247651	.154	.081	.2747	.2828	.00266	2/3	2	245 & 246
980	.242738	.185	.036	.7005	.7060	.00289	.247564	.155	.091	.2828	.2909	.00276	2/4	3	253 & 254
2,223	.242835	.168	.021	.6810	.6920	.00260	.247596	.155	.081	.2612	.2747	.00266	2/7	6	255 & 256
3,913	.242758	.180	.038	.6786	.6868	.00283	.247561	.155	.078	.2532	.2613	.00275	2/11	10	263 & 264
6,884	.242760	.176	.035	.6539	.6594	.00274	.247549	.154	.078	.2128	.2209	.00266	2/18	17	271 & 272
8,293	.242823	.183	.036	.6374	.6484	.00284	.247618	.163	.075	.1778	.1940	.00277	2/25	24	275 & 276
11,135	.242841	.188	.043	.6208	.6345	.00289	.247687	.158	.075	.1454	.1589	.00270	3/3	31	279 & 280
13,593	.242834	.187	.034	.6098	.6236	.00289	.247653	.165	.072	.1239	.1374	.00277	3/9	37	283 & 284
17,043	.242840	.187	.036	.5932	.6070	.00290	.247629	.166	.075	.0862	.0970	.00278	3/17	45	287 & 288
20,013	.242819	.184	.041	.5794	.5932	.00288	.247590	.158	.082	.0566	.0754	.00274	3/24	52	291 & 292
22,988	.242852	.186	.039	.5767	.5877	.00292	.247620	.169	.070	.0350	.0431	.00285	3/31	59	313 & 314
27,292	.242890	.192	.056	.5546	.5629	.00299	.247670	.173	.079	-.0135	.0000	.00293	4/10	69	317 & 318
28,891	.242865	.189	.044	.5383	.5465	.00297	.247673	.166	.083	-.0350	-.0269	.00285	4/14	73	328 & 329
31,773	.242884	.189	.041	.5190	.5272	.00293	.247676	.167	.082	-.0727	-.0619	.00284	4/21	80	344 & 345
34.868	.242857	.187	.038	.5244	.5272	.00290	.247615	.169	.077	-.0835	-.0754	.00283	4/28	87	358 & 359
36,598	.242834	.189	.041	.4972	.5027	.00292	.247612	.173	.082	-.1212	-.1159	.00290	5/5	94	366 & 367
39,161	.242899	.195	.045	.4861	.4943	.00304	.247674	.177	.090	-.1374	-.1320	.00299	5/11	100	374 & 375
40,886	.242826	.181	.055	.4752	.4779	.00283	.247602	.164	.100	-.1643	-.1589	.00280	5/15	104	378 & 379
	.243234	.184	.050	.3345	.3455	.00296	.247825	.167	.091	-.1534	-.1346	.00294	5/19	108	386 & 387

TABLE XI

STATIC CALIBRATION DATA

#41923, CONTROL, 100 PSIG						#41927, CONTROL, 100 PSIG								
Sensi-tivity	Line-arity	Hys-teresis	First Zero	Ending Zero	Standard Deviation	Sensi-tivity	Line-arity	Hys-teresis	First Zero	Ending Zero	Standard Deviation	Date	Test Days	Calibration Number
.035992	.068	.023	-.5617	-.5644	.00111	.036039	.041	.035	-.6141	-.6308	.00100	9/22		34 & 46
.035984	.059	.028	-.5673	-.5645	.00103	.036043	.043	.029	-.6335	-.6363	.00106	9/22		38 & 50
.035978	.057	.018	-.5702	-.5702	.00093	.036041	.042	.037	-.6335	-.6391	.00108	9/22		42 & 54
.035996	.022	.033	-.5751	-.5890	.00054	.036052	.047	.021	-.6353	-.6436	.00108	11/1	0	95 & 96
.035984	.048	.017	-.5921	-.5976	.00088	.036046	.042	.018	-.6188	-.6271	.00099	11/2	0	99 & 100
.035991	.033	.019	-.5863	-.6057	.00065	.036054	.050	.014	-.6407	-.6546	.00107	11/2	0	103 & 104
.035984	.029	.032	-.6792	-.6876	.00066	.036048	.042	.019	-.6780	-.6836	.00097	11/5	3	113 & 114
.035984	.037	.029	-.6868	-.6952	.00074	.036051	.042	.019	-.6772	.6828	.00101	11/12	10	123 & 124
.035988	.034	.020	-.6732	-.6760	.00064	.036048	.041	.021	-.6887	-.6887	.00099	11/22	20	135 & 136
.035979	.049	.017	-.6954	-.7010	.00086	.036050	.046	.021	-.6857	-.6885	.00107	11/26	24	143 & 144
.035980	.045	.020	-.7063	-.7119	.00085	.036055	.038	.018	-.6938	-.6966	.00095	12/3	31	147 & 148
.035991	.041	.022	-.6755	-.6783	.00075	.036061	.041	.017	-.6853	-.6880	.00103	12/10	38	155 & 156
.035987	.041	.020	-.6921	-.7005	.00075	.036056	.043	.021	-.6825	-.6880	.00104	12/17	45	163 & 164
.035987	.039	.024	-.7116	-.7199	.00071	.036058	.040	.022	-.6907	-.6935	.00100	12/23	51	171 & 172
.035992	.041	.013	-.6948	-.7059	.00071	.036058	.044	.013	-.6658	-.6769	.00099	12/30	58	179 & 180
.035987	.042	.014	-.7171	-.7310	.00075	.036057	.044	.020	-.6907	-.6990	.00105	1/7	66	187 & 188
.035984	.057	.025	-.7338	-.7422	.00091	.036055	.040	.019	-.6991	-.7046	.00100	1/17	76	195 & 196
.035988	.037	.017	-.7003	-.7170	.00068	.036058	.044	.015	-.6823	-.6934	.00098	1/21	80	203 & 204
.035988	.032	.013	-.7253	-.7365	.00062	.036058	.039	.024	-.6990	-.6990	.00097	1/28	87	211 & 212
.035984	.051	.010	-.7338	-.7393	.00084	.036058	.039	.022	-.7017	-.7045	.00098	2/4	94	247 & 248
.035983	.056	.008	-.7369	-.7453	.00089	.036054	.038	.022	-.6994	-.6994	.00097	2/11	101	257 & 258
.035984	.052	.011	-.7341	.7452	.00088	.036051	.039	.023	-.6883	-.6939	.00100	2/18	108	265 & 266

TABLE XII

STATIC CALIBRATION DATA

	#41921, CYCLED, 100 PSIG						#41933, CYCLED, 100 PSIG								
Cycles x 10^3	Sensi-tivity	Line-arity	Hys-teresis	First Zero	Ending Zero	Standard Deviation	Sensi-tivity	Line-arity	Hys-teresis	First Zero	Ending Zero	Standard Deviation	Date	Test Days	Calibration Number
0	.036047	.037	.016	-.0944	-.0999	.00086	.035461	.063	.006	-.0704	-.0788	.00156	9/22		32 & 56
0	.036042	.032	.014	-.0972	-.1083	.00076	.035463	.062	.017	-.0732	-.0845	.00150	9/22		36 & 58
0	.036032	.028	.006	-.1028	-.1083	.00071	.035461	.063	.009	-.0760	-.0845	.00152	9/22		40 & 60
0	.036040	.037	.013	-.0832	-.0916	.00084	.035462	.065	.016	-.0818	-.0902	.00160	11/1	0	97 & 98
0	.036033	.034	.016	-.1083	-.1166	.00085	.035457	.070	.015	-.0874	-.0903	.00162	11/2	0	101 & 102
50	.036074	.045	.019	-.2855	-.2911	.00107	.035433	.097	.062	.0000	-.0621	.00188	11/2	0	105 & 106
100	.036090	.057	.031	-.3551	-.3246	.00110	.035436	.073	.006	-.0593	-.0537	.00169	11/2	0	107 & 108
205	.036018	.046	.014	-.3693	-.3721	.00112	.035439	.079	.023	-.2822	-.2822	.00182	11/3	1	109 & 110
430	.036079	.046	.026	-.3385	-.3552	.00104	.035424	.099	.073	-.0424	-.1159	.00191	11/4	2	111 & 112
800	.036056	.051	.025	-.3973	-.4225	.00098	.035427	.106	.076	-.1555	-.2319	.00188	11/5	3	115 & 116
2,055	.036040	.038	.022	-.4946	-.4752	.00077	.035439	.081	.044	-.4182	-.3843	.00160	11/8	6	121 & 122
3,775	.036086	.030	.006	-.4353	-.4409	.00078	.035435	.081	.062	-.2033	-.2654	.00159	11/12	10	125 & 126
5,910	.036031	.027	.019	-.4723	-.4751	.00071	.035458	.057	.023	-.4884	-.4884	.00129	11/22	20	137 & 138
7,600	.036093	.033	.042	-.5740	-.5324	.00072	.035459	.077	.021	-.4290	-.4403	.00147	11/26	24	145 & 146
10,558	.036122	.030	.028	-.5928	-.5651	.00065	.035468	.090	.025	-.4175	-.4401	.00159	12/3	31	149 & 150
13,665	.036140	.035	.050	-.6478	-.5980	.00071	.035495	.083	.011	-.4989	-.4961	.00143	12/10	38	157 & 158
16,579	.036129	.032	.016	-.6147	-.6174	.00067	.035498	.094	.065	-.4790	-.5439	.00170	12/17	45	165 & 166
19,099	.036139	.033	.028	-.6809	-.6532	.00065	.035508	.094	.028	-.5521	-.5803	.00159	12/23	51	173 & 174
22,120	.036141	.032	.019	-.6919	-.6726	.00061	.035509	.091	.037	-.5634	-.6000	.00157	12/30	58	181 & 182
25,435	.036135	.030	.030	-.7058	-.7224	.00068	.035512	.085	.104	-.5971	-.7013	.00189	1/7	66	189 & 190
29,678	.036140	.052	.015	-.7472	-.7500	.00084	.035511	.119	.062	-.6591	-.7211	.00201	1/17	76	197 & 198
31,380	.036149	.037	.009	-.7553	-.7581	.00061	.035523	.099	.059	-.6842	-.7433	.00174	1/21	80	205 & 206
34,346	.036140	.037	.026	-.7583	-.7832	.00070	.035521	.095	.087	-.7180	-.8053	.00181	1/28	87	213 & 214
37,252	.036159	.048	.030	-.8436	-.8132	.00081	.035528	.124	.028	-.7798	-.8079	.00200	2/4	94	249 & 250
40,137	.036152	.055	.028	-.8636	-.8359	.00091	.035530	.123	.026	-.8534	-.8731	.00197	2/11	101	259 & 260
7 days rest	.036088	.045	.014	-.7375	-.7431	.00075	.035534	.117	.013	-.9968	-.9996	.00184	2/18	108	267 & 268

TABLE XIII

STATIC CALIBRATION DATA

#41920, CONTROL, 100 PSIG						#41925, CONTROL, 100 PSIG								
Sensi-tivity	Line-arity	Hys-teresis	First Zero	Ending Zero	Standard Deviation	Sensi-tivity	Line-arity	Hys-teresis	First Zero	Ending Zero	Standard Deviation	Date	Test Days	Calibration Number
.036098	.069	.033	.5530	.5419	.00161	.036157	.072	.020	.5077	.5049	.00118	4/20	0	332 & 333
.036101	.069	.015	.5502	.5419	.00161	.036159	.072	.009	.5188	.5160	.00117	4/20	0	338 & 339
.036097	.069	.013	.5447	.5336	.00158	.036152	.081	.010	.6299	.6271	.00131	4/28	8	352 & 353
.036096	.067	.024	.5336	.5252	.00157	.036149	.088	.013	.5272	.5245	.00142	5/5	15	360 & 361
.036096	.065	.018	.5364	.5336	.00157	.036148	.083	.010	.5883	.5855	.00134	5/11	21	368 & 369
.036097	.067	.008	.5447	.5364	.00156	.036151	.083	.013	.4578	.4551	.00136	5/19	29	380 & 381
.036092	.066	.011	.5475	.5364	.00155	.036147	.087	.011	.4357	.4301	.00142	5/22	32	388 & 389
.036095	.065	.013	.5419	.5308	.00150	.036150	.087	.011	.5383	.5328	.00141	5/26	36	392 & 393

TABLE XIV

STATIC CALIBRATION DATA

	#41924, CYCLED, 100 PSIG, AIR COOLED						#41928, CYCLED, 100 PSIG, AIR COOLED								
Cycles x 10^3	Sensitivity	Linearity	Hysteresis	First Zero	Ending Zero	Standard Deviation	Sensitivity	Linearity	Hysteresis	First Zero	Ending Zero	Standard Deviation	Date	Test Days	Calibration Number
0	.035973	.048	.029	-.5577	-.5605	.00122	.036180	.050	.026	.0998	.0970	.00098	4/20	0	334 & 335
50	.035965	.073	.036	-.5049	-.5411	.00138	.036170	.052	.042	.1248	.0832	.00119	4/20	0	336 & 337
100	.035962	.067	.024	-.5244	-.5440	.00142	.036171	.047	.019	.0971	.0777	.00115	4/20	0	340 & 341
200	.035962	.062	.039	-.4770	-.4881	.00143	.036171	.053	.029	.0638	.0555	.00120	4/21	1	346 & 347
665	.035962	.067	.017	-.4965	-.5133	.00143	.036171	.046	.014	.0582	.0444	.00107	4/25	5	348 & 349
1,070	.035956	.073	.031	-.4631	-.4938	.00143	.036166	.043	.028	.0638	.0361	.00116	4/26	6	350 & 351
2,028	.035949	.067	.024	-.4521	-.4716	.00146	.036162	.044	.020	-.0583	-.0749	.00114	4/28	8	354 & 355
3,760	.035946	.059	.032	-.5219	-.5302	.00141	.036161	.048	.026	-.0638	-.0746	.00117	5/5	15	362 & 363
6,191	.035948	.063	.023	-.4855	-.5051	.00137	.036162	.048	.025	-.0416	-.0666	.00119	5/11	21	370 & 371
9,613	.035949	.064	.025	-.5637	-.5888	.00135	.036160	.044	.028	-.0610	-.0888	.00111	5/19	29	382 & 383
10,878	.035950	.057	.025	-.5971	-.6111	.00135	.036160	.045	.024	-.0805	-.0999	.00113	5/22	32	390 & 391
4 days rest	.035956	.053	.020	-.5440	-.5468	.00120	.036172	.041	.019	-.0361	-.0333	.00102	5/26	36	394 & 395

TABLE XV

STATIC CALIBRATION DATA

Cycles	#41931, CONTROL, 15 PSIG Sensi-tivity	Line-arity	Hys-teresis	First Zero	Ending Zero	Standard Deviation	#41917, CYCLED, 22 PSIG (147% OVER RANGE) Sensi-tivity	Line-arity	Hys-teresis	First Zero	Ending Zero	Standard Deviation	Date	Test Days	Calibra-tion #
0	.235104	.083	.032	.3093	.3036	.00183	.246481	.139	.034	-.2165	-.2220	.00231	3/24	0	293 & 294
0							.246509	.138	.038	-.2246	-.2165	.00228	3/24	0	294A*
40,000	.235099	.079	.039	.3177	.3148	.00186	.246301	.138	.044	-.4792	-.4927	.00238	3/24	0	296 & 297
80,000	.235018	.074	.024	.3433	.3263	.00182	.246292	.141	.044	-.4819	-.5062	.00239	3/24	0	298 & 299
3 days rest 80,000	.235123	.076	.033	.2808	.2950	.00179	.246055	.150	.038	-.5394	-.5339	.00246	3/27	3	300 & 301
120,000							.246282	.142	.046	-.4900	-.5143	.00242	3/27	3	302
160,000							.246330	.146	.040	-.5358	-.5494	.00248	3/27	3	303
270,000	.235104	.081	.052	.3042	.3070	.00184	.246276	.132	.047	-.5943	-.5970	.00230	3/28	4	304 & 305
386,000							.246199	.135	.038	-.5615	-.5886	.00234	3/29	5	306
690,000							.246252	.127	.079	-.7103	-.5317	.00248	3/30	6	307
808,000							.246348	.149	.033	-.5881	-.6152	.00245	3/30	6	308
1,127,000	.235075	.069	.042	.3181	.3181	.00161	.246327	.138	.043	-.6235	-.6316	.00225	3/31	7	309 & 310
10 days rest 1,127,000	.235194	.076	.038	.2781	.2895	.00161	.246159	.147	.042	-.6290	-.6290	.00235	4/10	17	319 & 320
1,581,000							.246378	.136	.026	-.6177	-.6204	.00220	4/11	18	321
2,011,000							.246317	.131	.014	-.6259	-.6395	.00215	4/12	19	322
2,454,000							.246332	.153	.036	-.5820	-.5928	.00247	4/13	20	323
2,768,000	.235079	.064	.027	.3205	.3035	.00160	.246352	.149	.044	-.5982	-.6171	.00238	4/14	21	324 & 325
4,541,000	.235066	.075	.024	.3205	.3120	.00168	.246374	.147	.044	-.6225	-.6387	.00239	4/19	26	330 & 331

* Calibrated to 30 psi

TEST AND CALIBRATION EQUIPMENT FOR PRESSURE TRANSDUCER DURABILITY INVESTIGATION

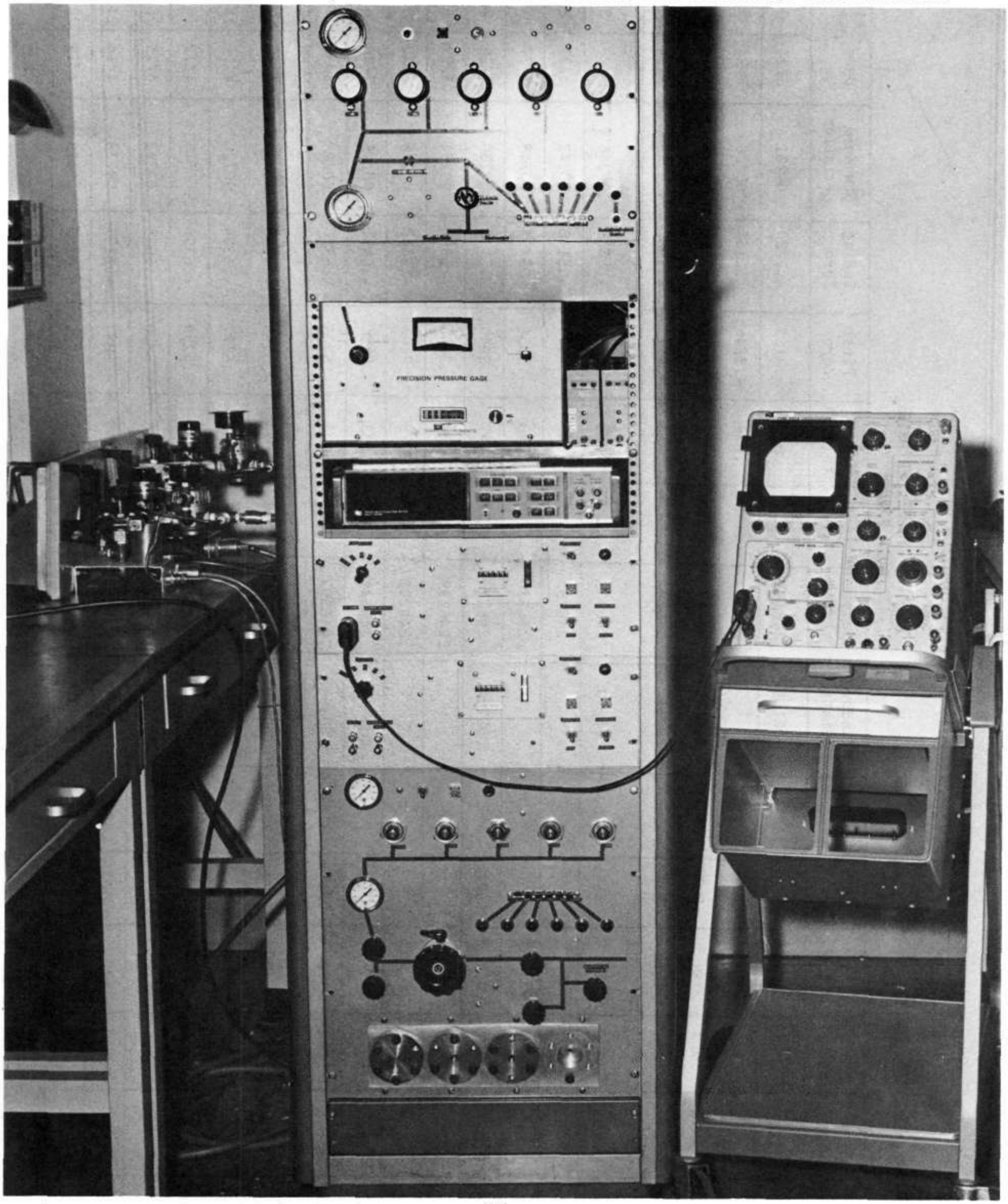
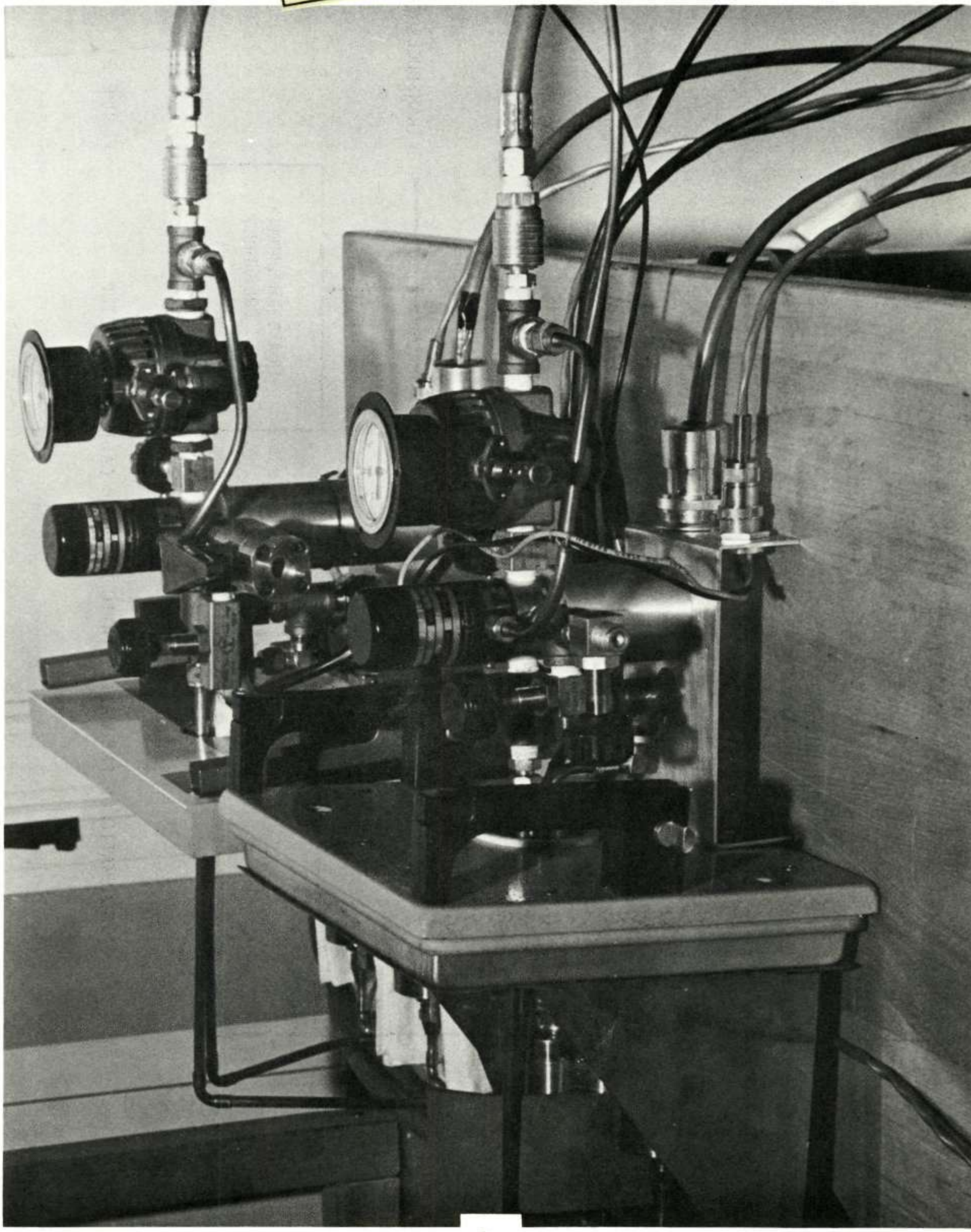
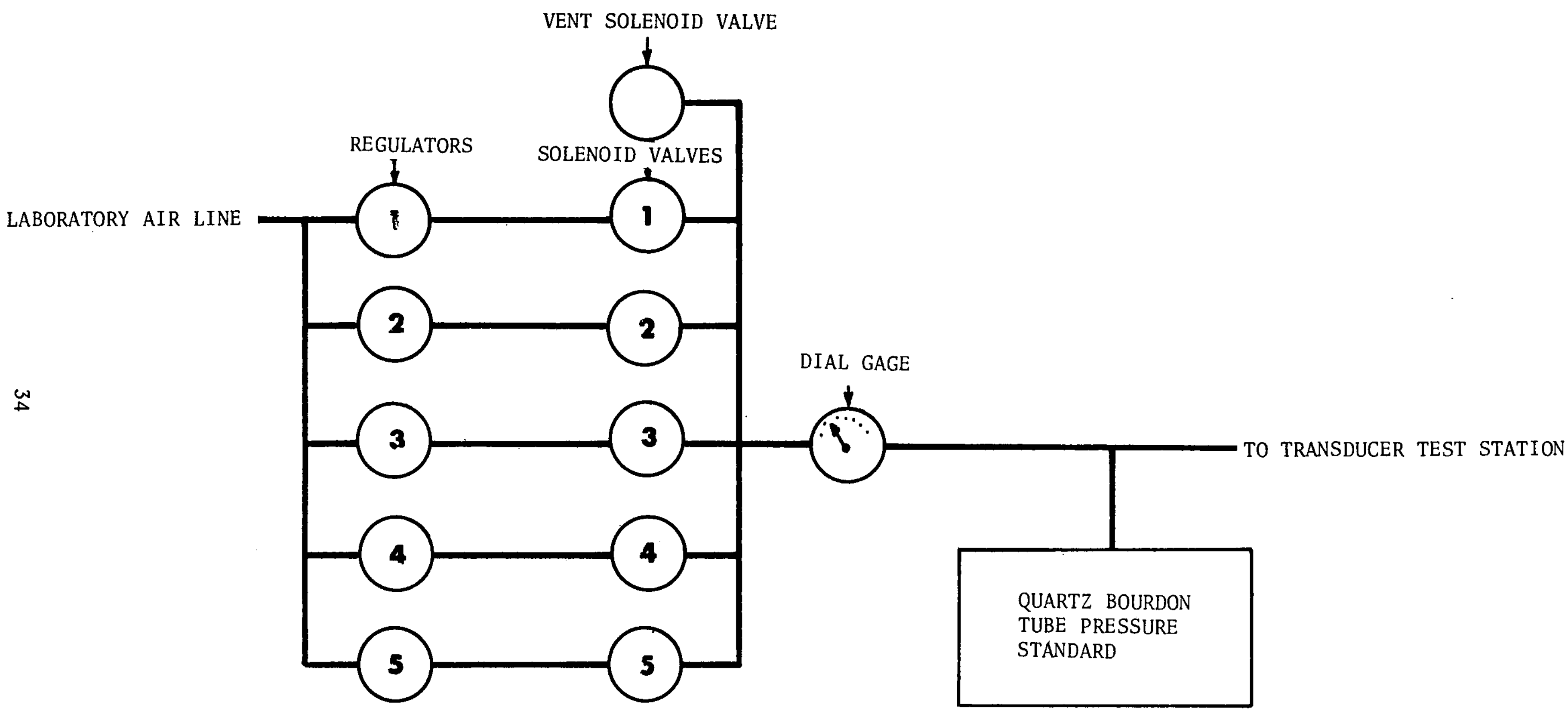


Figure 1



VIEW OF TRANSDUCER TEST STATIONS

Figure 2



SCHEMATIC OF PNEUMATIC STATIC PRESSURE CALIBRATION SETUP

FIGURE 3

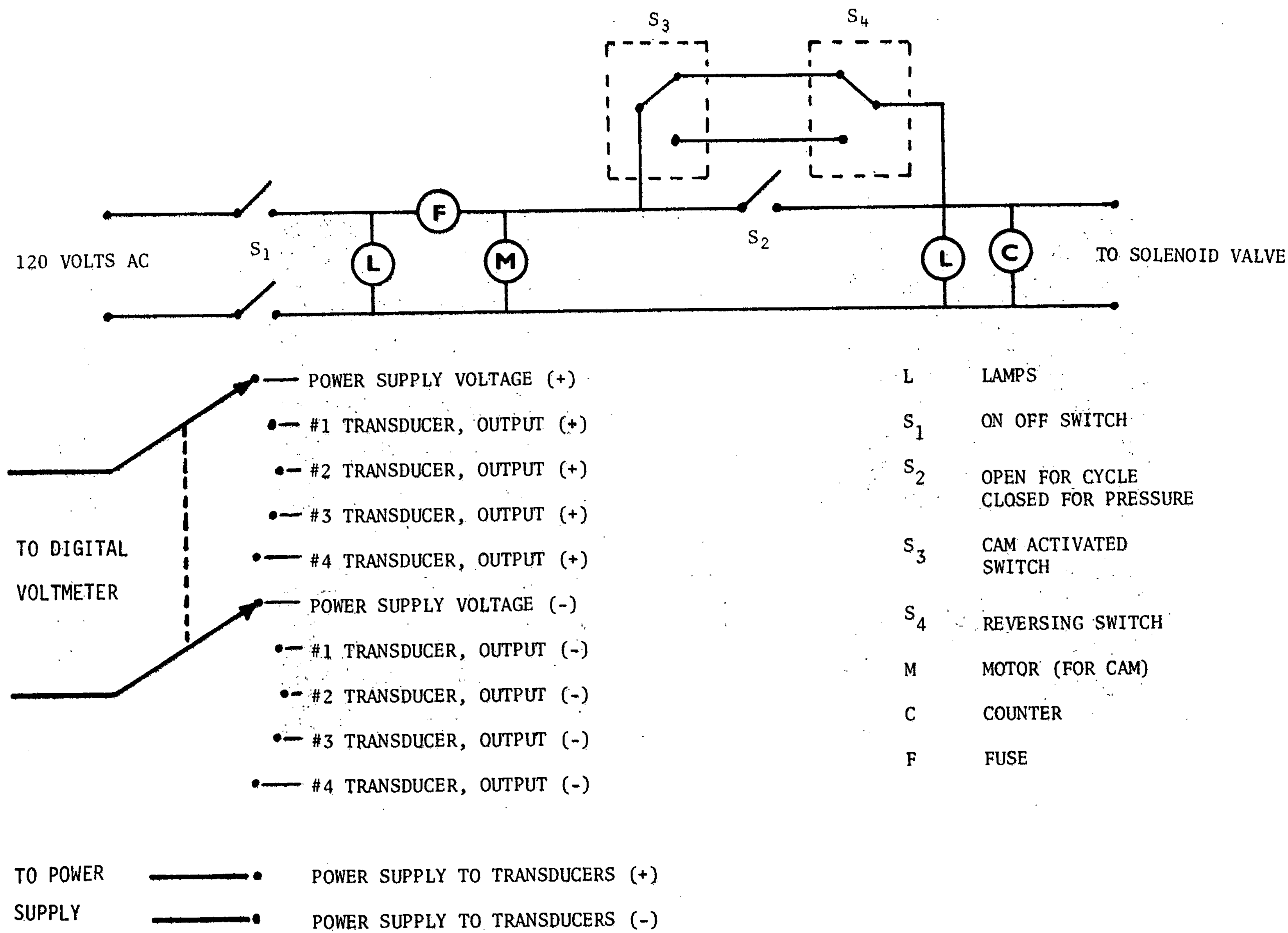


FIGURE 4 SCHEMATIC OF PATCH PANEL AND PRESSURE CYCLING CONTROL

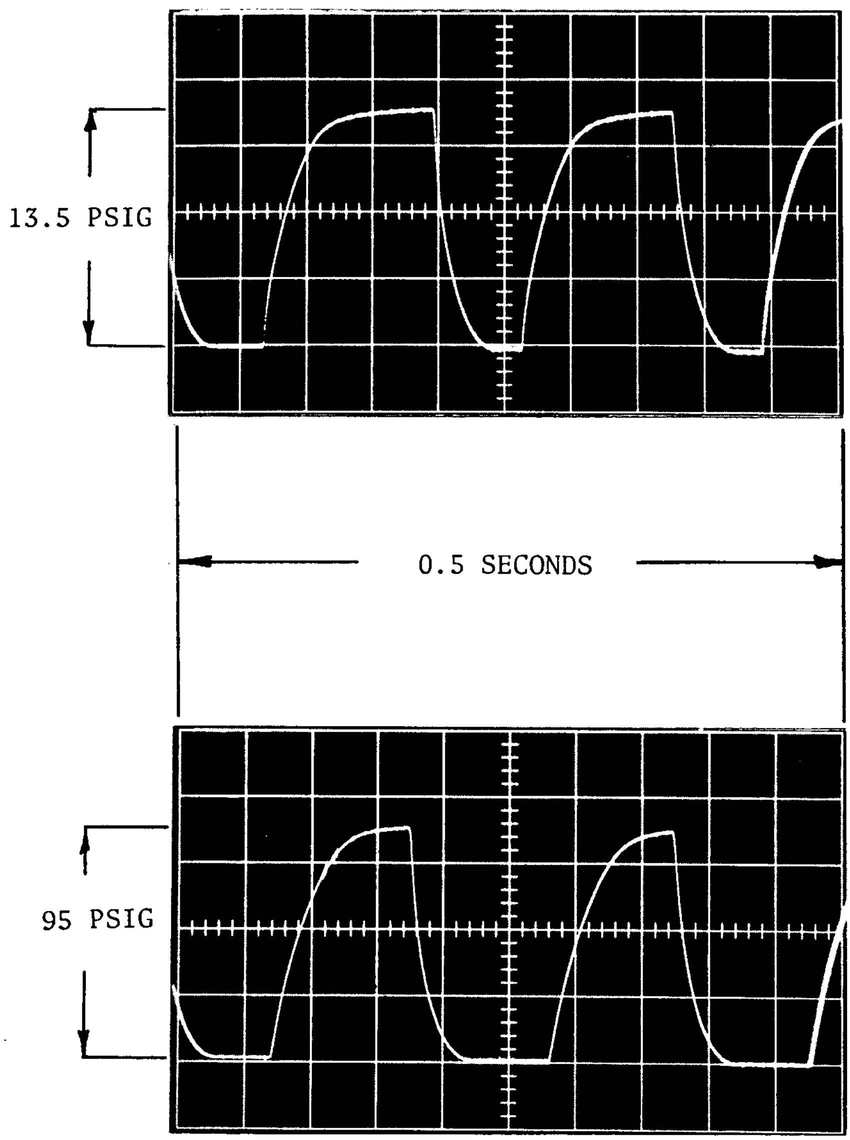


FIGURE 5 WAVE SHAPES OF PRESSURE CYCLING INPUT TO TEST TRANSDUCERS

TEMPERATURE OF 100 PSIG TRANSDUCER WITH & WITHOUT EXTERNAL COOLING, 5 Hz RATE

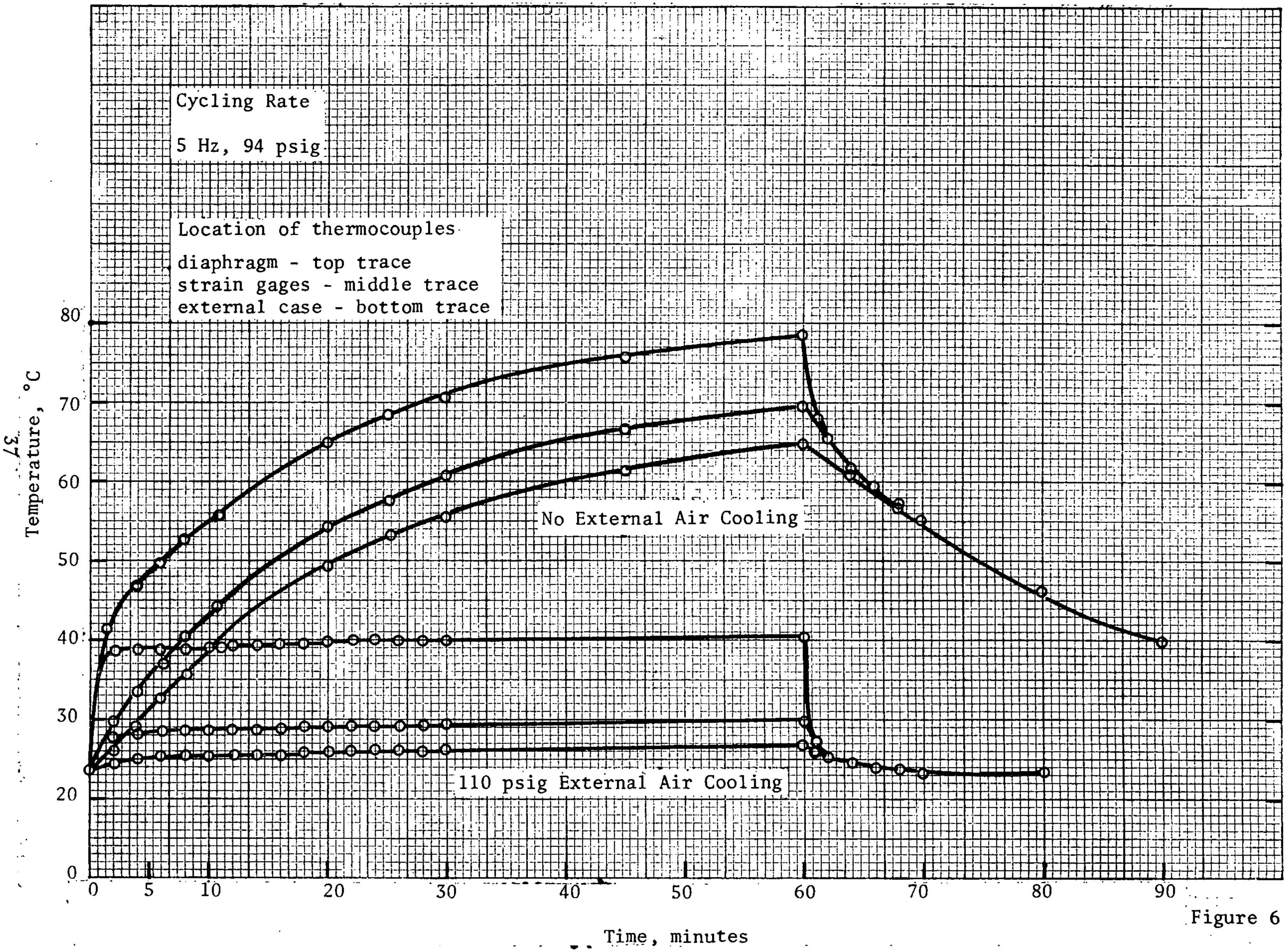


Figure 6

SENSITIVITY VS TIME & CYCLING, 15 PSIG TRANSDUCERS

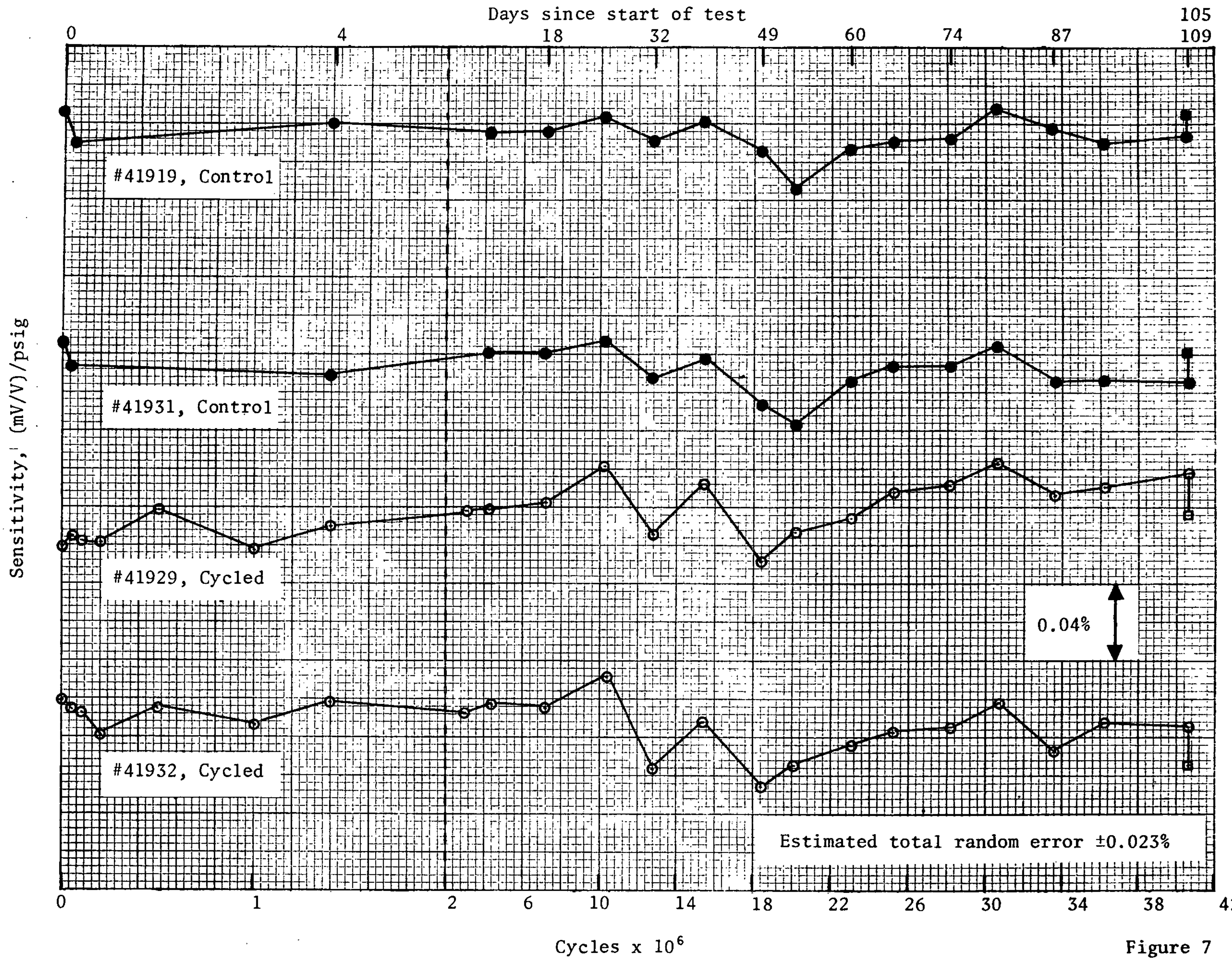


Figure 7

SENSITIVITY VS TIME AND CYCLING, 15 PSIG TRANSDUCERS, 150°F

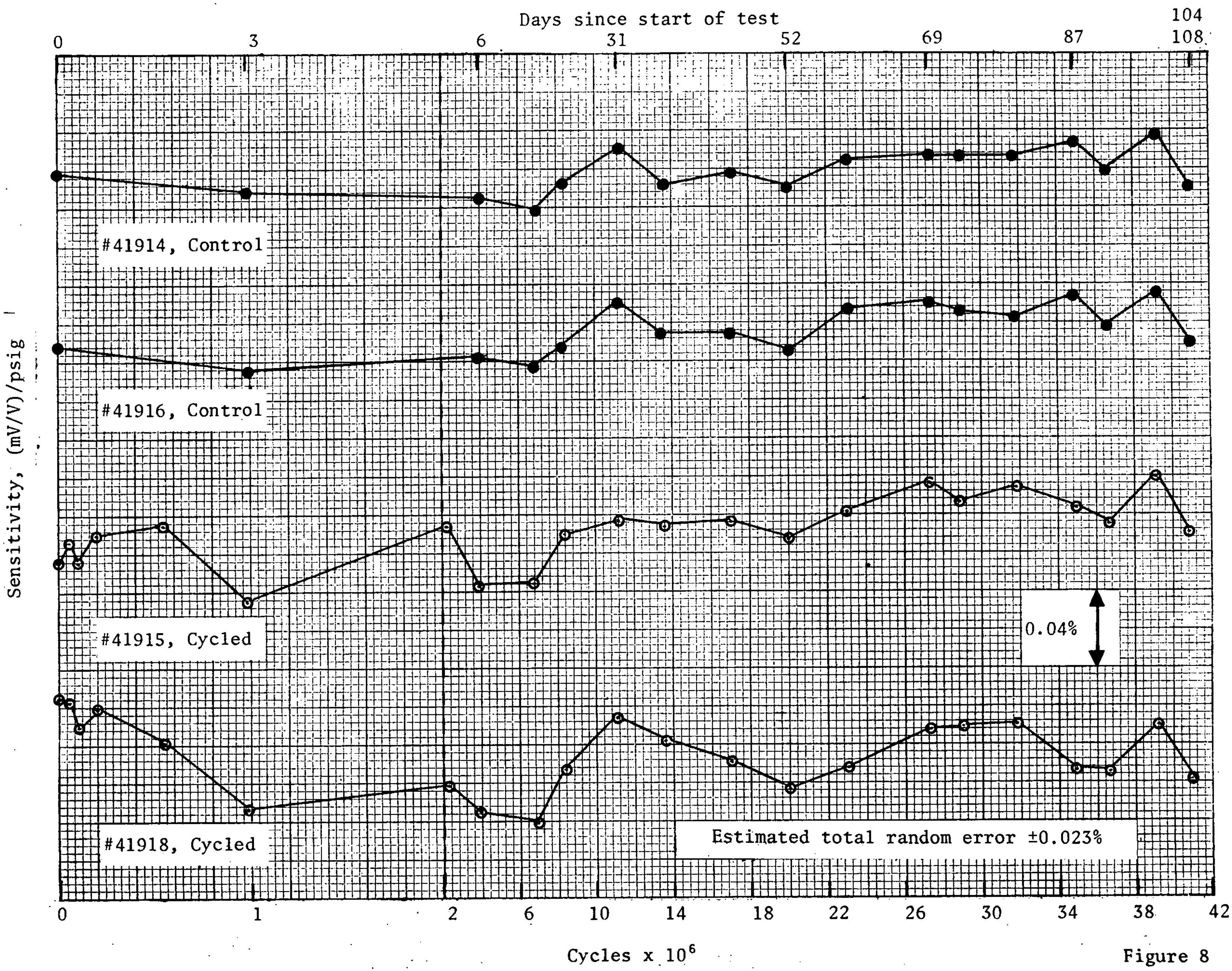


Figure 8

SENSITIVITY VS TIME & CYCLING, 100 PSIG TRANSDUCERS, NO AIR COOLING, CONTROLS AT LABORATORY AMBIENT TEMPERATURE

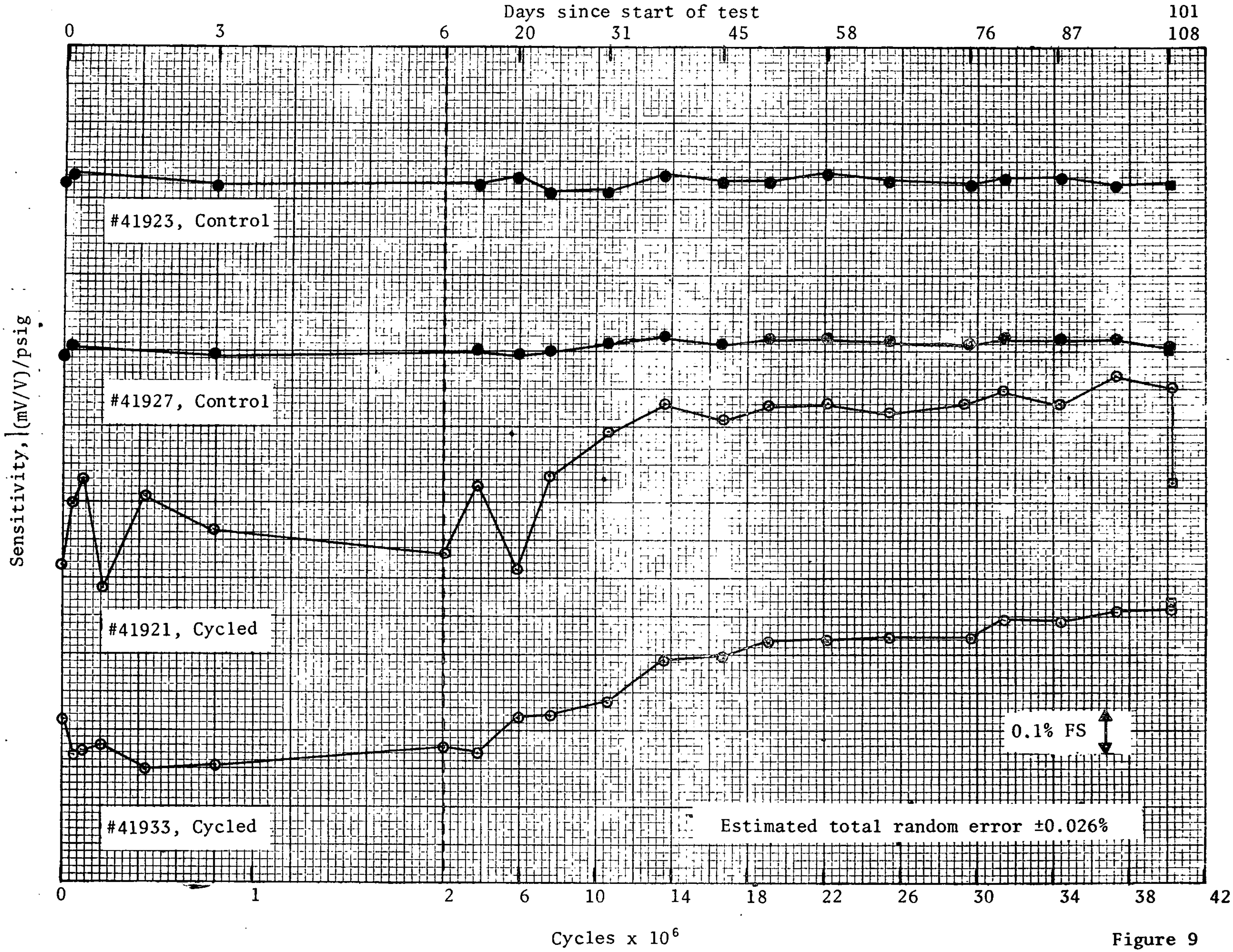


Figure 9

SENSITIVITY & ZERO PSIG GAGE OUTPUT VS TIME & CYCLING, 100 PSIG TRANSDUCERS, AIR COOLED

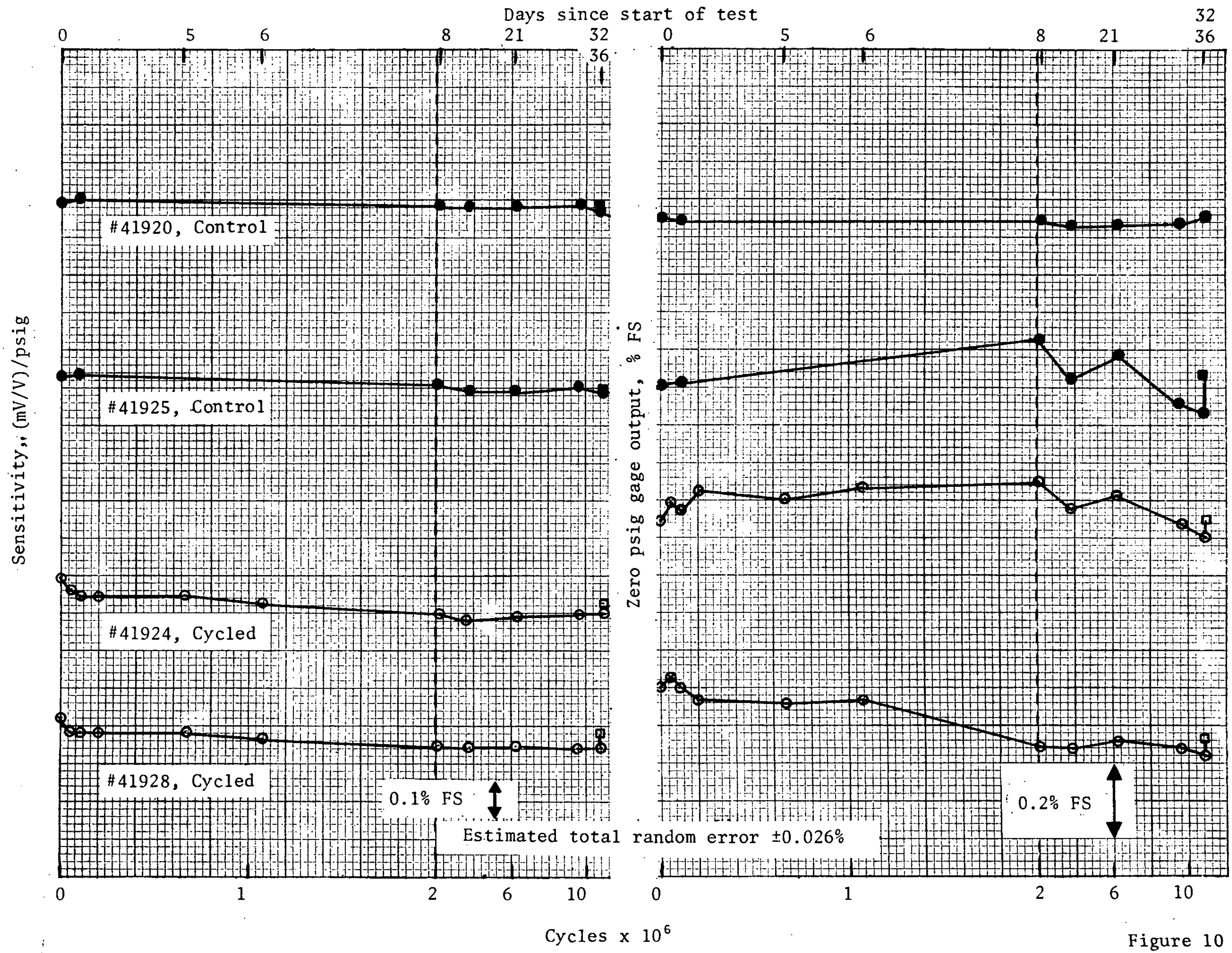


Figure 10

ZERO PSIG GAGE OUTPUT VS TIME & CYCLING, 15 PSIG TRANSDUCERS

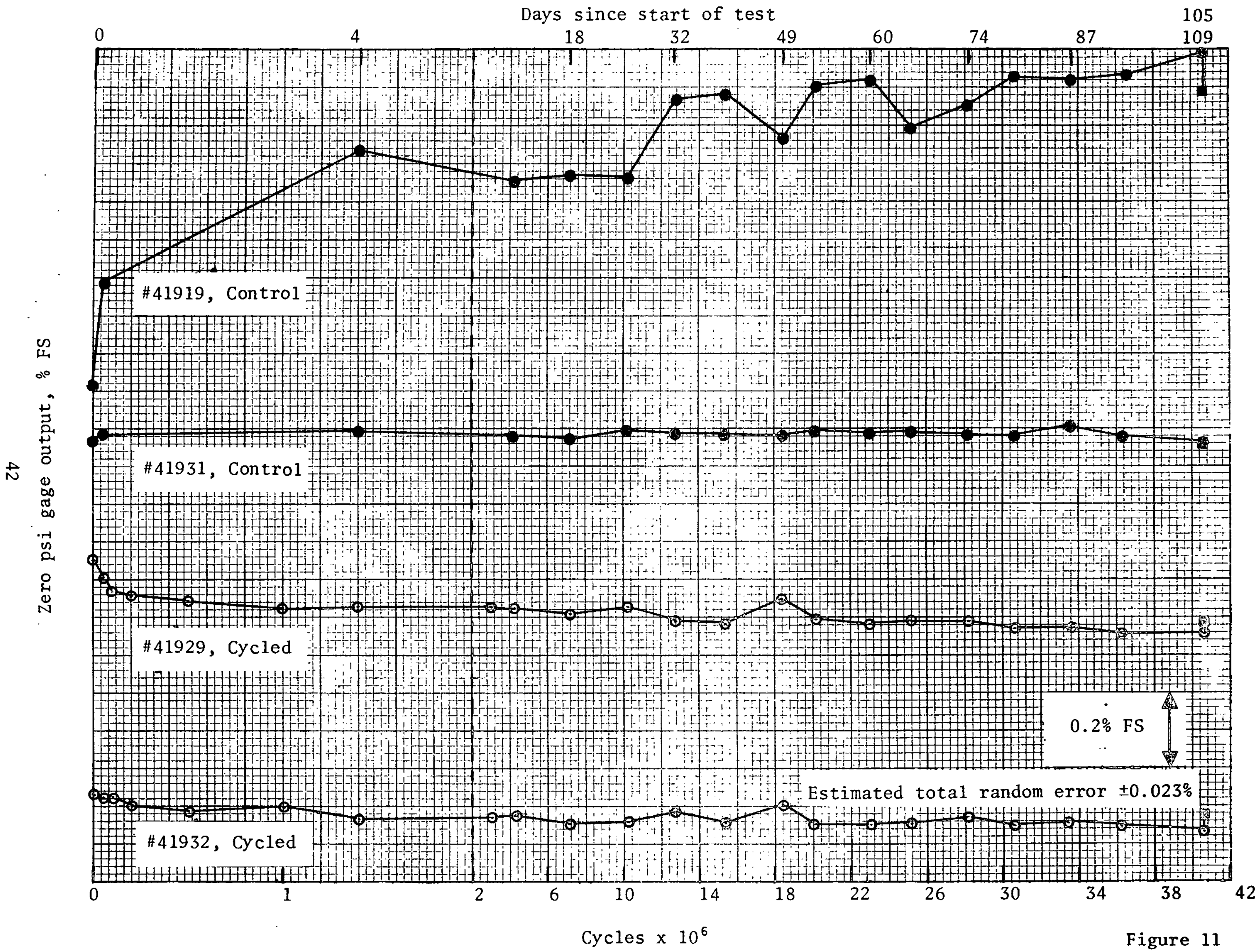


Figure 11

ZERO PSIG GAGE OUTPUT VS TIME & CYCLING, 15 PSIG TRANSDUCERS, 150°F

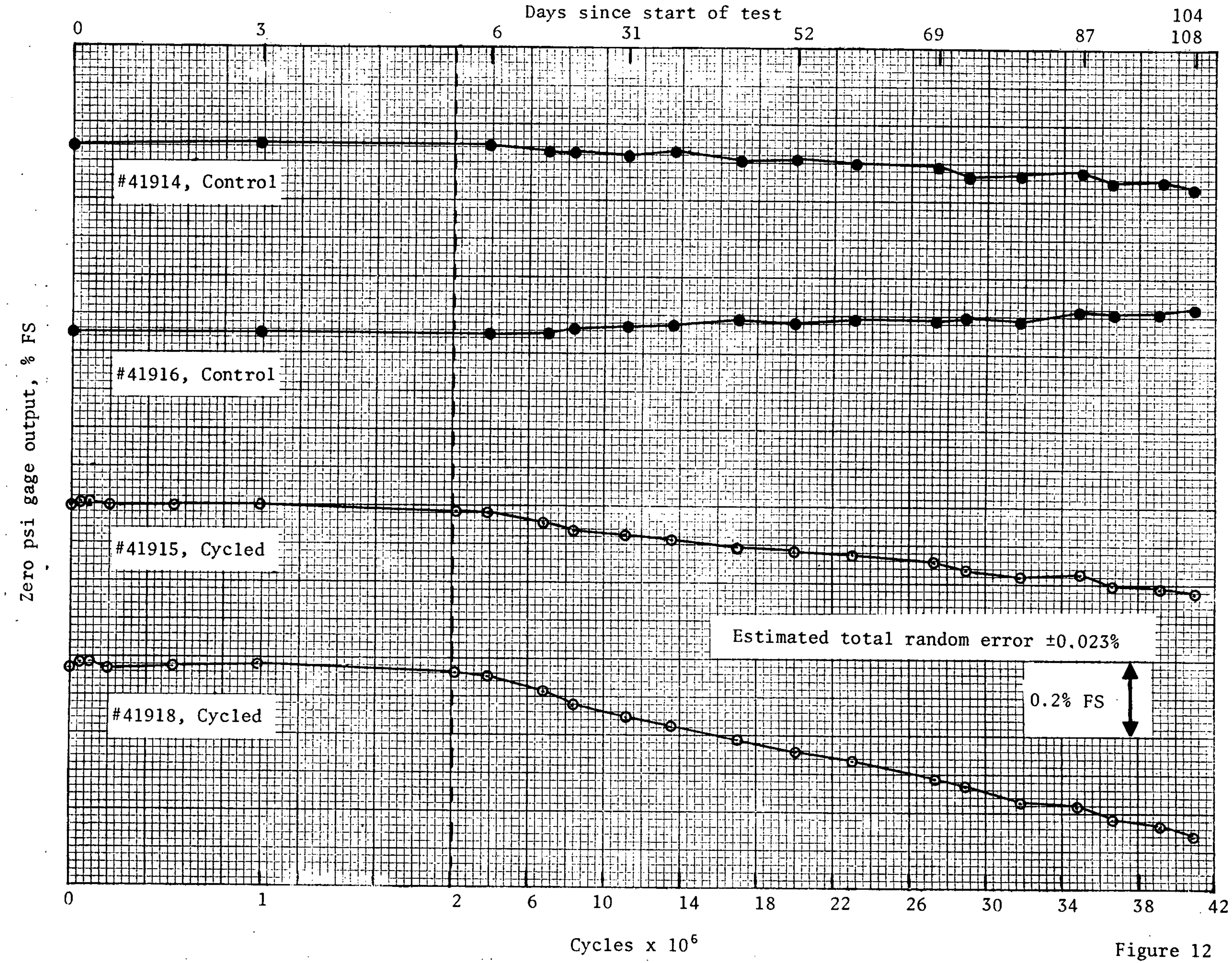


Figure 12

ZERO PSIG GAGE OUTPUT VS TIME & CYCLING, 100 PSIG TRANSDUCERS, NO AIR COOLING

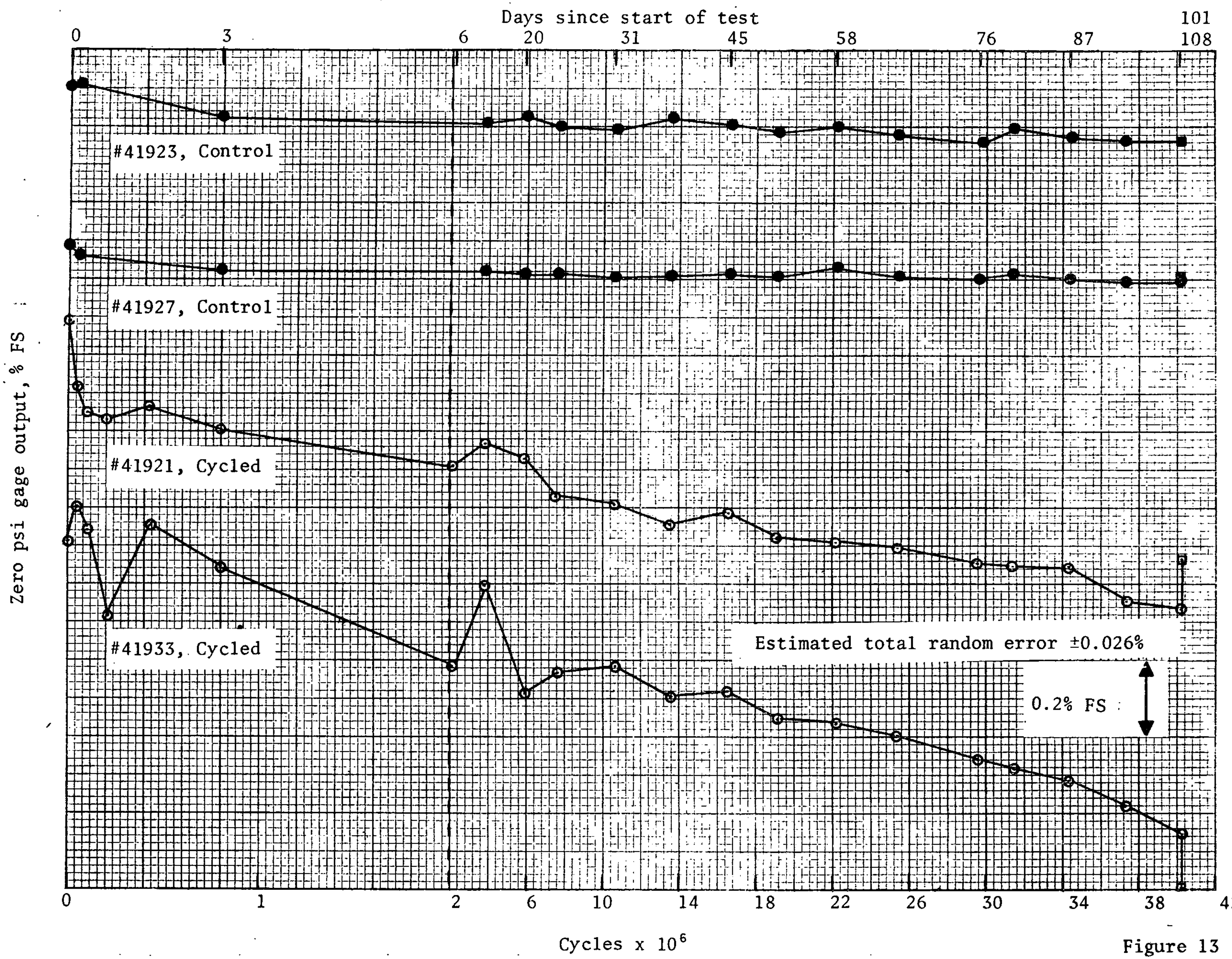


Figure 13

LINEARITY & HYSTERESIS, 15 PSIG CONTROL TRANSDUCERS

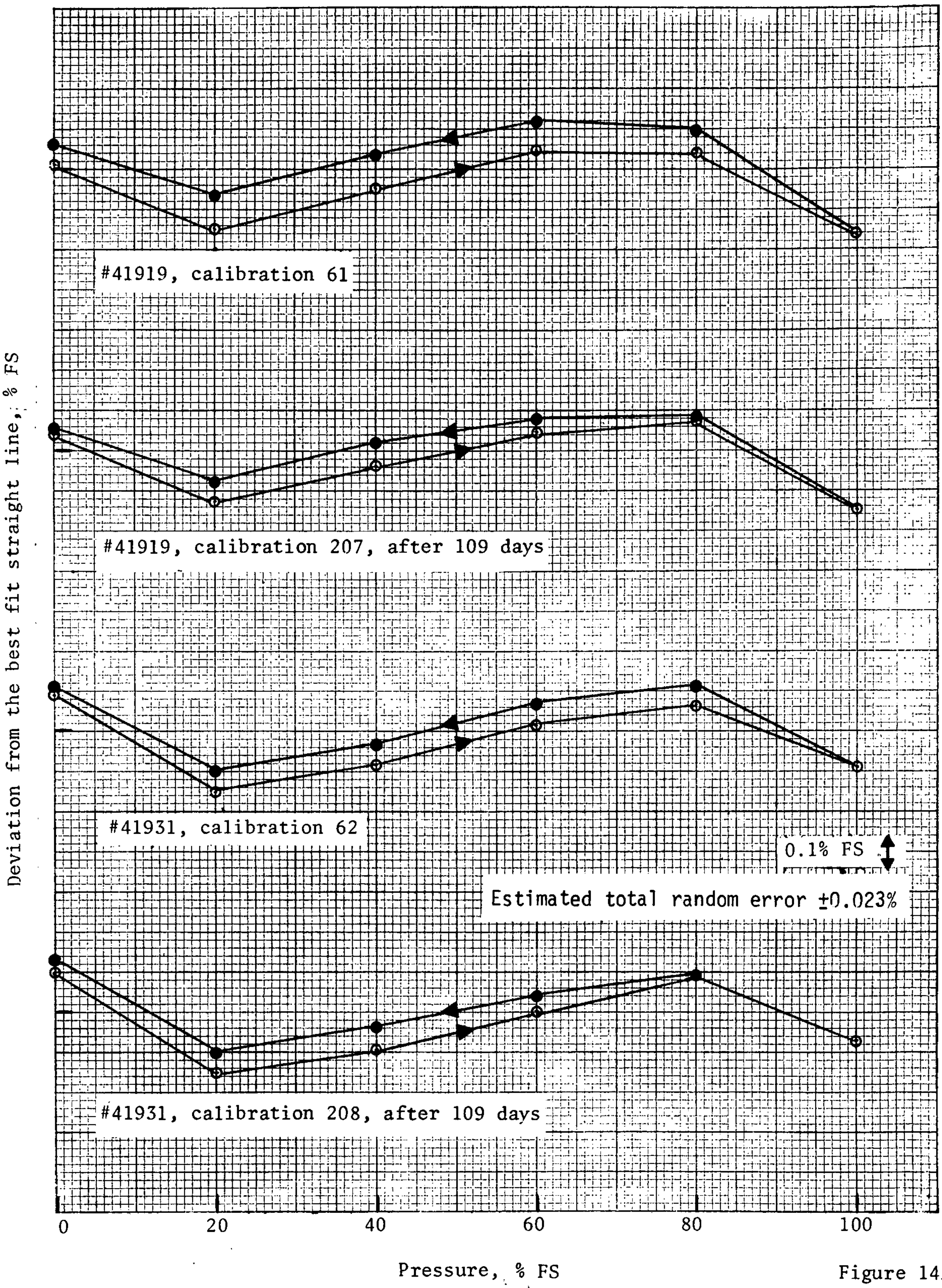


Figure 14.

EFFECT OF CYCLING ON LINEARITY & HYSTERESIS, 15 PSIG TRANSDUCERS

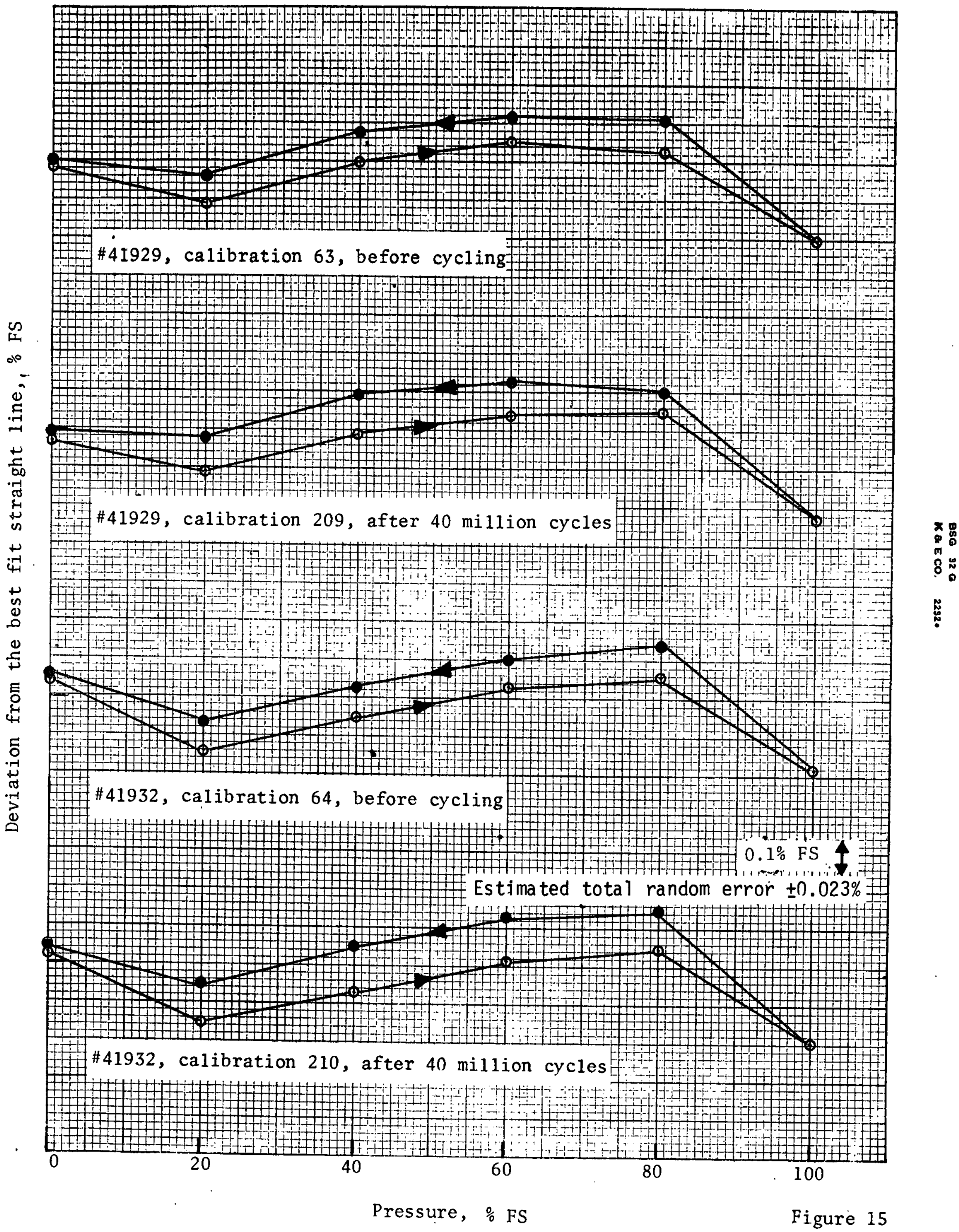


Figure 15

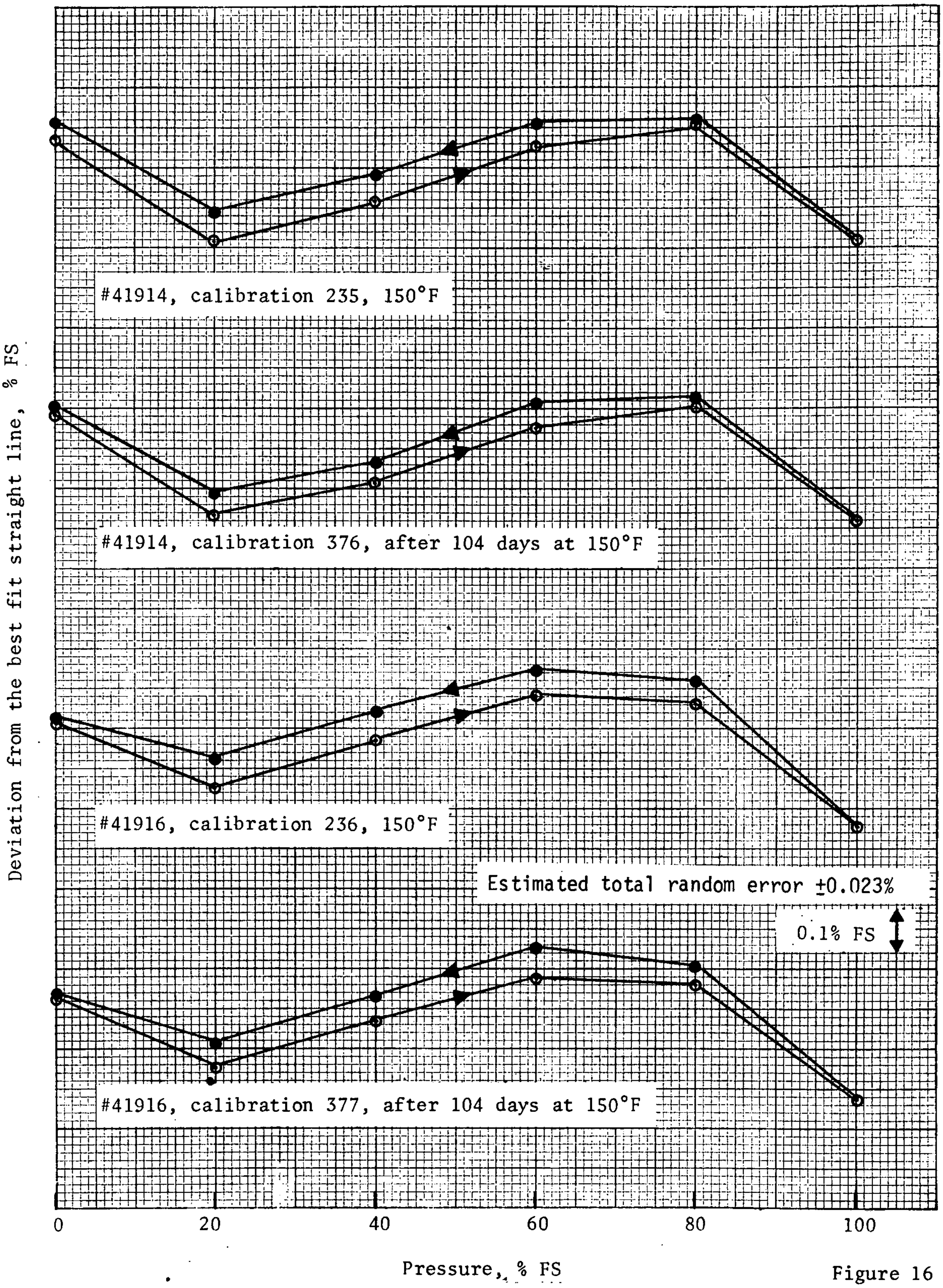

#41914, calibration 235, 150°F
#41914, calibration 376, after 104 days at 150°F
#41916, calibration 236, 150°F
Estimated total random error ±0.023%
0.1% FS
#41916, calibration 377, after 104 days at 150°F
Deviation from the best fit straight line, % FS
0
20
40
60
80
100
Pressure, % FS

Figure 16

EFFECT OF CYCLING ON LINEARITY & HYSTERESIS, 15 PSIG TRANSDUCERS, 150°F

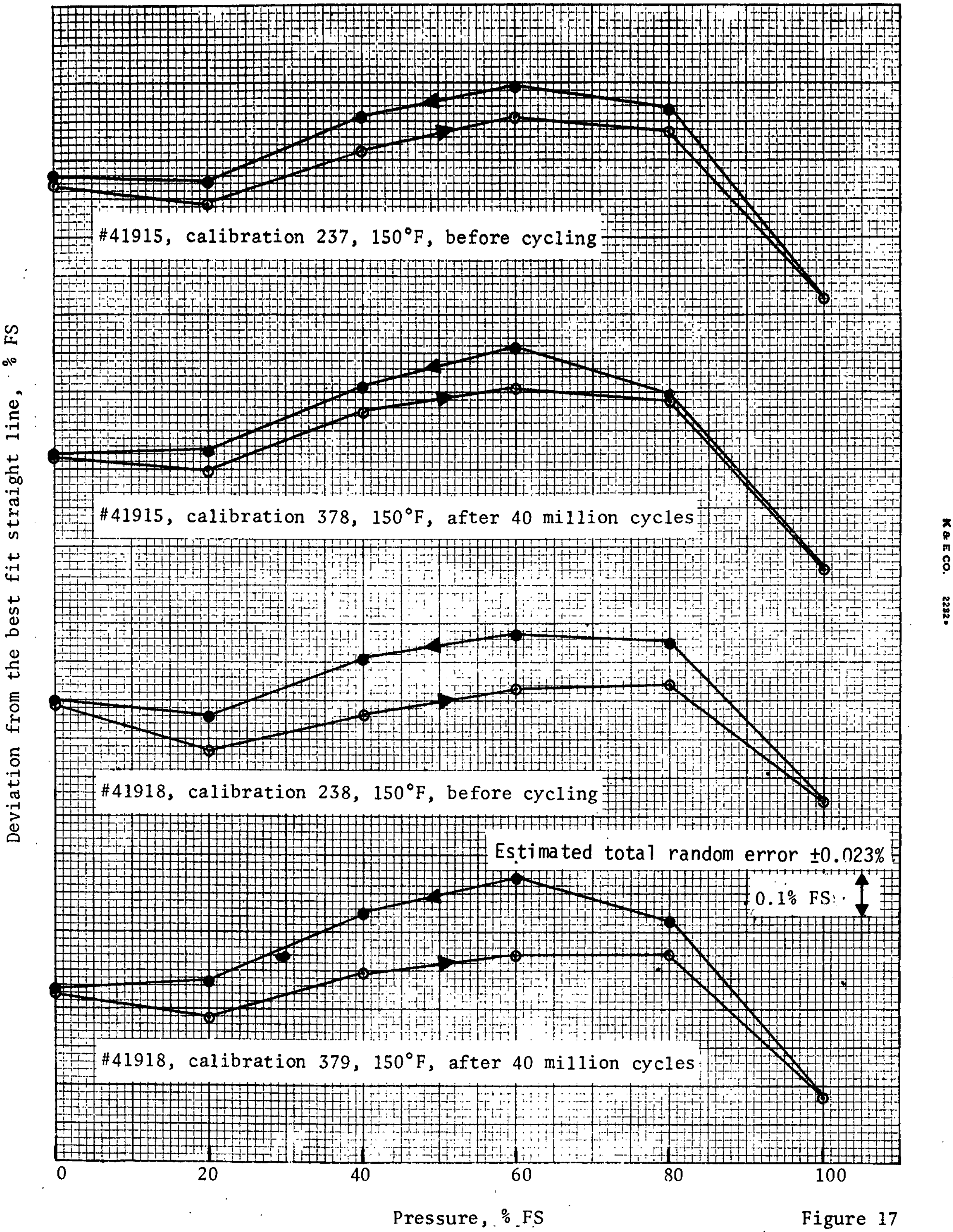


Figure 17

LINEARITY & HYSTERESIS, 100 PSIG CONTROL TRANSDUCERS

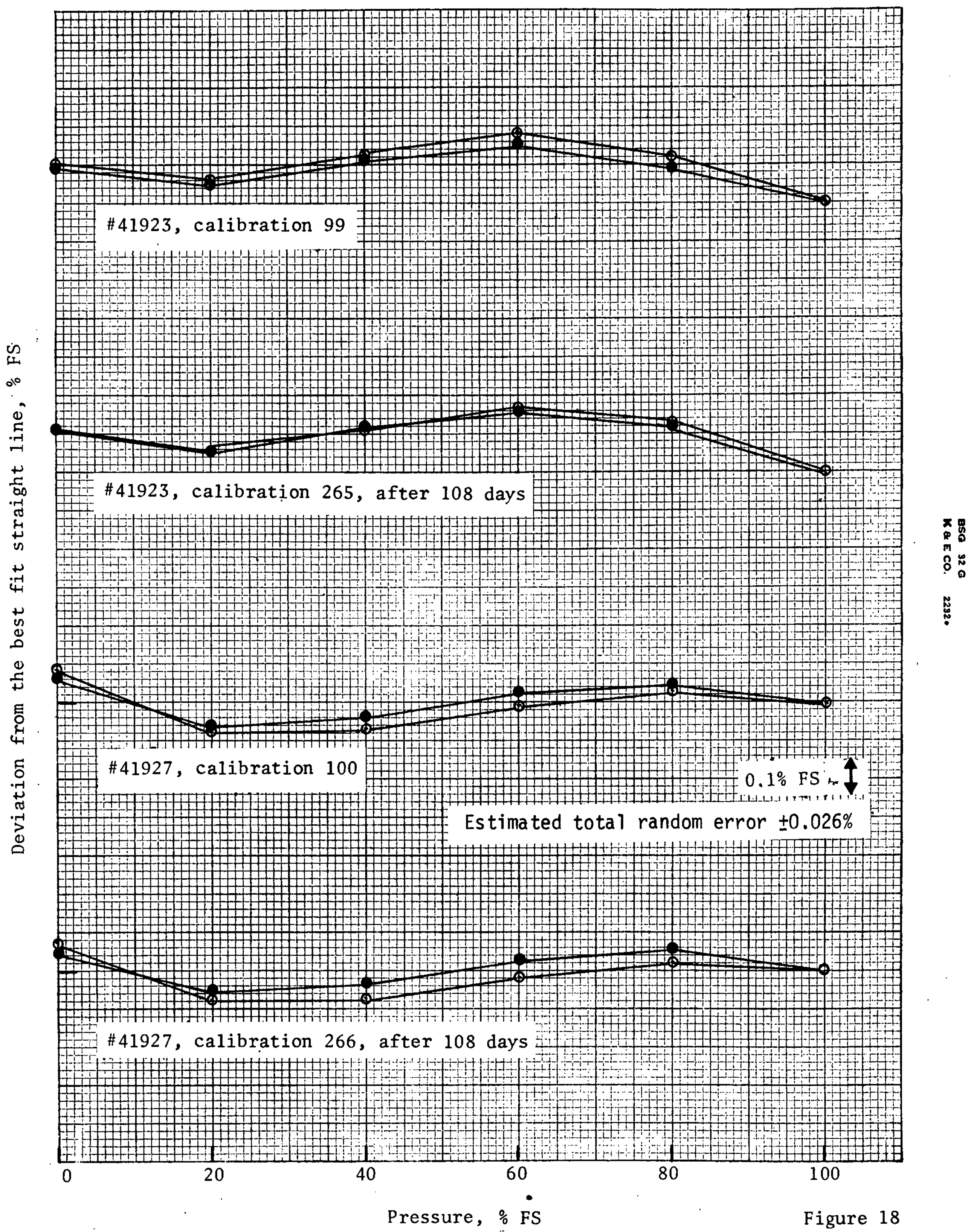


Figure 18

EFFECT OF CYCLING ON LINEARITY & HYSTERESIS, 100 PSIG TRANSDUCERS, NO AIR COOLING

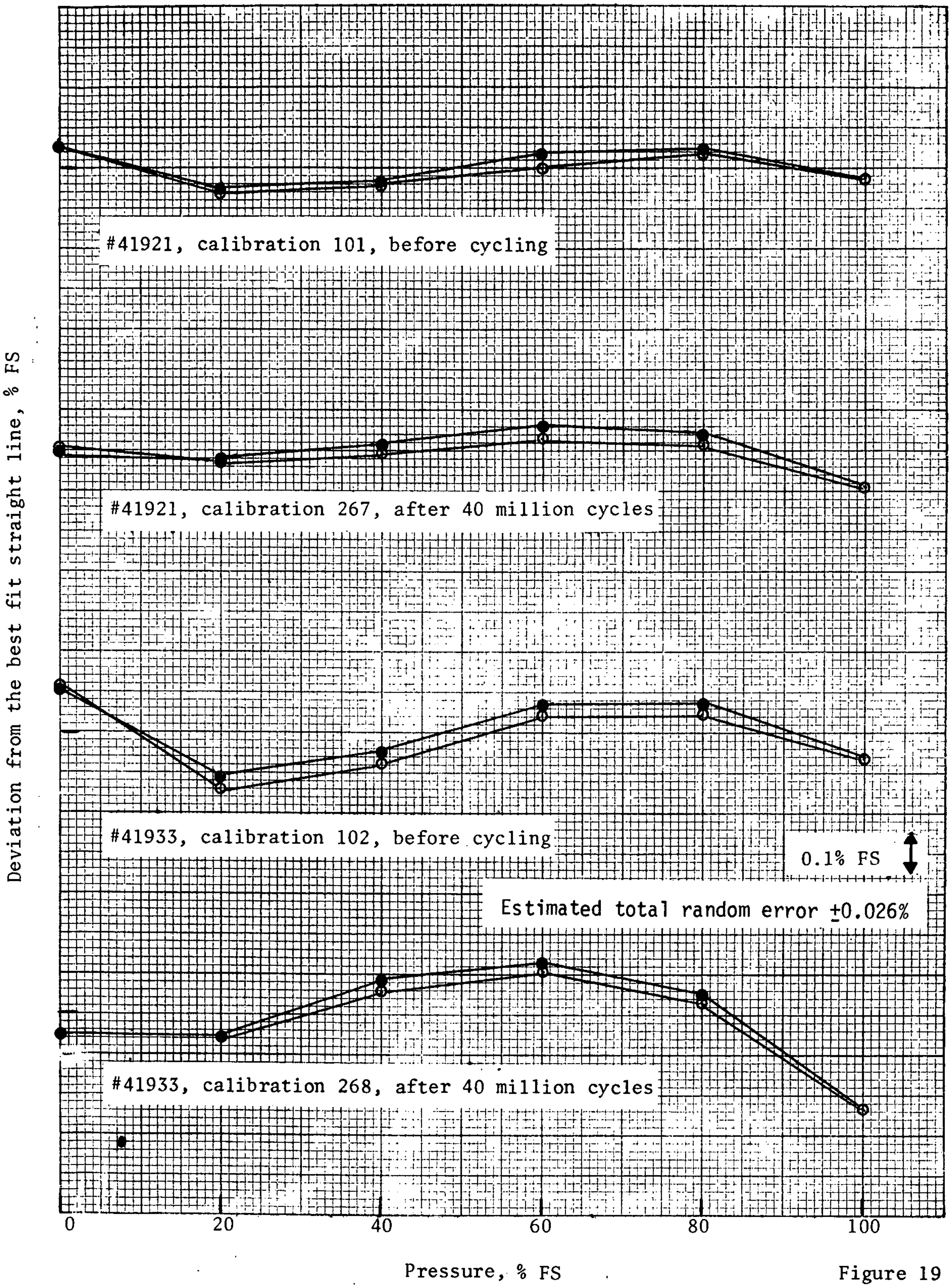


Figure 19

LINEARITY & HYSTERESIS, 100 PSIG CONTROL TRANSDUCERS

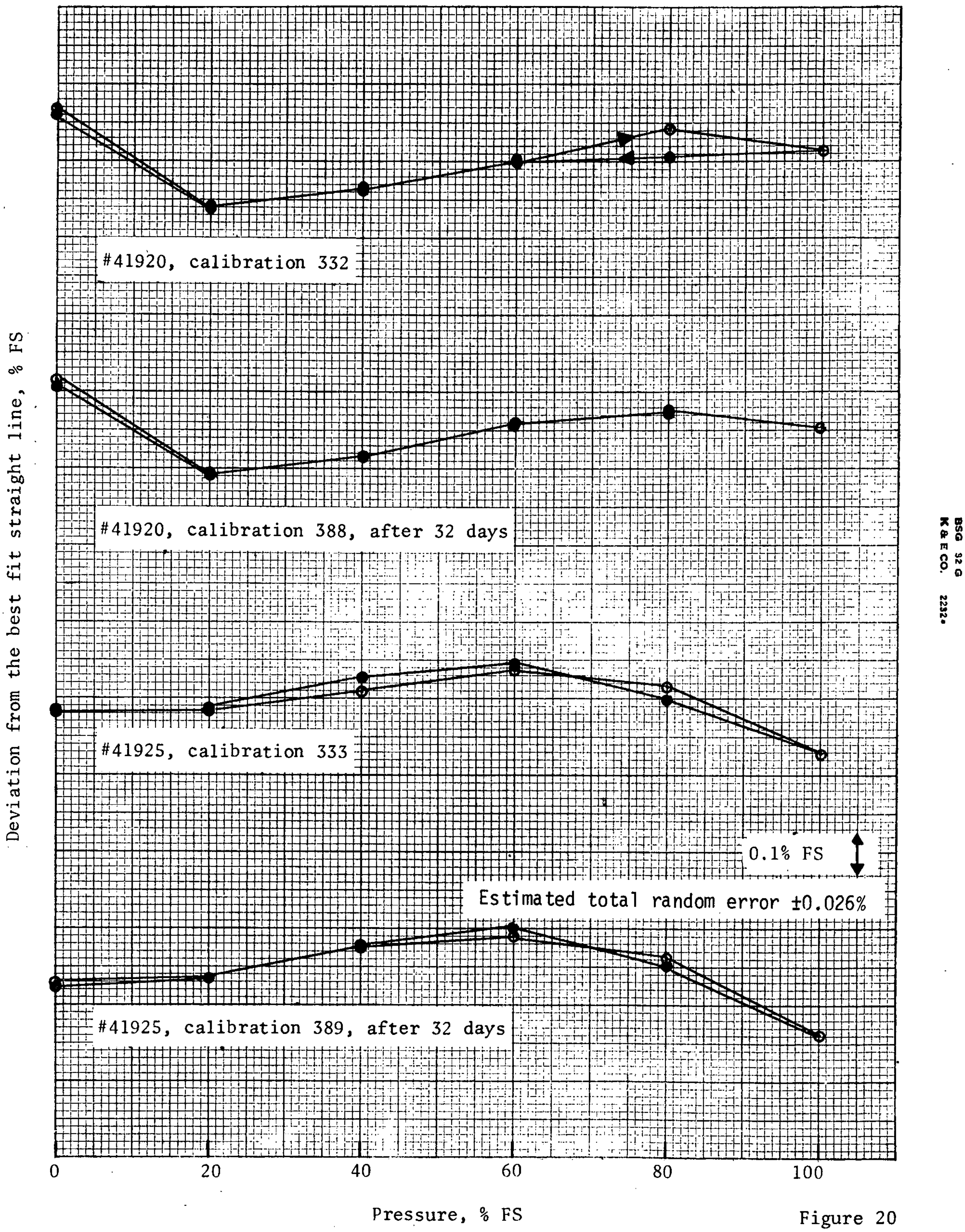


Figure 20

EFFECT OF CYCLING ON LINEARITY & HYSTERESIS, 100 PSIG TRANSDUCERS, AIR COOLED

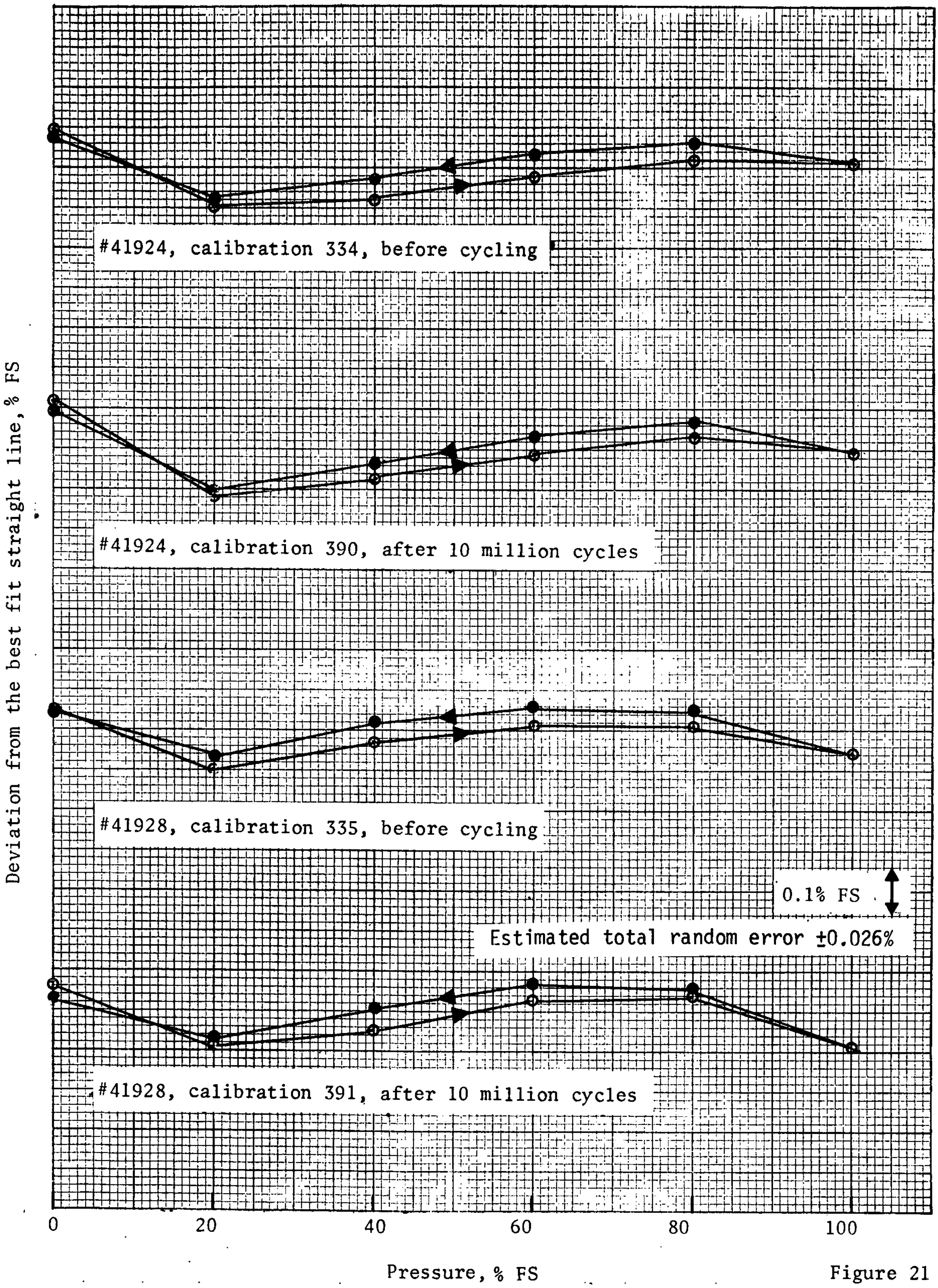


Figure 21

SENSITIVITY & ZERO PSIG GAGE OUTPUT VARIATIONS OVER THE ENTIRE TEST PERIOD, 15 PSIG TRANSDUCERS

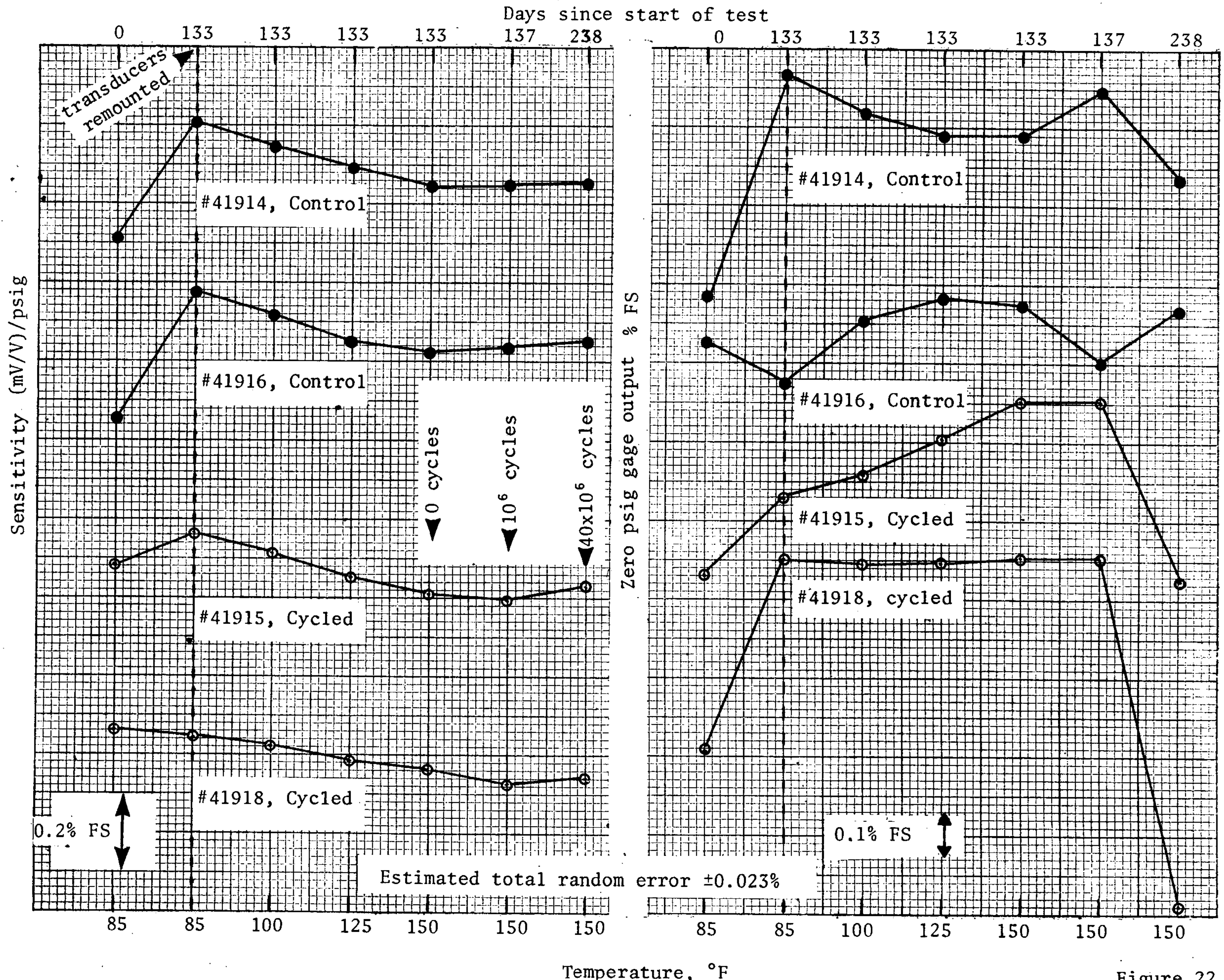


Figure 22

SENSITIVITY & ZERO PSIG GAGE OUTPUT VS TIME & OVER PRESSURE CYCLING, 15 PSIG TRANSDUCERS

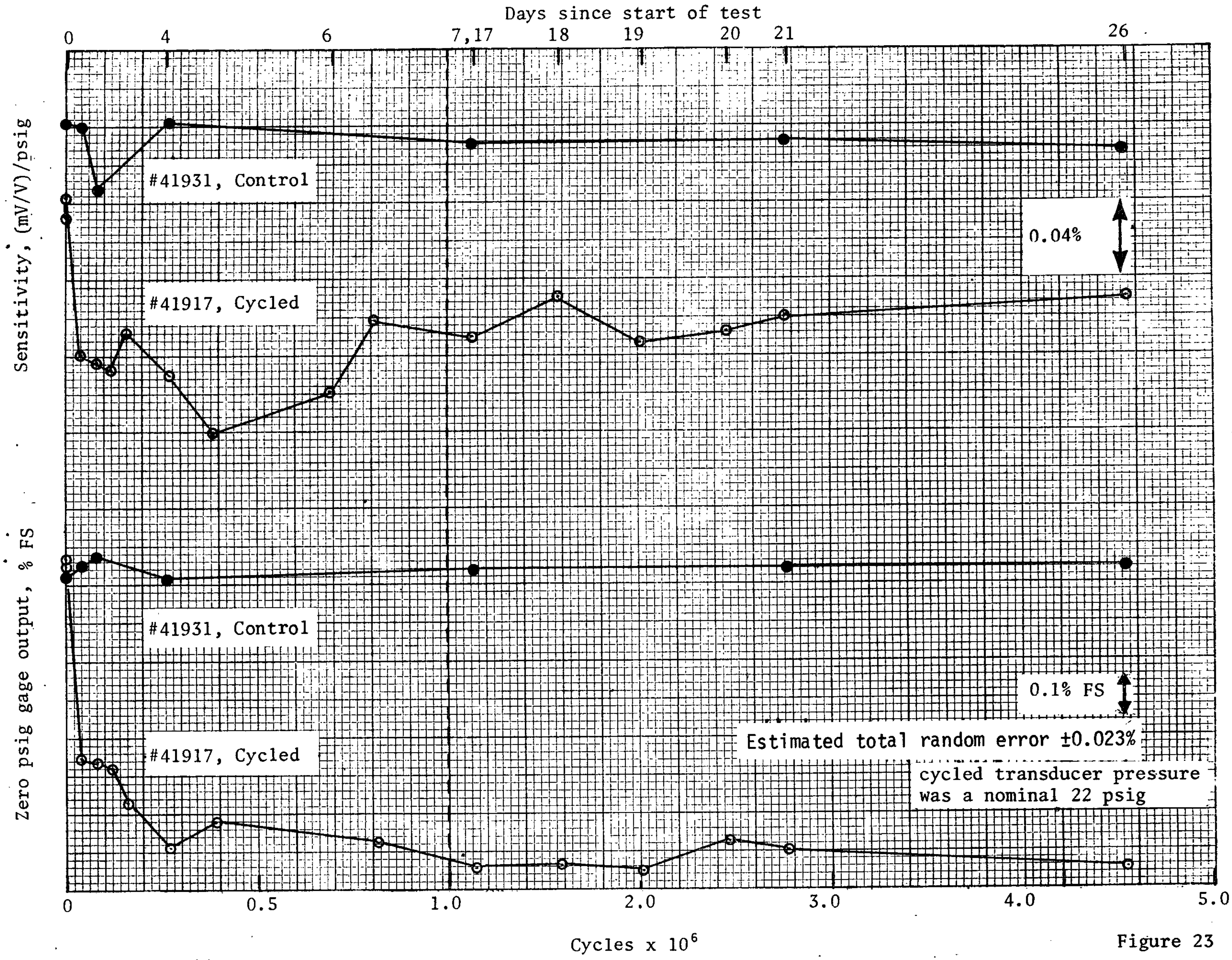


Figure 23