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DISPLACEMENT SENSOR FOR MEASUREMENT OF FUEL ROD ELONGATION IN THE LOFT REACTOR

MASTER

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DISPLACEMENT SENSOR FOR MEASUREMENT OF
FUEL ROD ELONGATION IN THE LOFT REACTOR

1.0 SUMMARY AND CONCLUSIONS

Qualification tests conducted for a period of 700 hours of each of three displacement measuring (LVDT) sensors confirmed applicability of the design for use in the Loss-of-Fluid-Test (LOFT) reactor. Operationally, the sensor satisfies all specified requirements for LOFT. Even for imposed temperature transients at rates up to 100°F/s, the indicated displacement remained within the allowed maximum error band of ± 10% of reading. The 0.6-inch O.D. by 5.5-inch long sensor exhibited a linearly related signal output variation for displacement variations of up to 1-inch range. Long term operation at temperatures of 100°F to 800°F caused no perceptible permanent change of operating characteristics. Furthermore, the severe and varied test rigor to which the displacement sensor was subjected during qualification tests justify the following conclusions:

- All sensors yielded linear variations of signal output with displacement changes for a range of one inch and exhibited a change of sensitivity of less than 5% over the temperature range of 100 to 800°F.

- For imposed temperature transients, by use of either laboratory ovens or an autoclave, the maximum measurement error of 2% of reading remains less than the allowed value (± 10% of reading) for inaccuracy of LOFT displacement sensors.

- Thermal shielding of the sensor as provided by the installation design within the LOFT reactor should further improve displacement measurement accuracy, especially during temperature transients.

- The sensor speed of response to rapid displacements of the core easily satisfied the specified 100 millisecond requirement for LOFT.

- Vibrations expected to occur during a LOFT transient should incur only minimal spurious signal response, as vibration tests at reactor system frequencies caused no discernable signals superimposed on the quiescent value.

- Signal output voltage of the sensor/signal conditioning remained constant during long term stability tests indicating negligible permanent signal drift.

- Because short term noise has an amplitude of approximately 0.5 millivolts, the displacement sensor should resolve rod length variations as small as 1 milliinch.

- Operating reliability of the sensor and conditioning electronics has been proven by subjecting each of the three test units to 700 hours of testing, sometimes with the sensor in severe environments.

2.0 SUBJECT OF REPORT

This report summarizes development and qualification testing of displacement measurement instrumentation intended for use in the LOFT reactor. Loss of coolant fluid will cause a rapid increase of fuel rod temperature resulting in their expansion. Three of the total number of fuel rods will be instrumented to permit evaluation of the magnitude and time sequence of rod elongation. Technical specifications and operating environment for the required displacement sensor influenced the decision to use a linear variable differential transformer (LVDT) for the application.

Based on development test results, five qualification sensors were purchased from a single vendor. The test plan required at least three qualification sensors to withstand the total test rigor. Multiple iterations of each test were conducted during a total specified test period of 700 hours, the final 200 hours in an autoclave. Briefly, the test series included the following described procedures.

1. Calibration of the sensor for incremental displacements of 0.1-inch for a range of one inch and at temperatures from 100 to 800°F at 100°F increments.

2. For temperature change at rates as rapid as possible, vary the temperature immediately adjacent to the sensor between 650°F and 325°F.

3. For constant displacements of 0.1, 0.5, and 0.9 inch each maintained for about two minutes, and at a sensor temperature of either 75 or 650°F, measure the variation of output signal.

4. For a constant displacement of 0.5 inches, measure the output voltage as pressurized water, initially at 2700 psig and 650°F, is exhausted at depressurization rates up to -105 psi/s.

5. Test mechanical integrity of sensor by maintaining 75°F water at a pressure of 3125 psig for 15 minutes.

6. Displace sensing core as rapidly as possible through the total one inch range. Determine the resultant 10 to 90% time response by measuring output voltage during the core movement.

7. Vibrate the sensor at accelerations of 0.5G for 40 seconds and of 2.0G for 100 milliseconds. Frequency of the vibrations shall occur at 40 to 50 Hz.

8. At an initial temperature of 800°F, cool the sensor as rapidly as possible to 200°F.

The dominant reason for performing these tests concerns the requirement to provide (for the LOFT reactor) instruments of known operational characteristics, reproducibility, and reliability. However, the described displacement sensor should be useable in other applications at temperatures up to 800°F and steady pressures up to 2500 psig.

3.0 SENSOR REQUIREMENTS

Functionally, the specified displacement sensor provides a measurement of elongation or contraction of the fuel rod length. This measurement is useful for predicting the mechanical dynamics of a nuclear fuel bundle during loss of coolant fluid. Inside the reactor, the sensor will be mounted inside a thermal shield cannister attached to an orifice plate. For much of its service life, the sensor will operate at the design pressure of 2000 psig and 650°F. During imposed transients, pressure and temperature of the water or steam surrounding the sensor will undergo rapid variations. Table 3.1 delineates important technical specifications for the sensor.

4.0 SENSOR DESCRIPTION

The LVDT operates on the principle of mutal inductance between primary and secondary windings of a transformer. The transducer consists of a primary and two secondary windings inductively coupled via a mechanically separate soft iron core (sensing core). At a primary excitation frequency of 10 kHz, the primary induces a voltage, dependent upon the position of the core, into each secondary coil. The identical and symmetrically displaced (relative to the primary coil) secondary coils are connected in series opposition, and null output voltage results for the sensing core axially centered between the secondary coils. As the core moves off-center, a net positive or negative voltage of magnitude proportional to the core offset results. Demodulation of the resulting ac voltage yields a dc output signal proportional to the position of the sensor core relative to the two secondary coils.

The coils wound on a common cylindrical form, are enclosed in a 0.6-inch O.D. by 5.5-inch long cylindrical hermetically sealed Inconel envelope. A 0.093-inch O.D. by 2.75-inch long soft iron core inside a 12.2-inch long by 0.190-inch O.D. cylinder attached to the fuel rod is displaced along the central axis of the sensor coils as the rod elongates during the reactor blowdown. A sixteen foot long, 1/16-inch O.D. dual conductor, Inconel-sheathed cable attaches to each of the three coils. An outline drawing of the qualification sensors (Figure 4.1) illustrates major dimensions. A pictorial (Figure 4.2) of the sensor, three attached signal cables, and signal conditioning electronics shows the core being positioned within the coil assembly.

5.0 TEST PROCEDURE

Qualification tests require the imposition of both stable and rapidly changing environments. Calibrations, noise tests, and some temperature transient tests occur with the sensor installed within laboratory ovens typically as shown in Figure 5.1. Depressurization tests require use of an autoclave.

Of a total test duration of 700 hours, the sensor is immersed in pressurized water in an autoclave for nearly 200 hours.

During qualification testing, data is acquired and plotted using a HP-3052A system. For calibrations, precise core positions depend on use of a digital stepper motor driving a rotary to linear mechanical motion translator. Temperature measurements originate from Type K thermocouples attached to the sensor or other monitored assemblies.

6.0 TEST RESULTS AND INTERPRETATIONS

Data representative of general operational characteristics of the three tested qualification units are included in this report. Uniformity of

TABLE 3.1

DISPLACEMENT SENSOR PERFORMANCE REQUIREMENTS AND OPERATING ENVIRONMENT

Performance:

Range	Zero to 1.0 inch
Accuracy	$\pm$10% of reading or $\pm$0.020 inch, whichever is larger
Resolution	$\pm$0.004 inch or less
Response Time	100 millisecond or less (10% to 90% of final value)

Operating Environment:

Media	LOFT water chemistry
Radiation	2×10^{13} n/cm^2 sec
	2×10^{8} R/hr
Pressure	Atmosphere to 13.8 MPa (2000 psig)
	$\frac{dp}{dt}$ = 722 kPa/sec (105 psi/sec)
Temperature	70 to 650°F
	800°F for 100 seconds
	$\frac{dT}{dt}$ = 225°F/sec

response to the various test conditions of all three sensors becomes apparent by comparing plotted data from each of the sensors. Data are grouped by the particular test performed with operational characteristics of each sensor represented. Programs used to acquire data and the data are recorded and preserved on magnetic tape in the event that future retrieval is required.

6.1 Calibration

At each 100°F temperature increment from 100 to 800°F, displacement of the core between extremes of the range at 0.1-inch increments yields a variation of signal output as shown in Figures 6.1, 6.3, and 6.5. For each of the sensors a linear characteristic results, with sensitivity remaining nearly constant for any temperature in the test range as may be confirmed by referring to plots of the straight line fits which follow each calibration summary. For example, a least squares straight line fit (Figure 6.6) of calibration data of Figure 6.5 shows that data at the extremes of the range (-0.5-inch and 0.5-inch) deviate from the best fit by less than +.011-inch and -.008-inch. These deviations equate to maximum inaccuracies of +2.2% and -1.6% of the values given by the best fit straight line. Consequently, the displacement indicated by the LVDT should be within the (LOFT) specified maximum allowable error at any sensor temperature within the range of 100 to 800°F. Multiple iterations of the calibration obtained periodically throughout the initial 500 hours of testing confirmed operational stability of the sensors, as similarity of data obtained from each of the iterations indicates.

6.2 Temperature Transient

For this test, positioning of two tube ovens collinearly enabled the rapid displacement of the test article along a quartz tube between one oven at 300°F and the other at 650°F. Normally, the test sequence began and ended with the sensor at the lower temperature, and at the higher temperature for an intermediate time period sufficient for the sensor to attain thermal equilibrium. Type K thermocouples, one attached directly to the sensor body and another within 1/4 inch of the sensor envelope, measure temperature of the sensor and of its adjacent medium. The core remains in a static position -- mechanically fixed to the sensor body. For these conditions, Figure 6.7 to 6.10 portray the time sequence of sensor temperature and the effect upon signal output of temperature variations at rates up to 138°F/s. The maximum signal change equals about 1.2% of reading, equivalent to an indicated displacement variation of .006-inch.

6.3 Short Term Stability

Figures 6.11 and 6.12 illustrate the variation of output signal for the core positioned statically (at 0.1-, 0.5-, and 0.9-inch) and the sensor temperature at ambient or at about 800°F. Because of minute movement of the core relative to the sensor body and of electrical noise inherent in the signal conditioning, the output signal varies by a maximum of 0.0011 volts. Each data point represents the difference of the output voltages at two consecutive data acquisition times differing by 13 seconds. All sensors exhibited short term stability necessary to obtain high resolution measurements of displacement during transient tests.

6.4 Transients Provided by Blowdown in Autoclave

This test most nearly approximates environmental conditions expected to exist during actual use of the displacement sensor in LOFT. However, because of the complexity of remotely adjusting the core position of the sensor when mounted inside the autoclave, a constant core position (with respect to the body) is maintained for this test. Maximum rate depressurization of the 6.4 liter autoclave, initially filled with water at 650°F and 2700 psig, causes a temperature decrease of 200 to 300°F within about 15 seconds.

Rate of expulsion of water/steam depends upon the effective area of the exhaust orifice. Most blowdowns were conducted with maximum attainable exhaust orifice area, although some were rate limited by restricting the exhaust area. For the majority of blowdowns, the exhaust valve was closed and the autoclave feed water pump activated immediately after depressurization. Output signal amplitude variations measured during the blowdown transient and for the ensuing 23 minutes - while water refilled the autoclave - relate to the effect upon the displacement transducer of temperature gradients near the sensor envelope.

For autoclave depressurization, the displacement sensor output signal varies due to a rapid variation of temperature. Figures 6.13 to 6.18 show typical responses for depressurization and also the rates of temperature change sustained by the sensor. At a nominal sensitivity of 16 volts/in. the maximum variation of voltage during transients corresponds to .016-inches of displacement, or an inaccuracy of 3.2% of reading. Even for the temperature rates of 75°F/s as shown in Figure 6.16 occurring during the initial phases of the blowdown, the sensor remains within the accuracy limit specified for the LOFT displacement sensor.

It is evident from the data plot of Figure 6.19 that the signal output changes even for relatively slow temperature variations. However, the total variation of about 6% occurs for a total temperature change of nearly 600°F.

After a period of 200 hours, during which multiple transient and steady state tests occurred, the sensor exhibited insignificant signal drift as determined by comparison data at the beginning and conclusion of the test period.

During time intervals between blowdown tests, the sensor signal output was measured to determine its stability for relatively long time durations. For the interval, sensor temperature was maintained constant at about 650°F. Signal output of the sensor for time periods of nearly 50 hours exhibited minor variations with the test temperature similar to the characteristic shown in Figure 6.20. Small discontinuities of the temperature appear in plotted data because of a short time lapse (when the temperature changes) for acquisition of consecutive data files.

To assure mechanical integrity of the LVDT envelope, a static pressure of 3125 psig is applied for a period of 15 minutes. During the time period the output signal remained nearly constant. Post test visual examination verified the absence of structural damage. Further, during subsequent vibration tests the sensor responded normally with negligible correlation of signal output with either applied vibration frequencies or accelerations.

6.5 Time Response

The time required for the sensor to respond to rapid displacements was determined by mechanically displacing the sensor core and simultaneously recording the output voltage. Even though the input displacement does not occur discontinuously, movement is rapid enough to verify an instrumentation response time of 21 milliseconds. The specified value of less than 100 milliseconds is easily satisifed. Figure 6.21 graphically depicts the variation of output signal as the core is displaced from one to the other extreme of the range.

6.6 Quench Test

Another method of subjecting the sensor to quite rapid temperature changes involves placement of the transducer in an 800°F environment for at least 100 seconds followed immediately by a quench in water at 200°F. For this test, the sensor was placed in a vertically oriented oven at 800°F. After at least 100 seconds at 800°F, the sensor was lowered into a 2 liter bath of 200°F water. Figures 6.22 and 6.23 confirm the survival and continued normal operation of the measurement system after this very severe test.

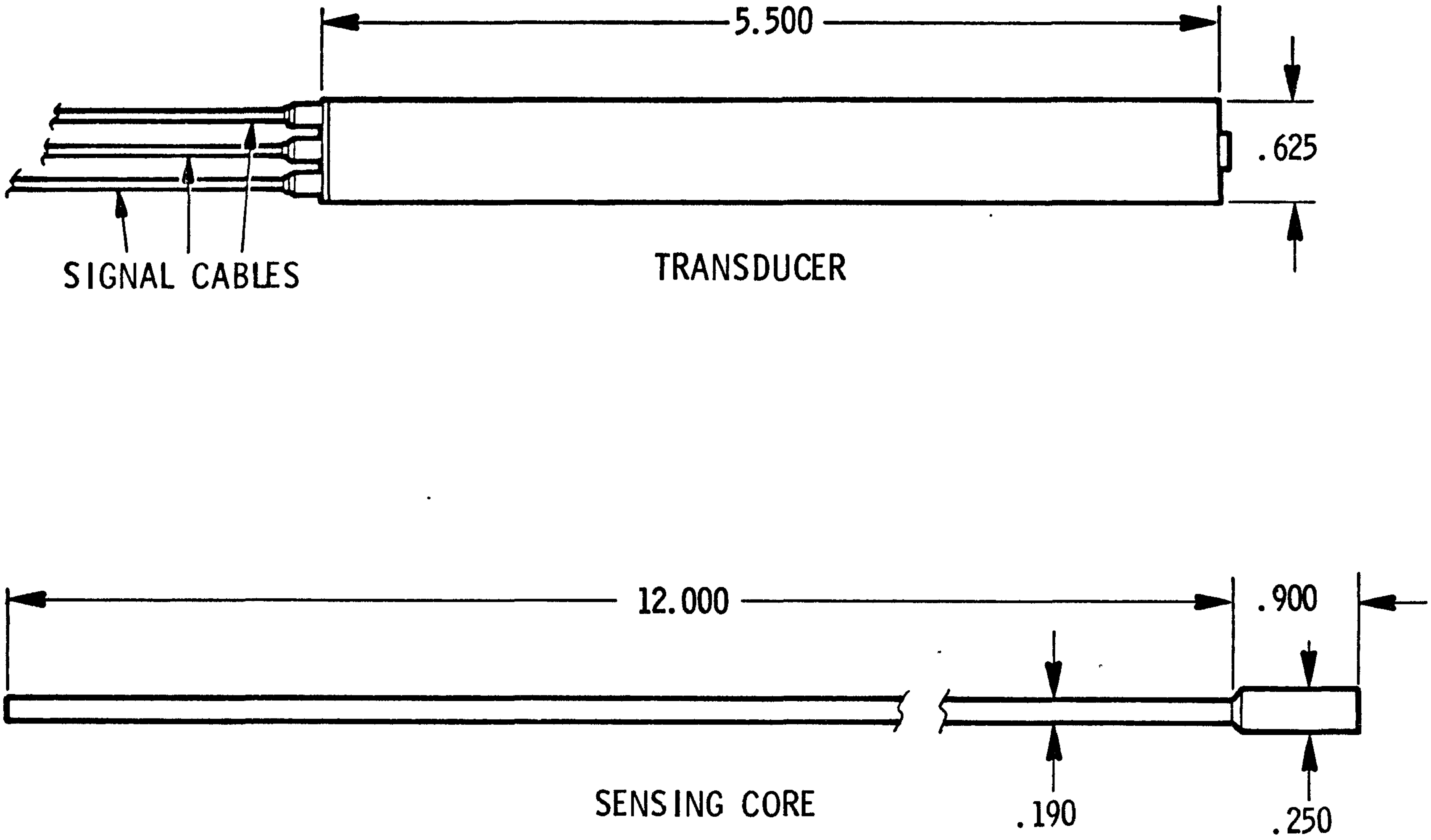

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FIGURE 4.1. Outline Depiction of Qualification Displacement Sensor for LOFT. Dimensions in inches.

FIGURE 4.2. Pictorial of Displacement Measuring Instrumentation.

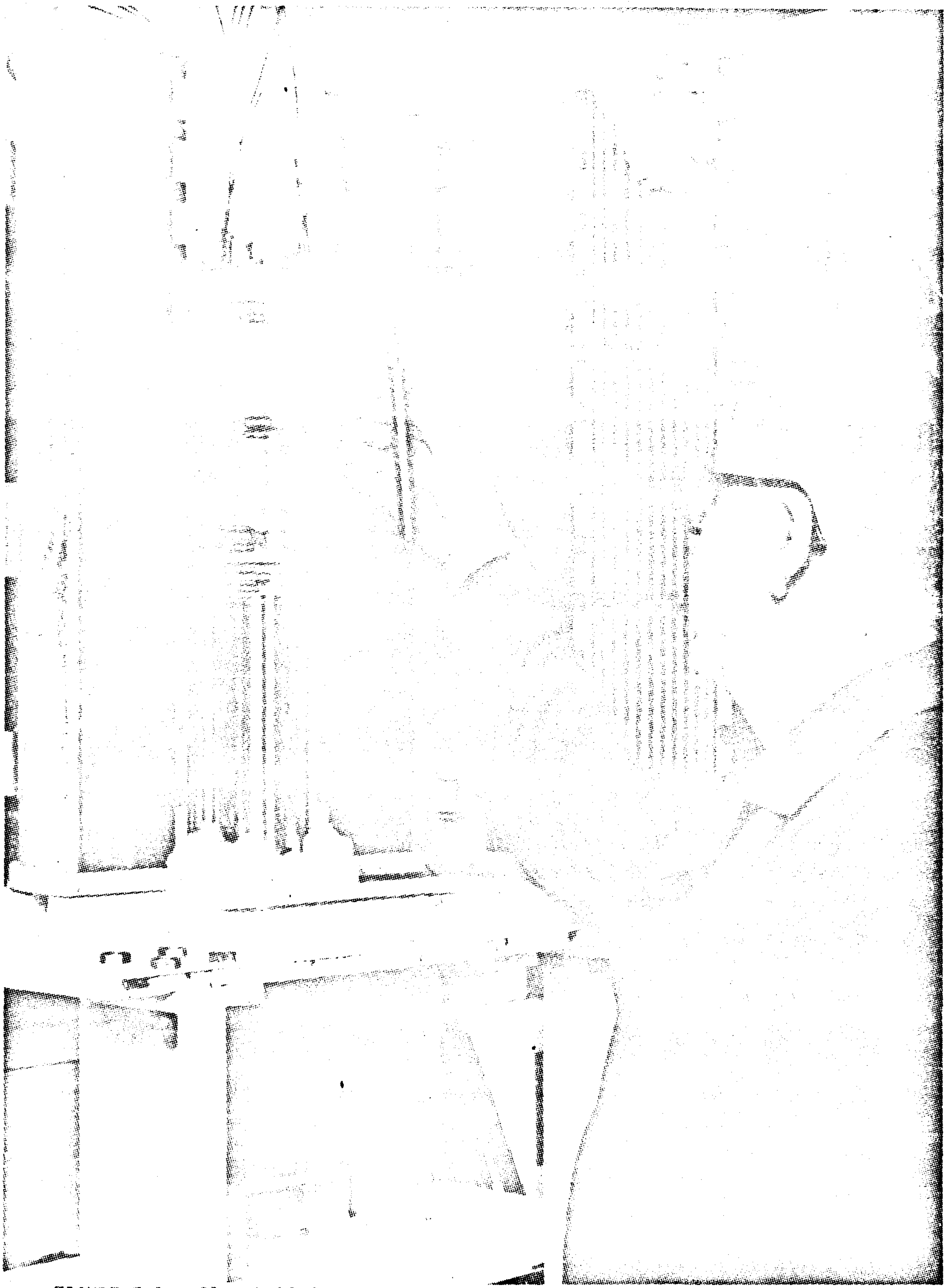

FIGURE 5.1. Clamshell Oven Used for Calibration of Qualification Displacement Sensor.

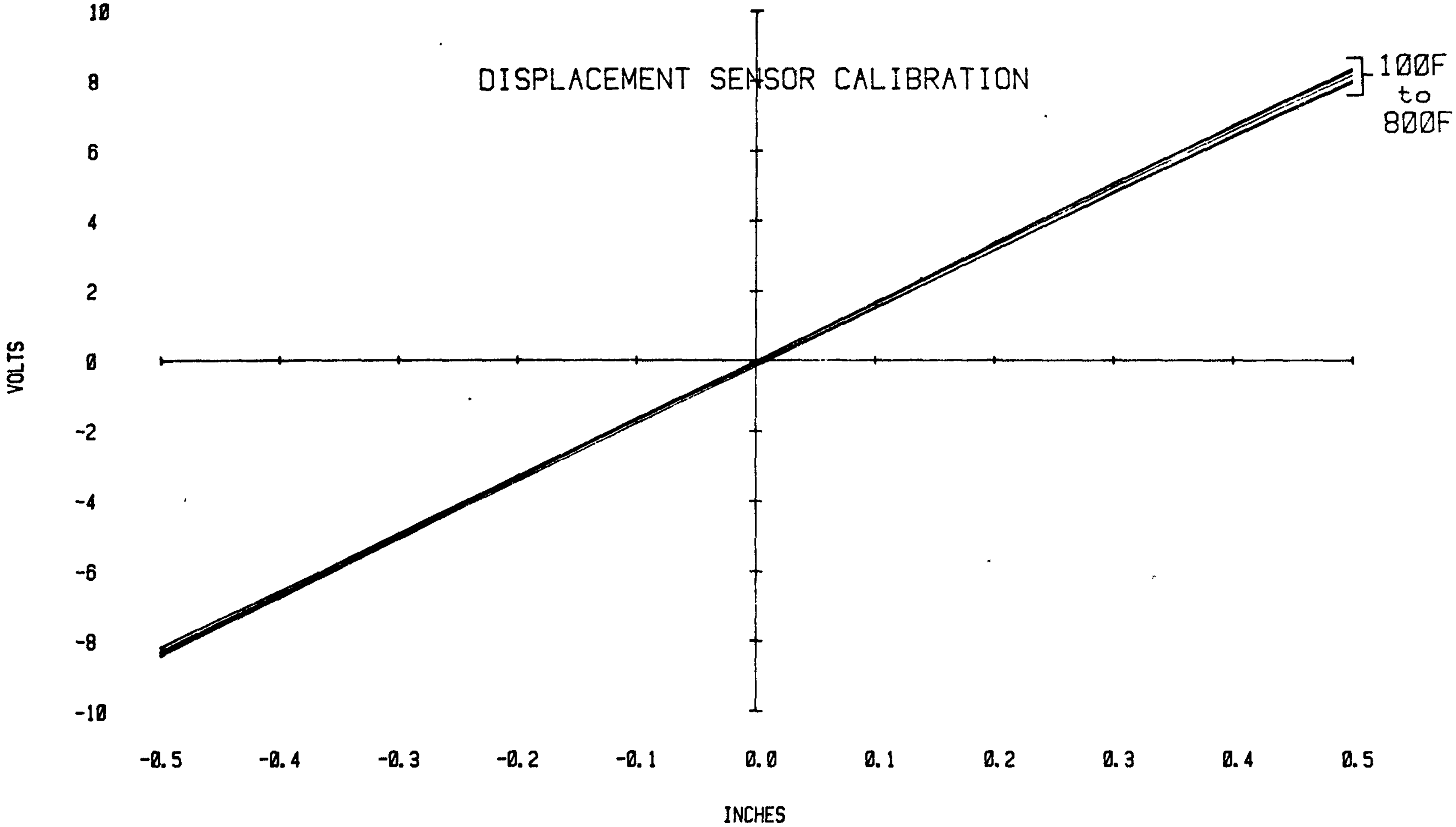

FIGURE 6.1. Calibration of Sensor S/N-01.

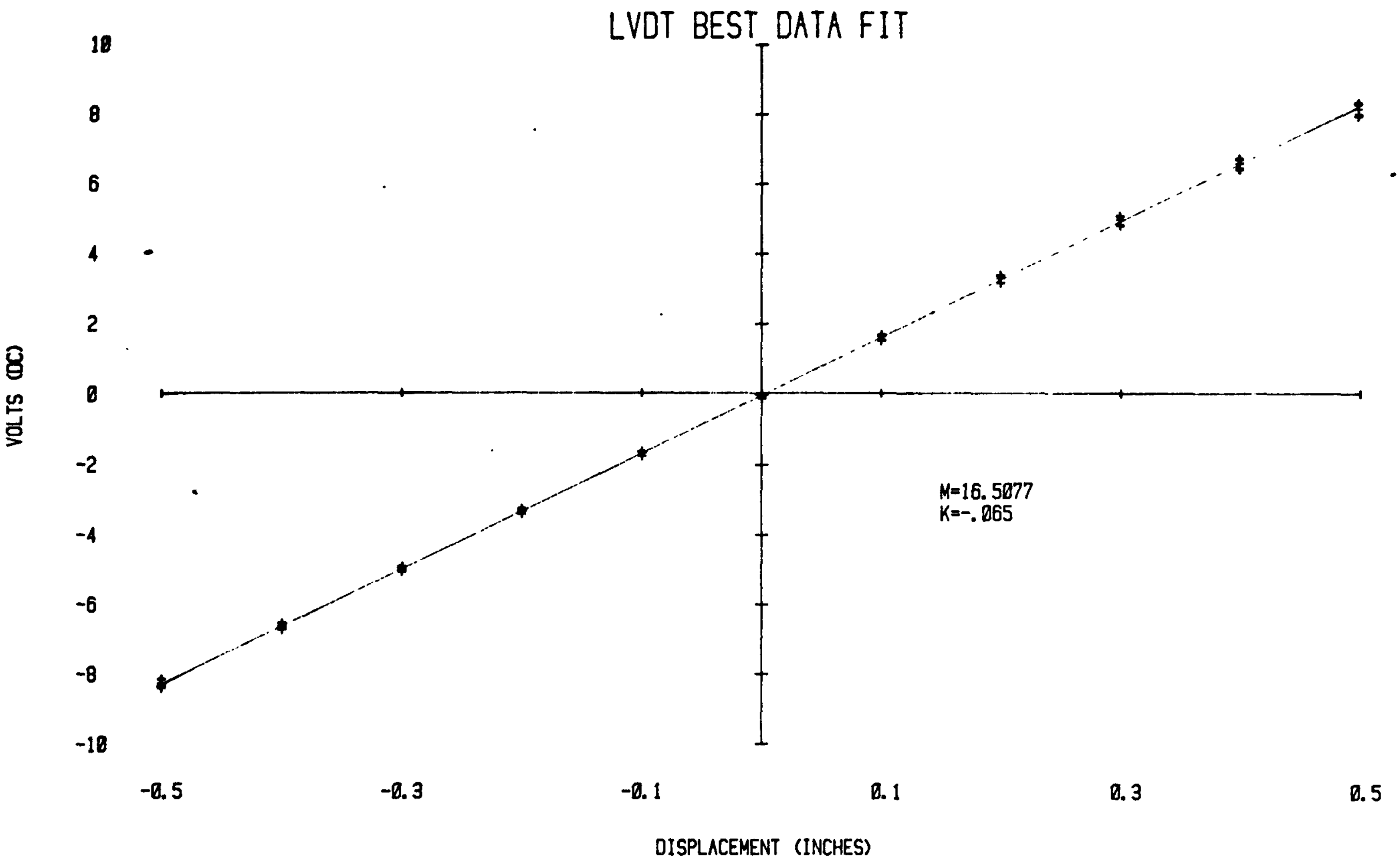

FIGURE 6.2. Least Squares Straight Line Fit for Data of Figure 6.1.

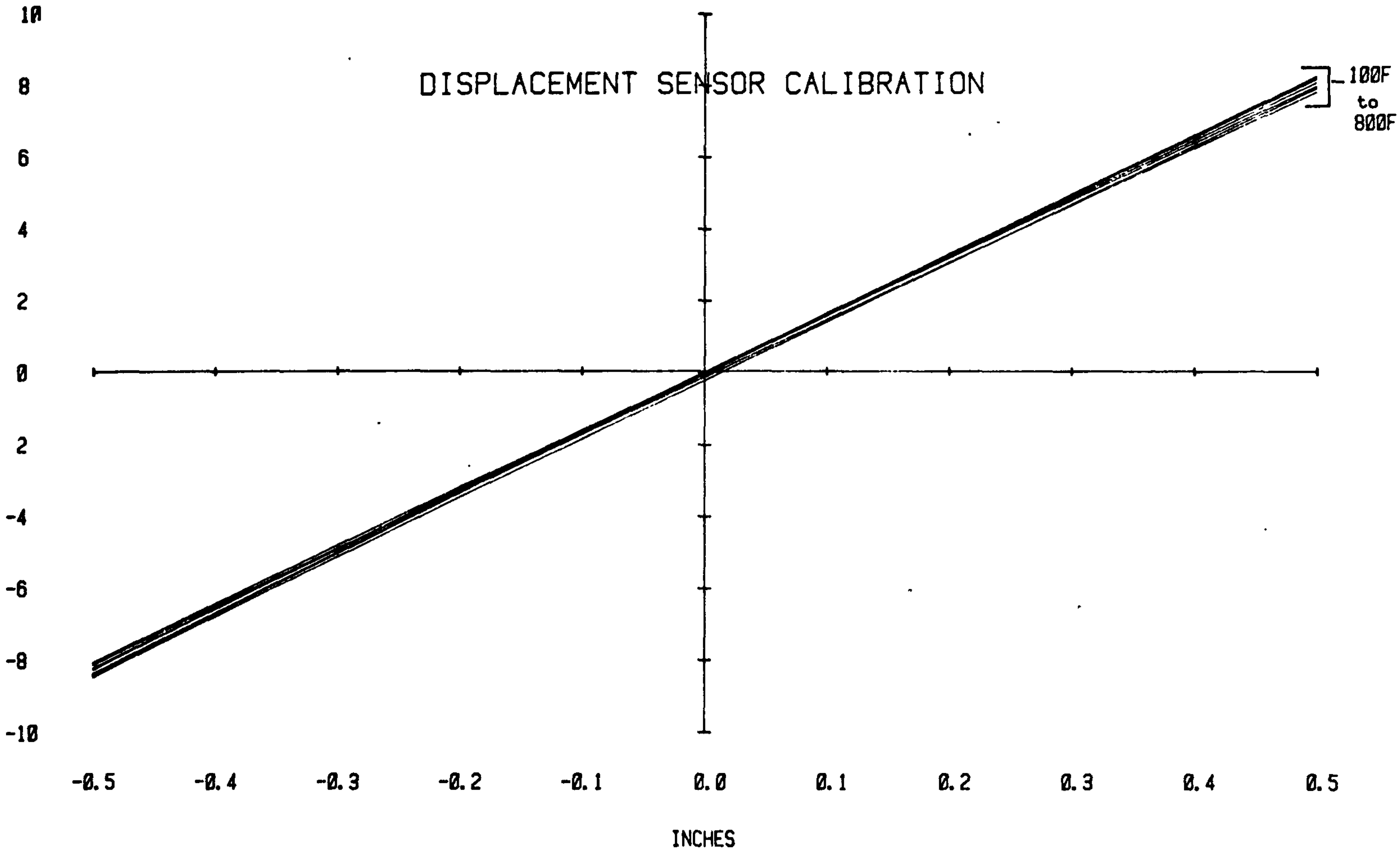

FIGURE 6.3. Calibration of Sensor S/N-02.

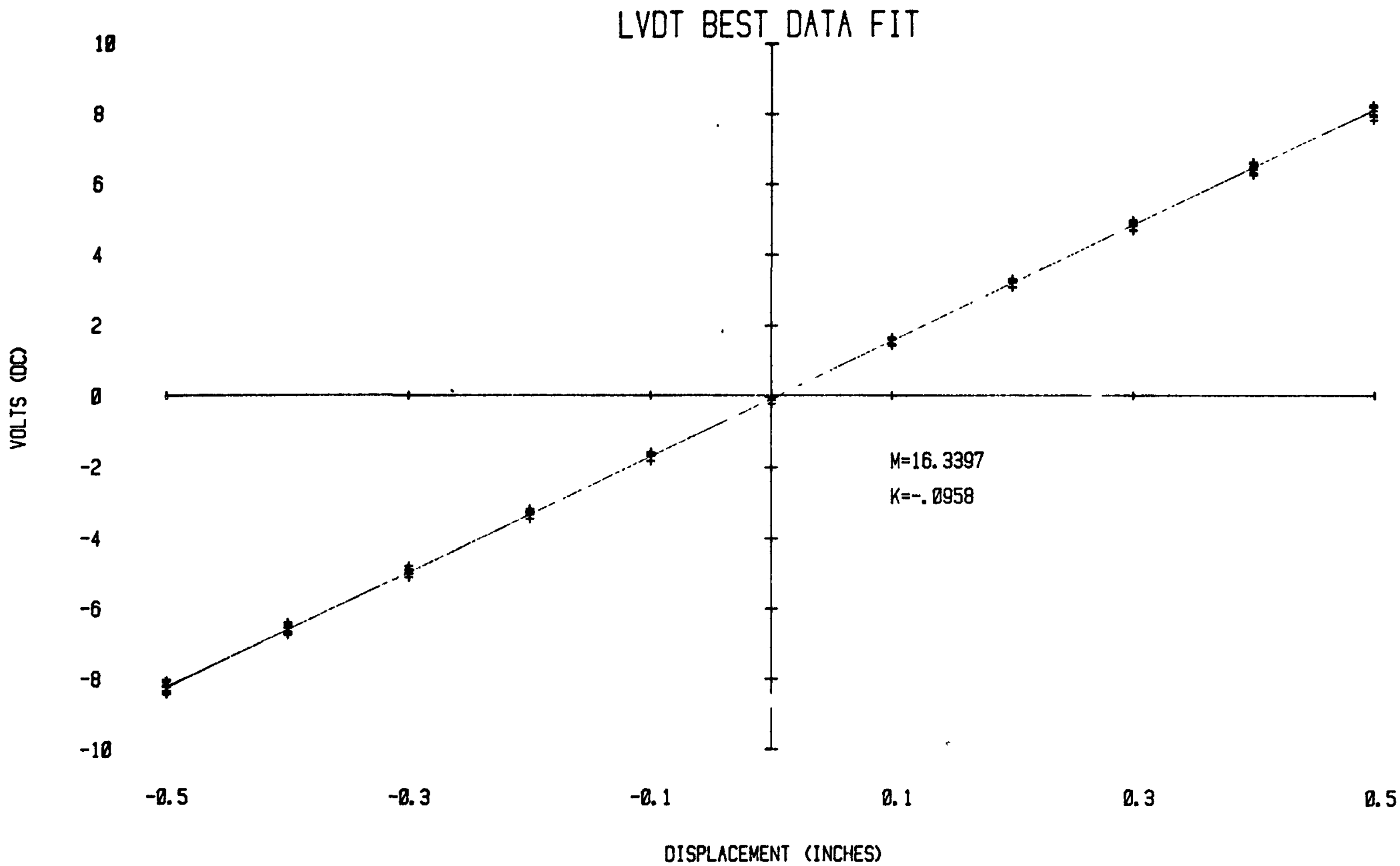

FIGURE 6.4. Least Squares Straight Line Fit for Data of Figure 6.3.

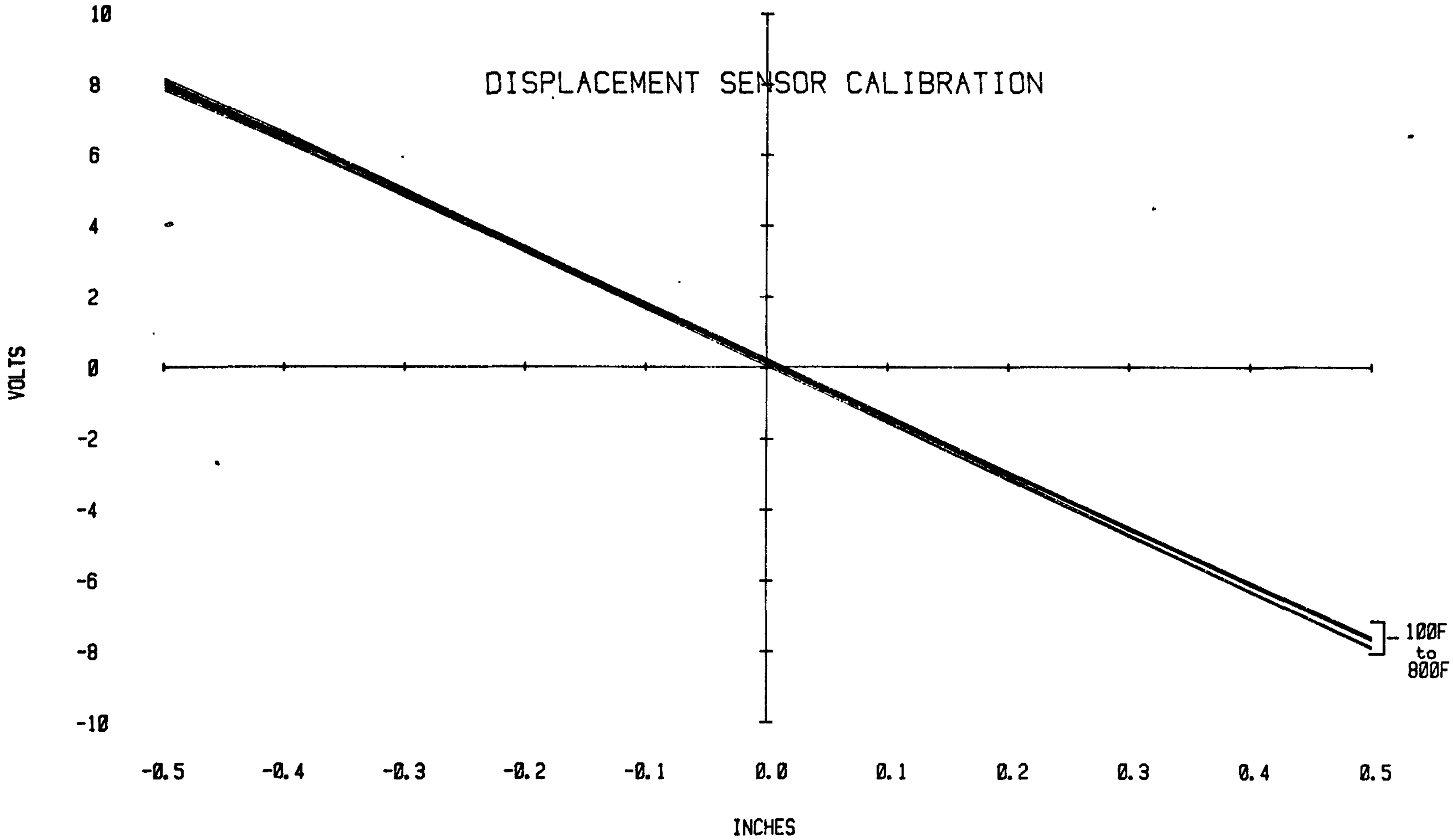

FIGURE 6.5. Calibration of Sensor S/N-03. Output Signal Polarity Reversed.

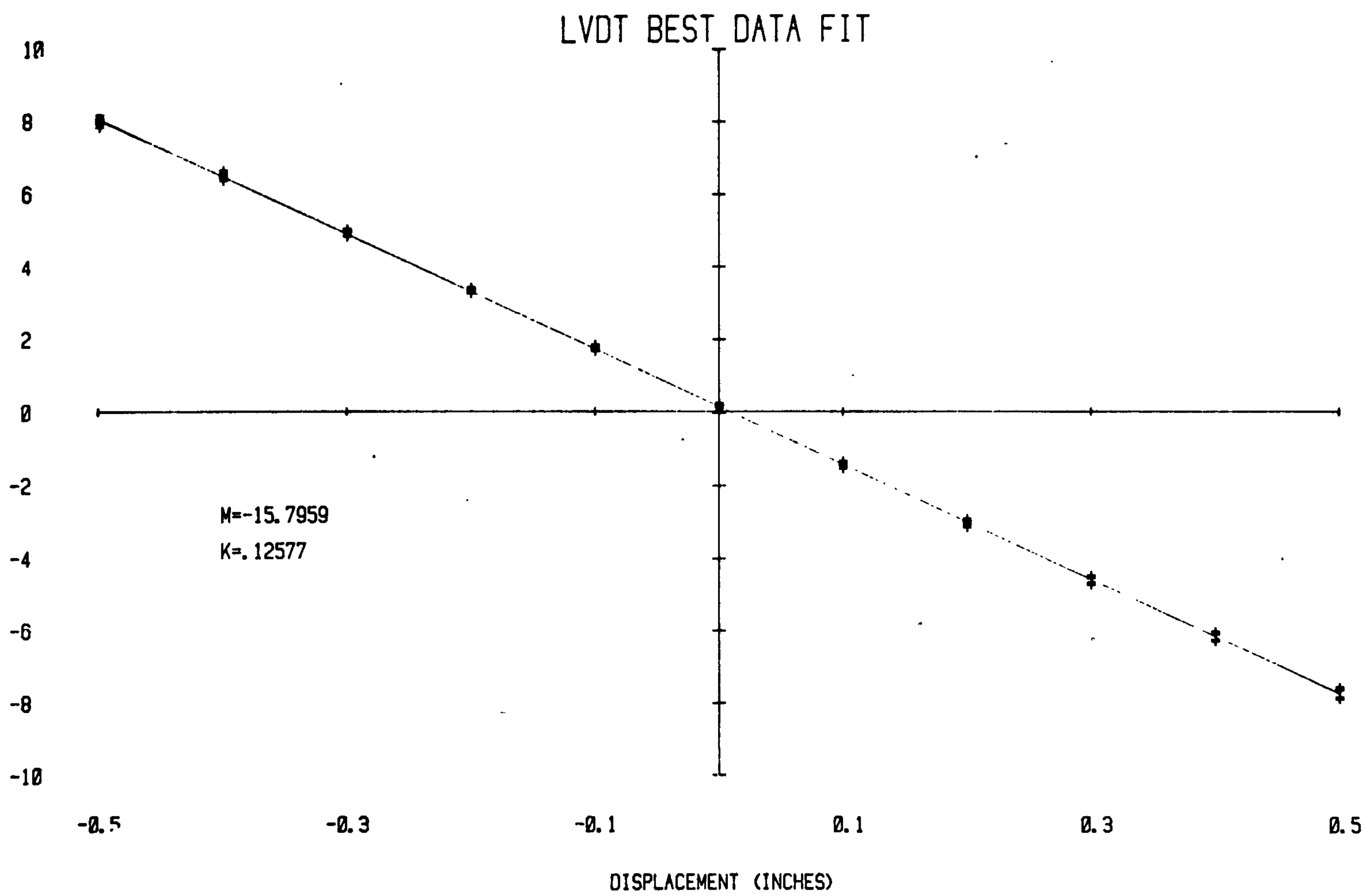

FIGURE 6.6. Least Square Straight Line Fit for Data of Figure 6.5.

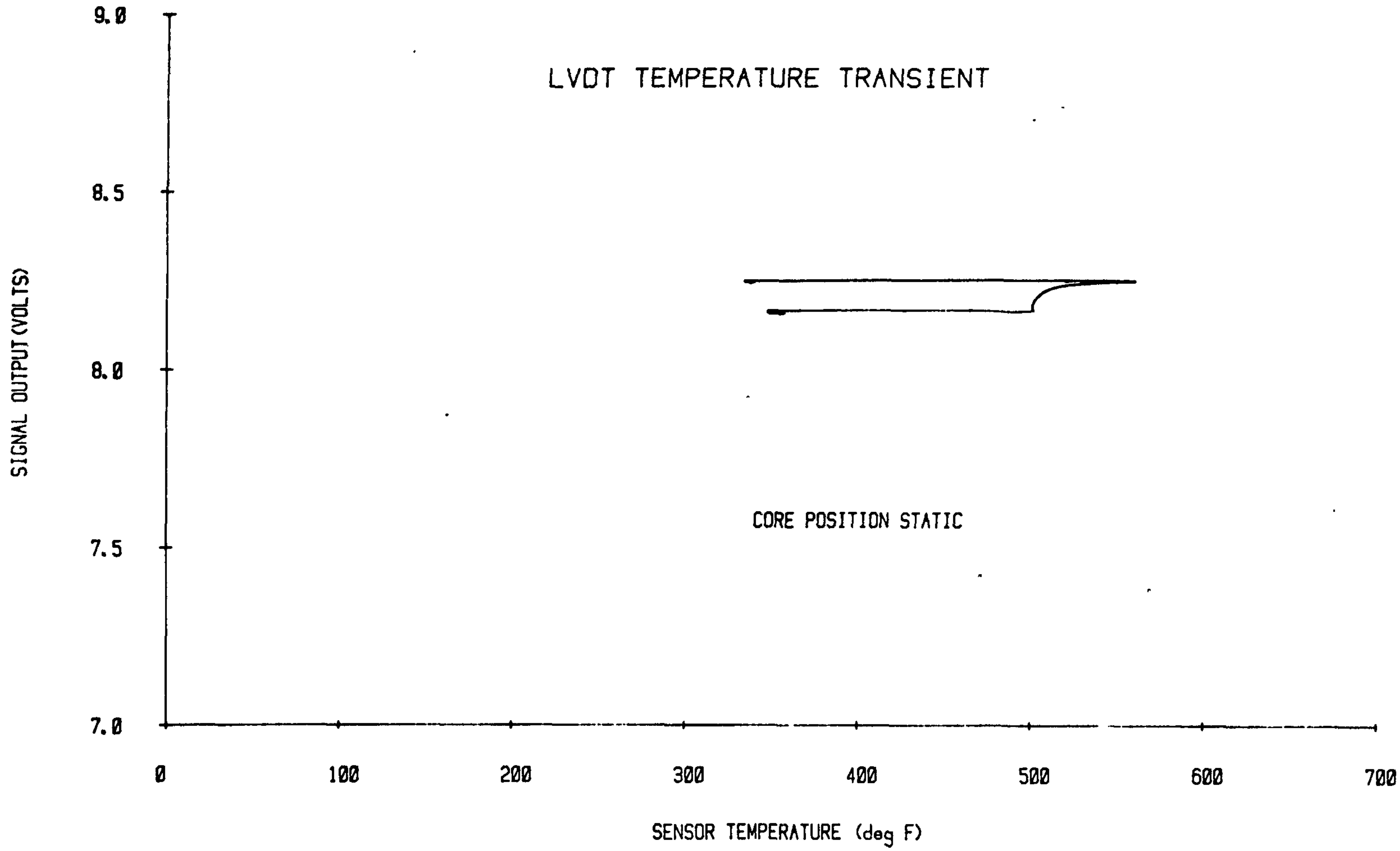

FIGURE 6.7. Signal Response of Sensor S/N-01 for Applied Fast Temperature Change.

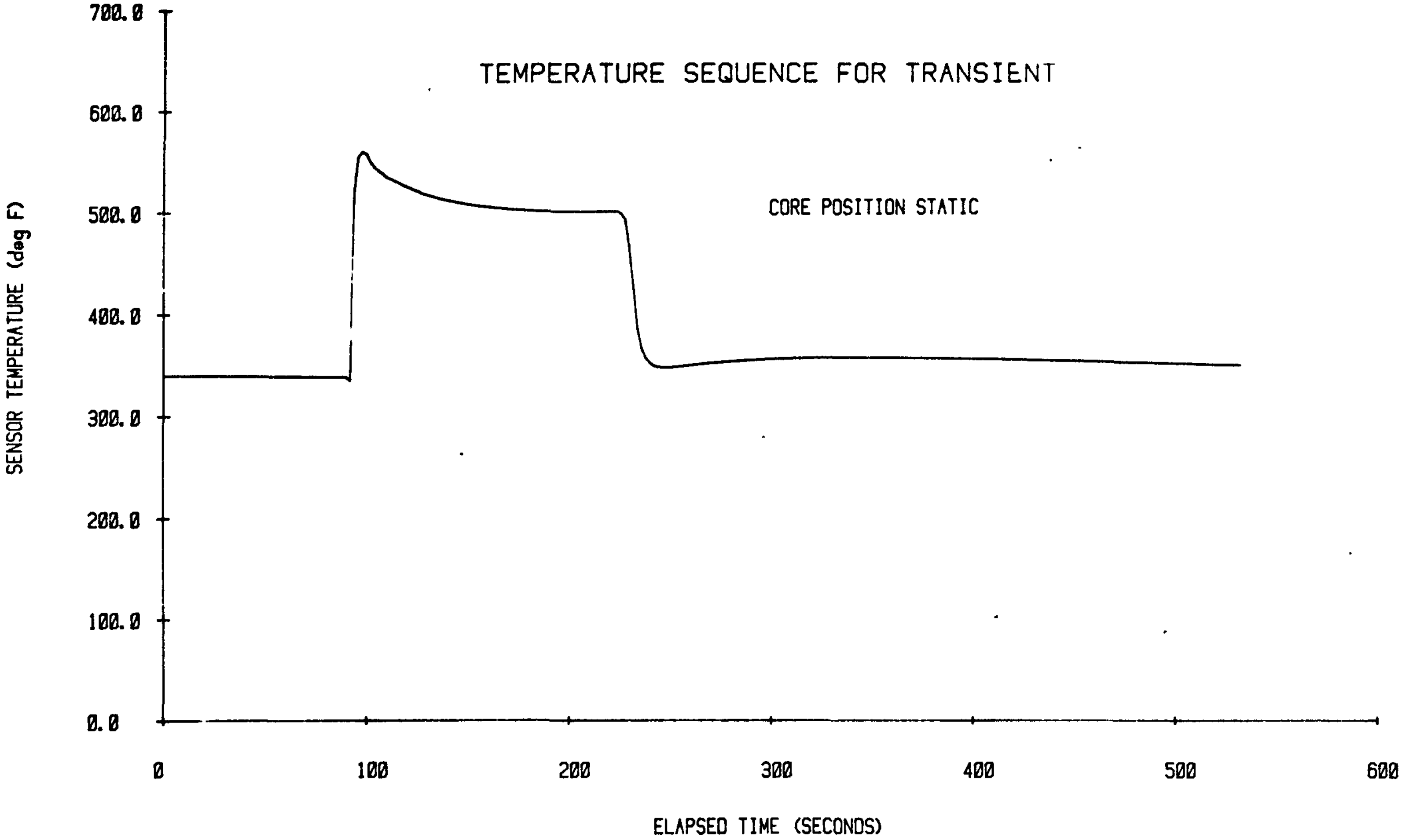

FIGURE 6.8. Time Sequence of Temperature for Transient Test of Figure 6.7.

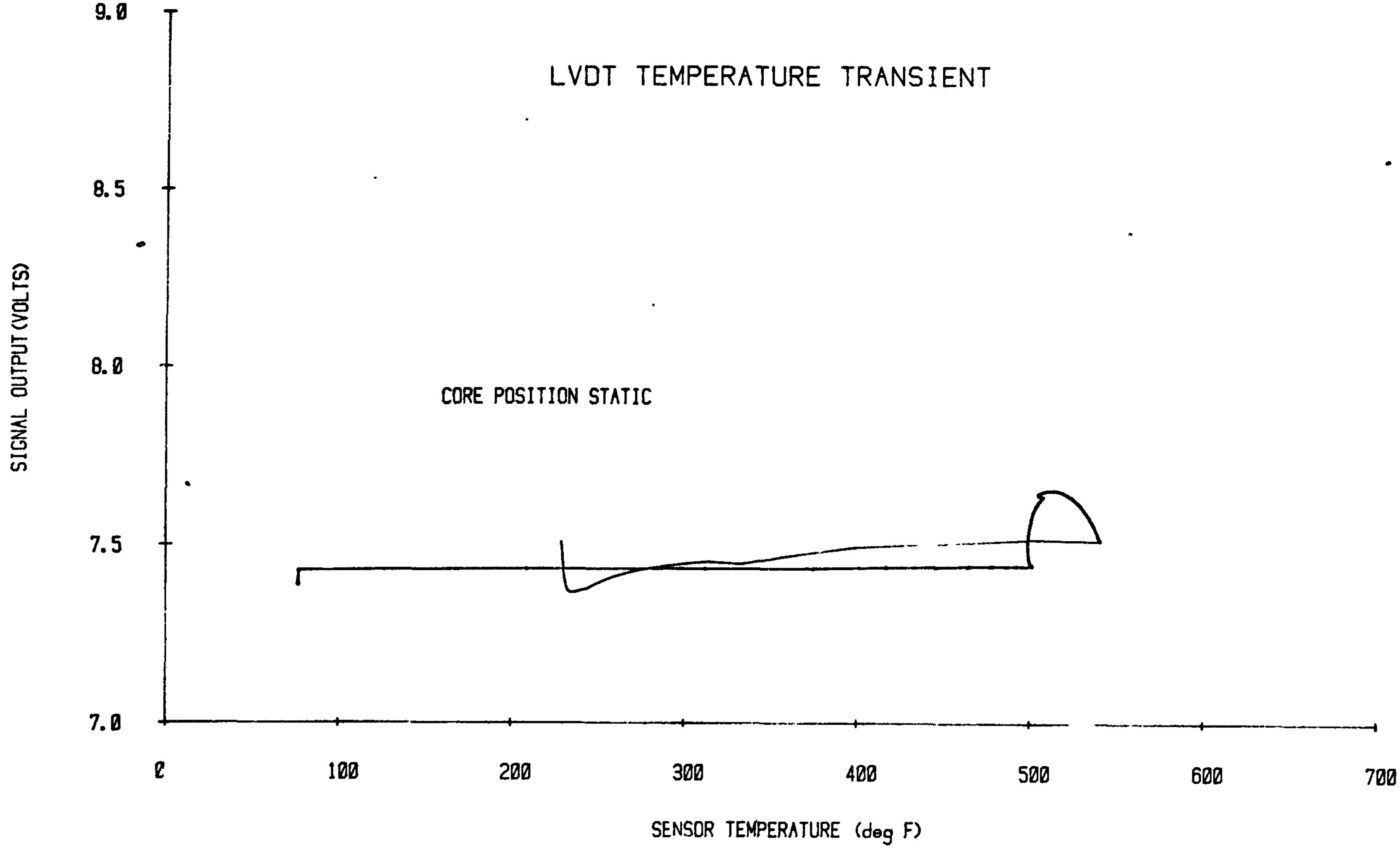

FIGURE 6.9. Signal Response of Sensor S/N-03 for Applied Fast Temperature Change.

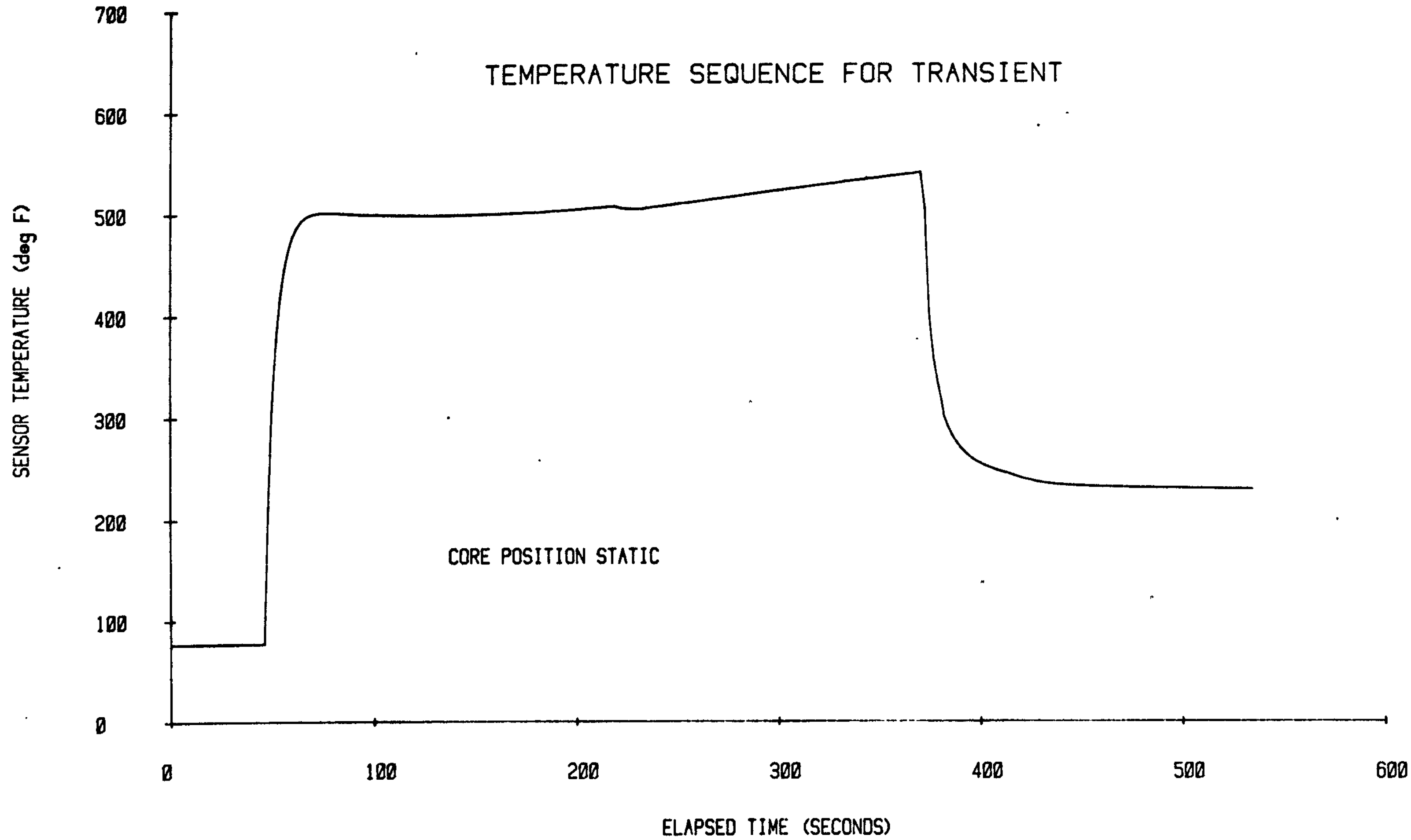

FIGURE 6.10. Time Sequence of Temperature for Transient Test of Figure 6.9.

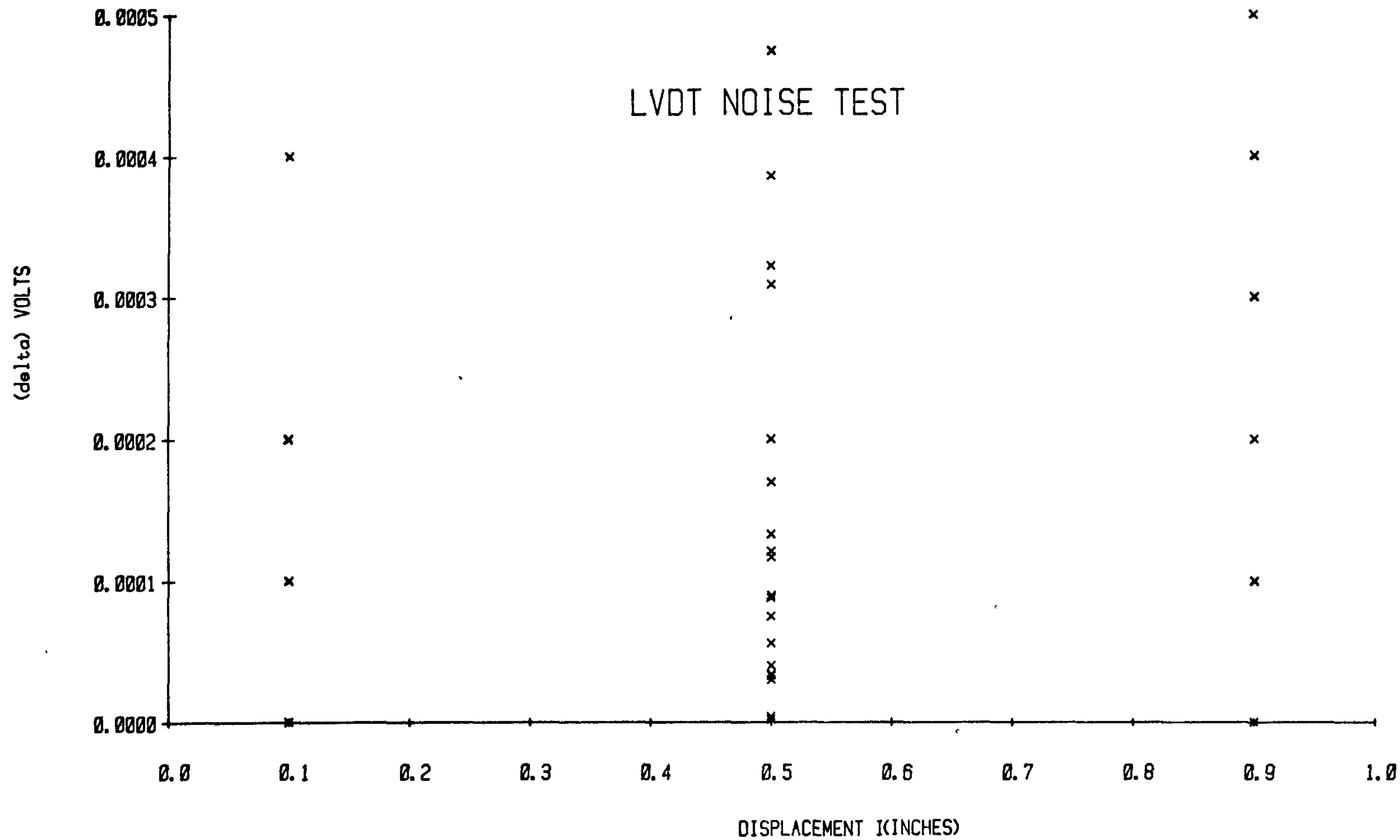

FIGURE 6.11. Short Term Stability of Signal Output for Sensor S/N-01.

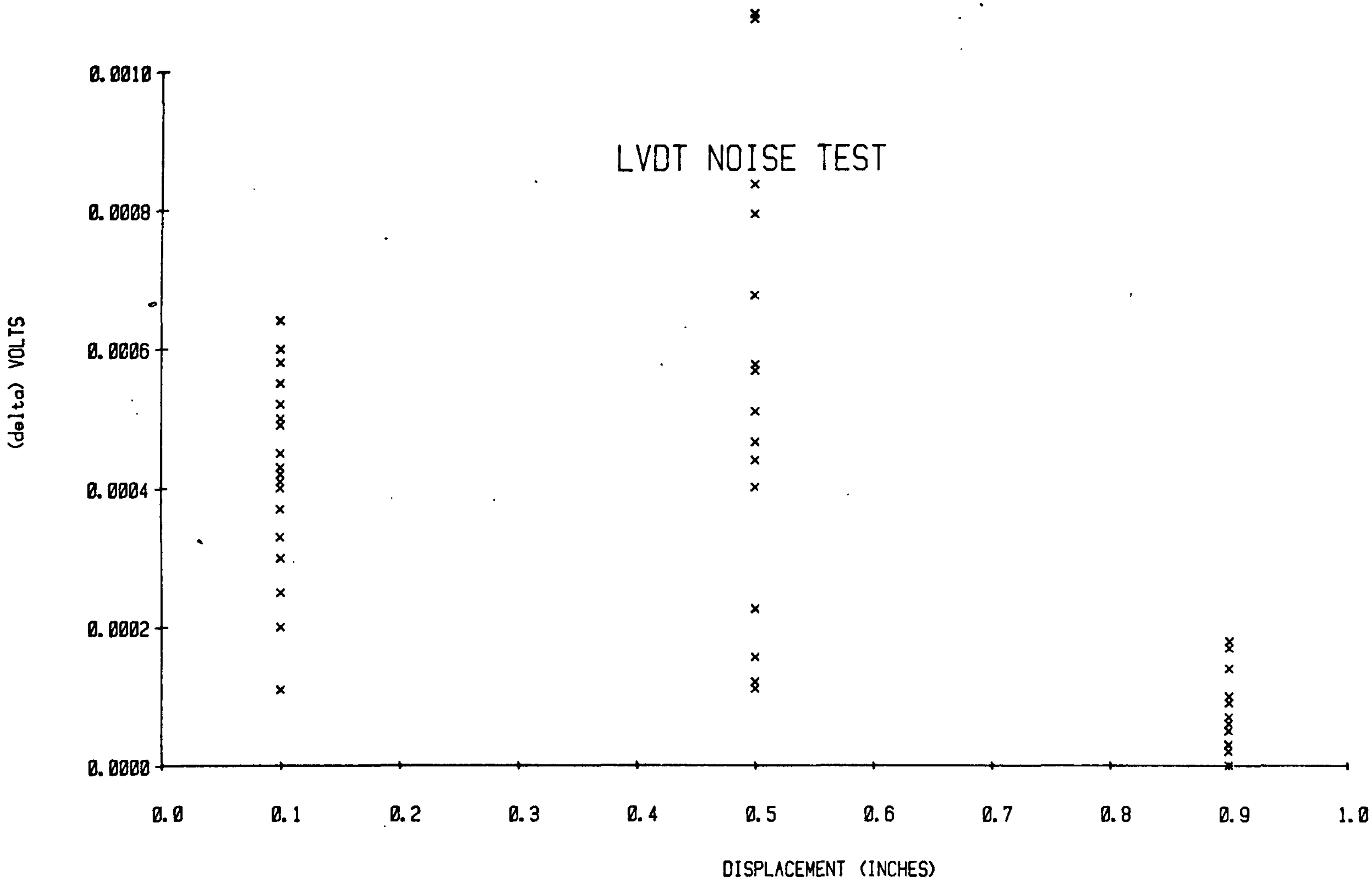

FIGURE 6.12. Short Term Stability of Signal Output for Sensor S/N-03.

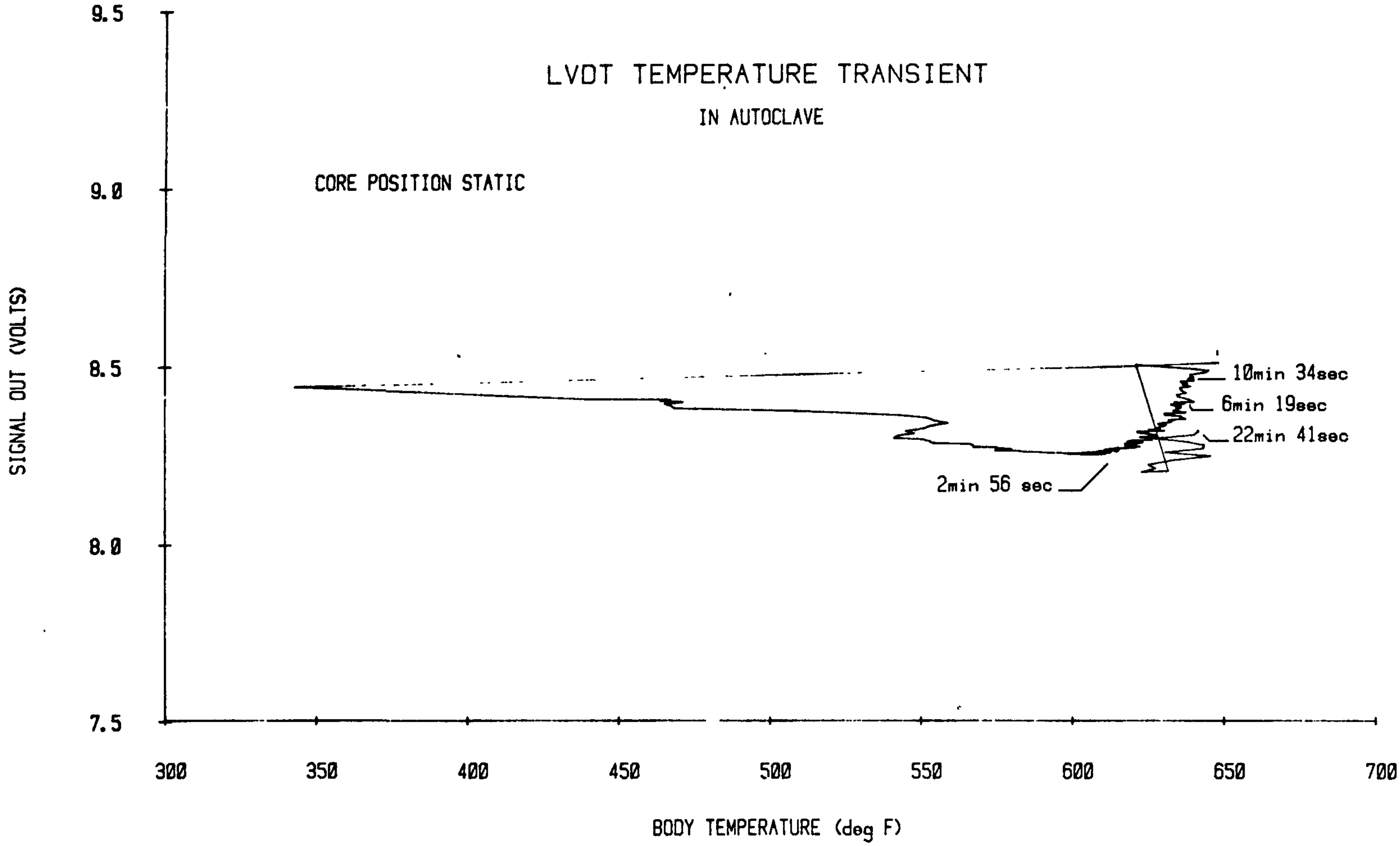

FIGURE 6.13. Variation of Signal Output of Sensor S/N-01 for Autoclave Blowdown.

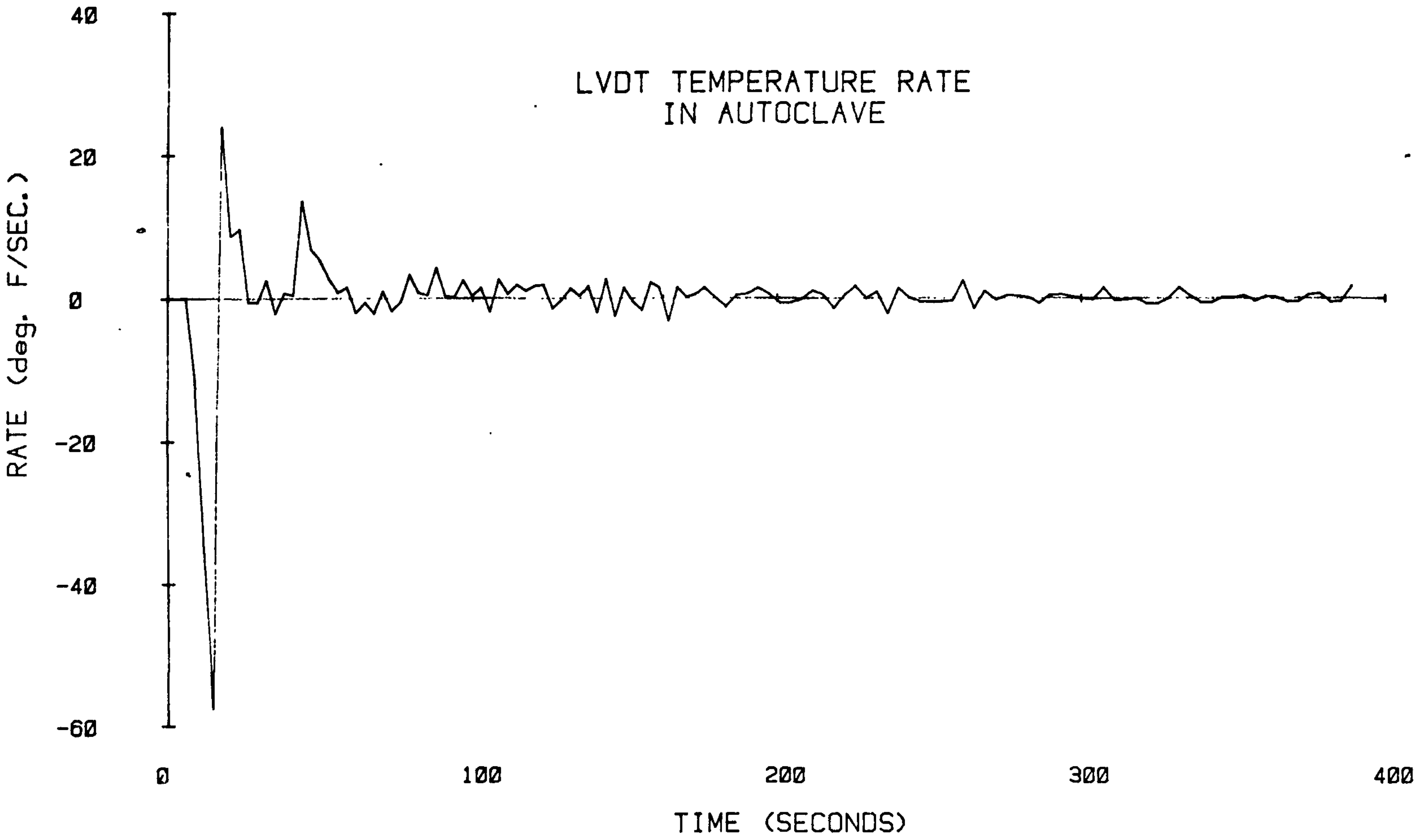

FIGURE 6.14. Rate of Temperature Change for Blowdown Test of Figure 6.13.

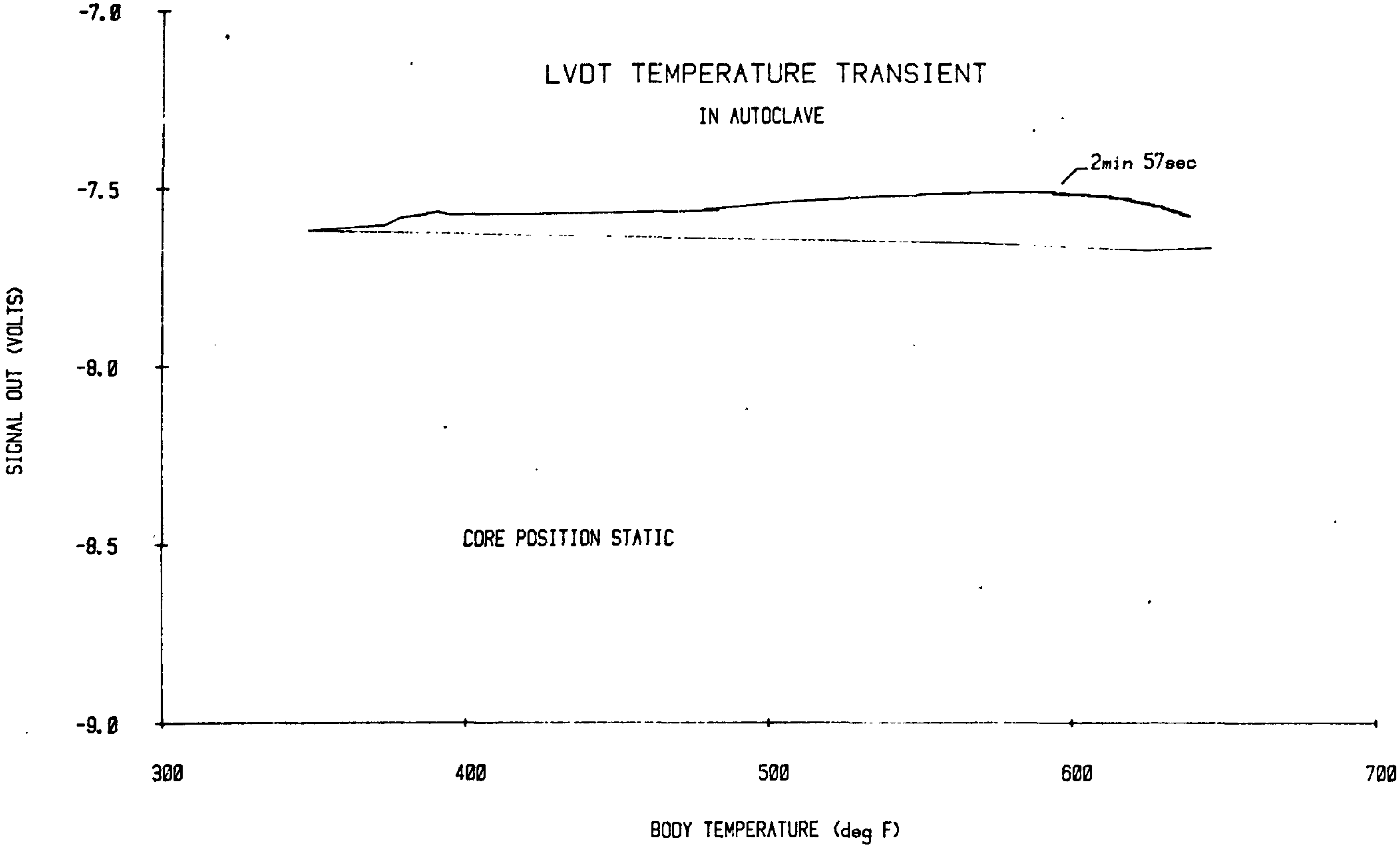

FIGURE 6.15. Variation of Signal Output of Sensor S/N-02 for Autoclave Blowdown.

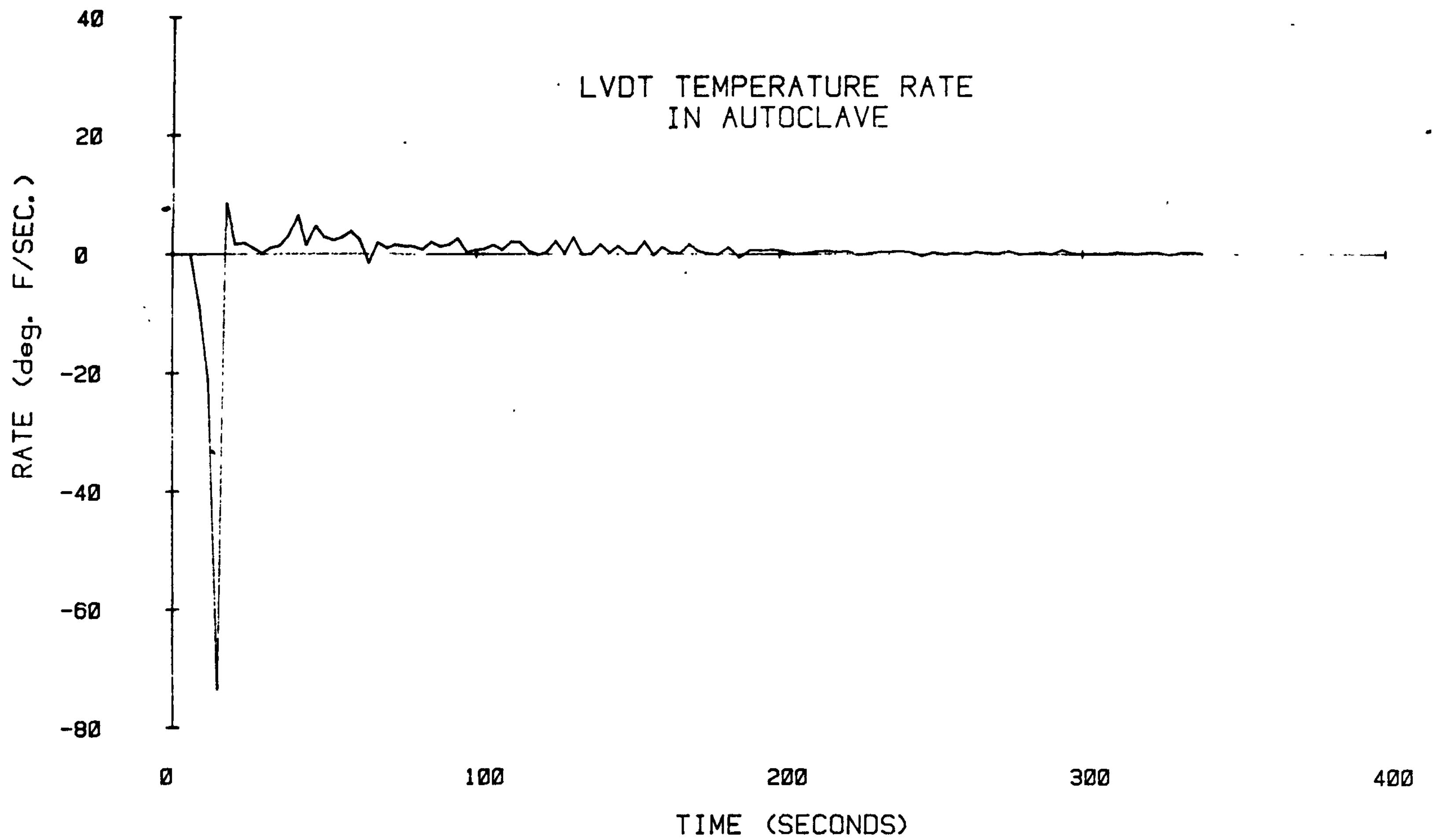

FIGURE 6.16. Rate of Temperature Change for Blowdown Test of Figure 6.15.

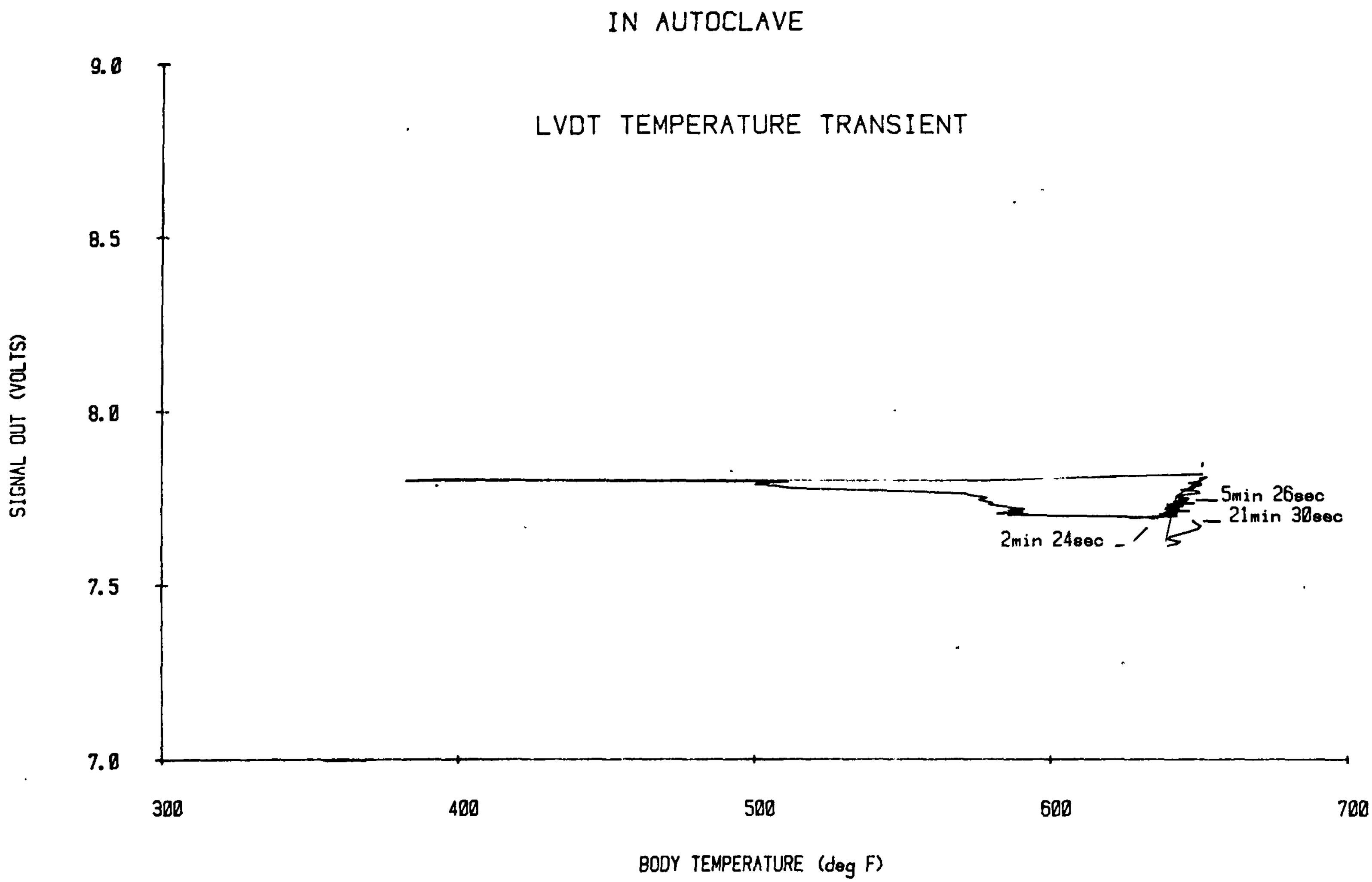

FIGURE 6.17. Variation of Signal Output of Sensor S/N-03 for Autoclave Blowdown.

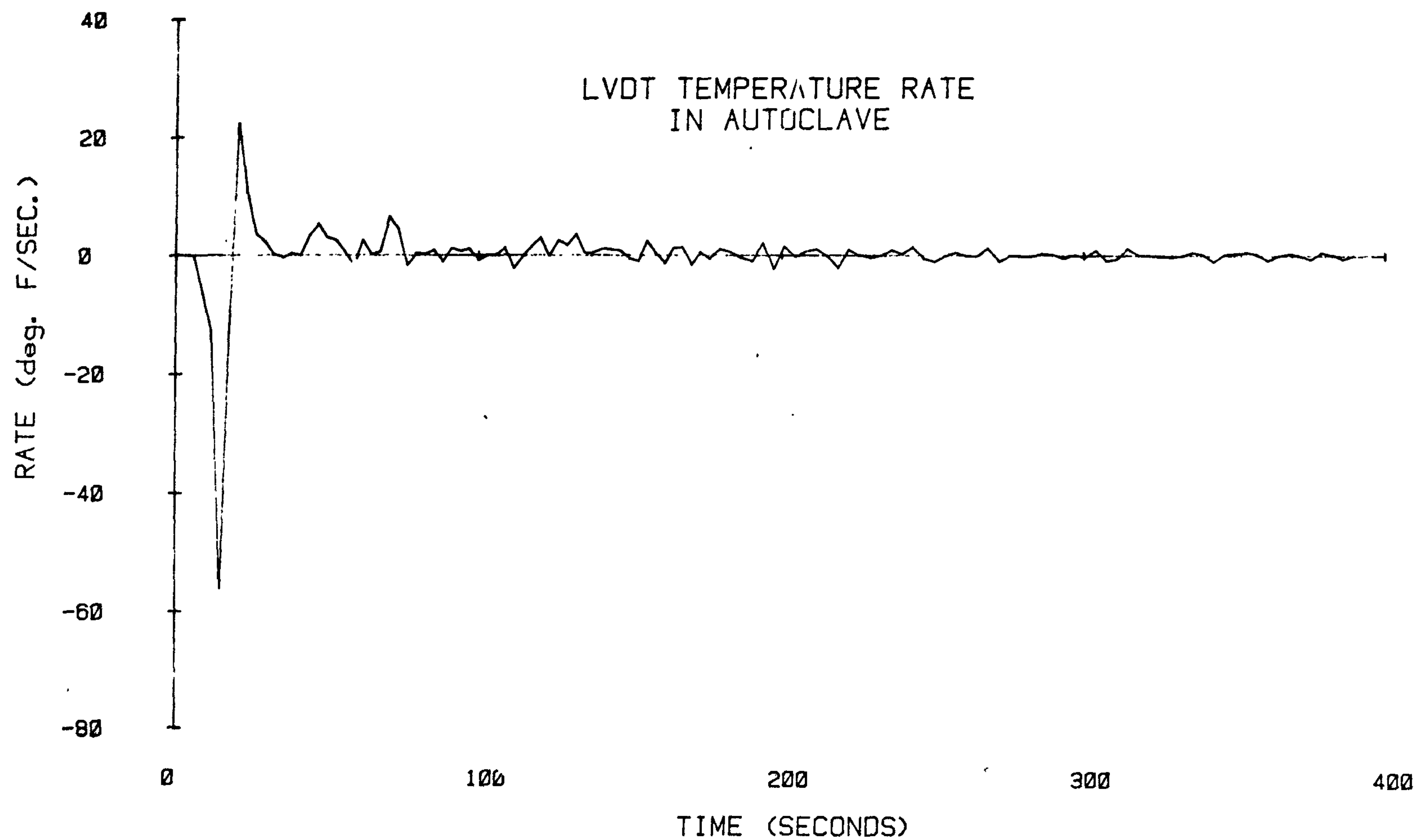

FIGURE 6.18. Rate of Temperature Change for Blowdown Test of Figure 6.17.

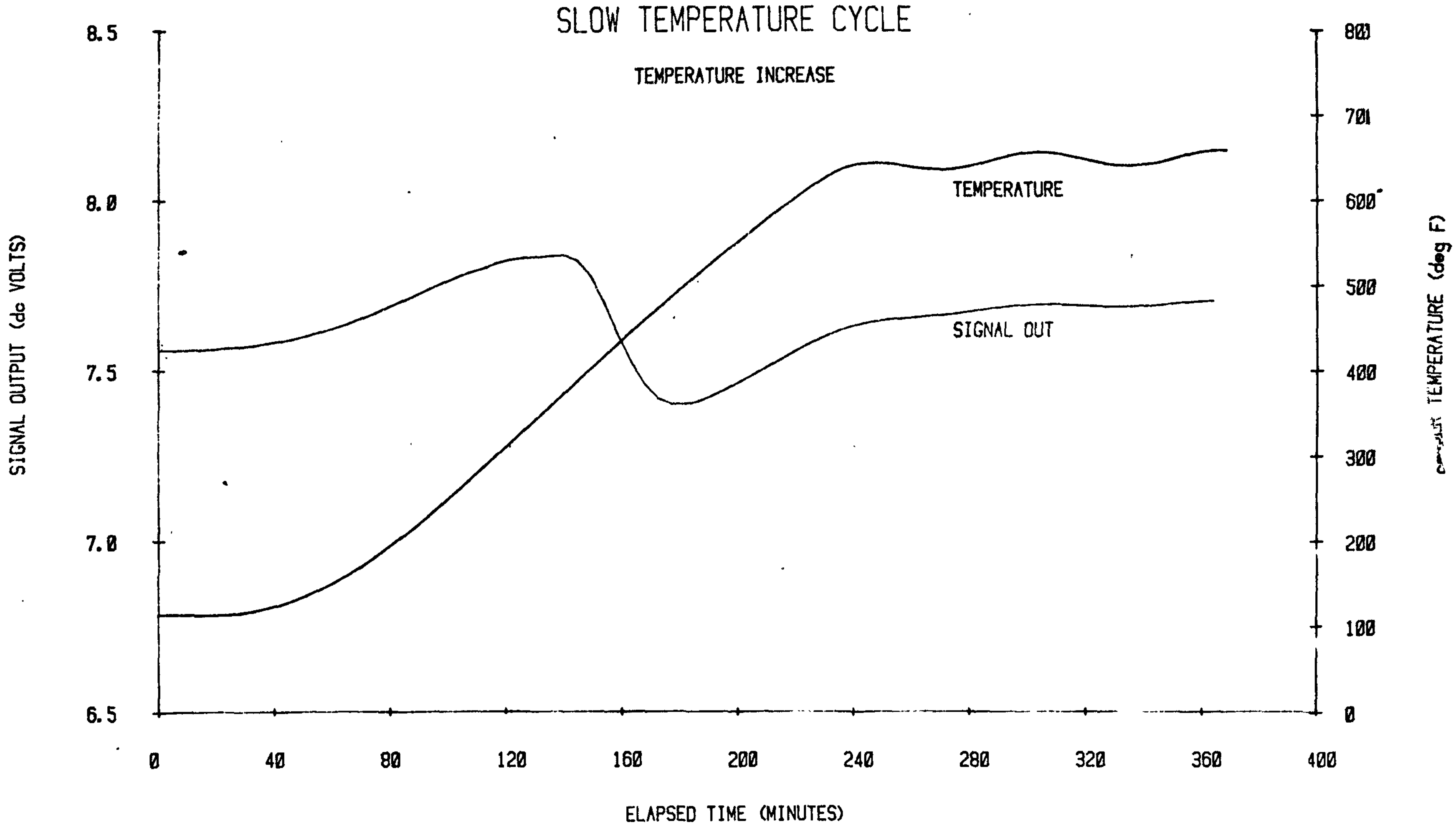

FIGURE 6.19. Variation of Signal Output for Slow Increase of Sensor Temperature.

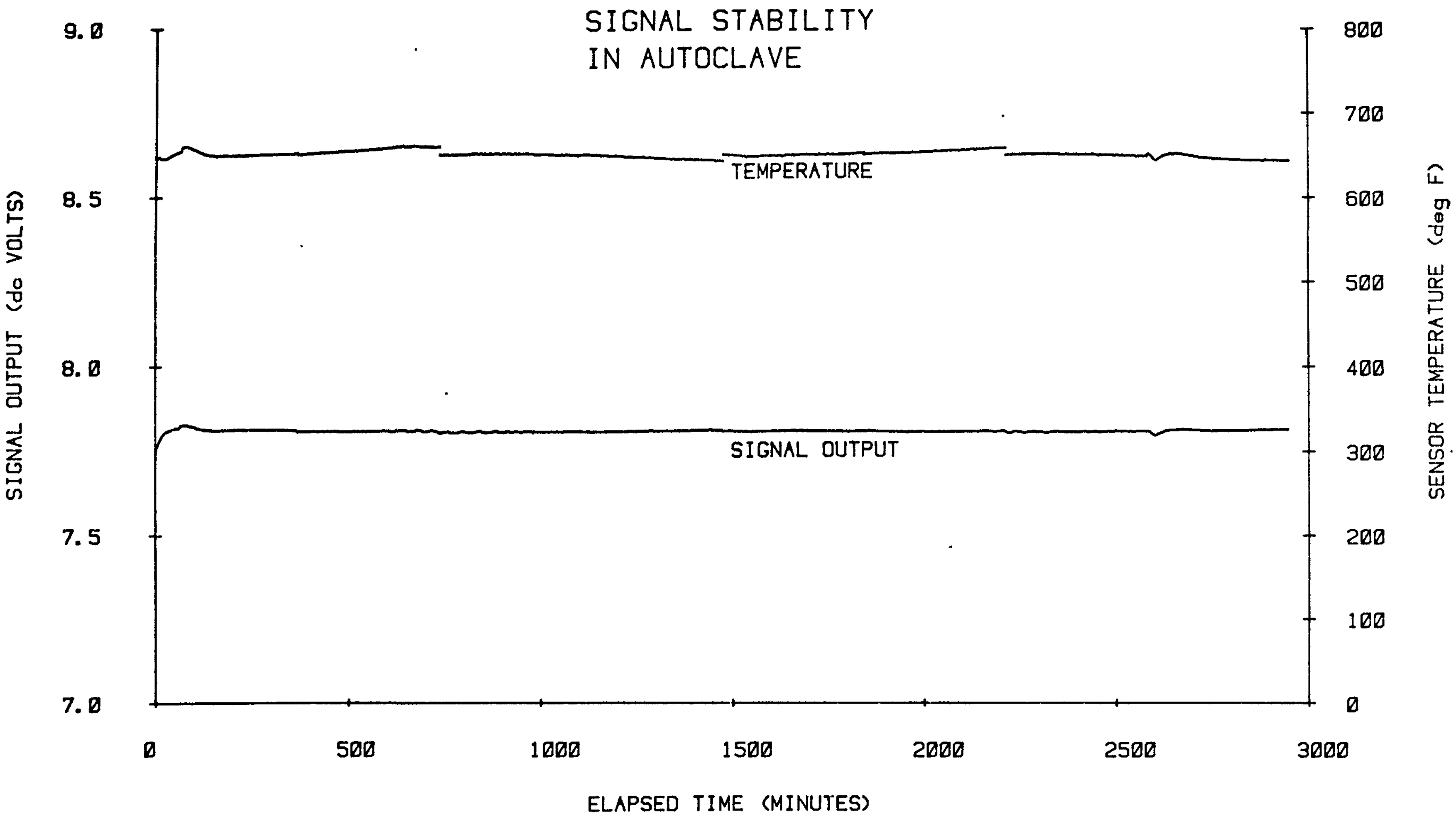

FIGURE 6.20. Long Term Signal Output Stability for LVDT in Autoclave at 650°F.

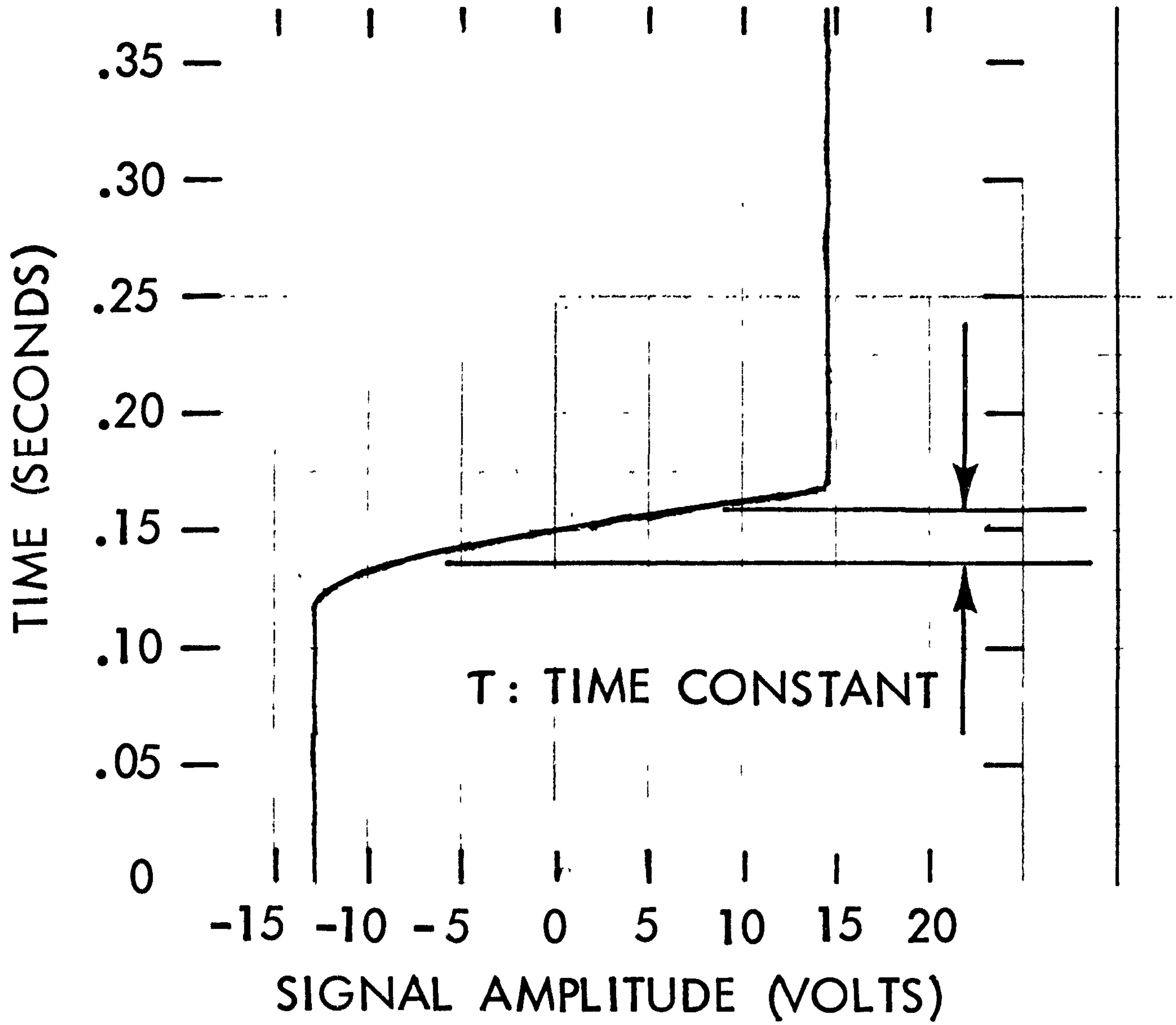

FIGURE 6.21. Reseponse of the Sensor for Rapid Displacement of the Sensing Core. T Represents 10% to 90% Time Response.

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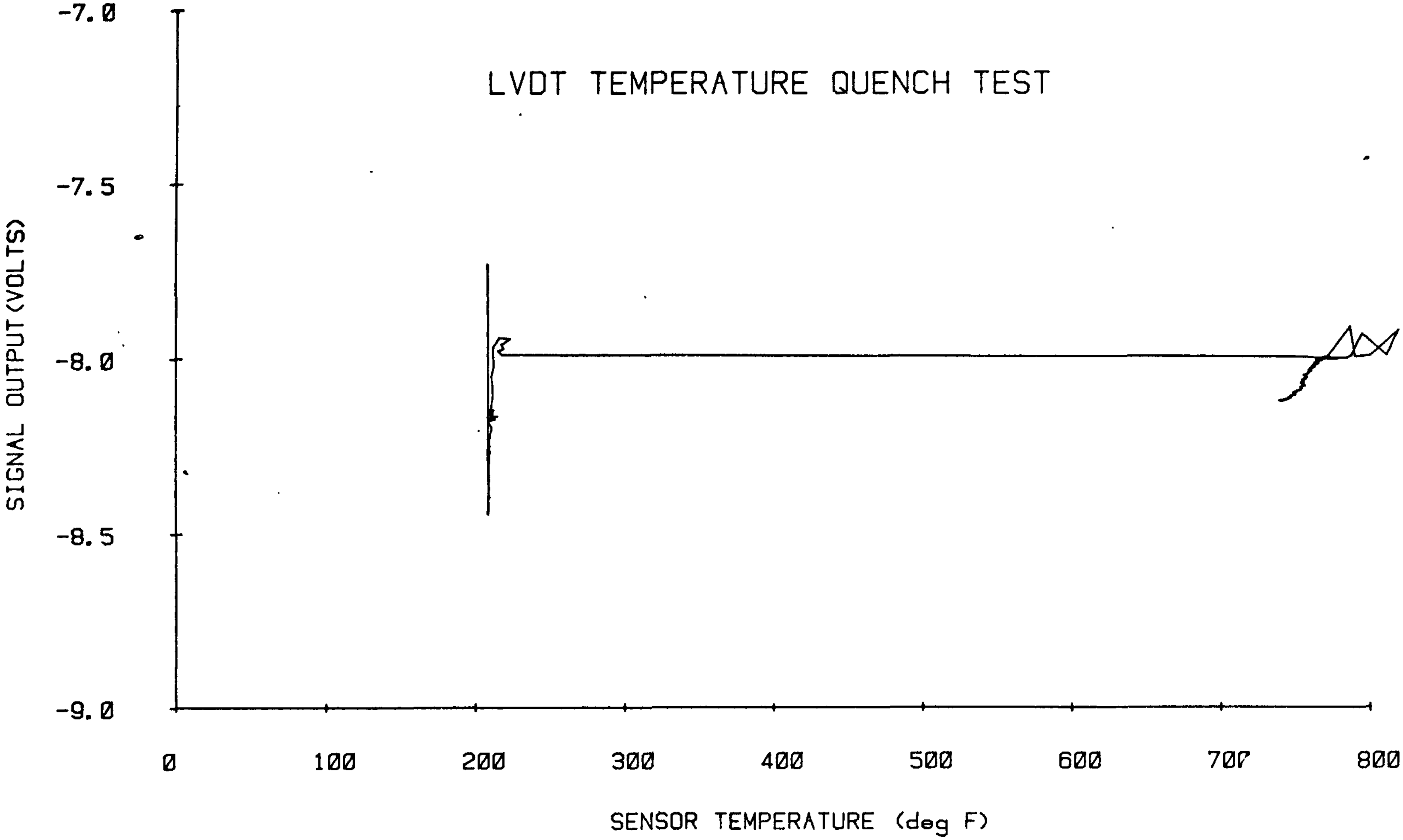

FIGURE 6.22. Displacement Sensor Output Signal Variation for Quench of Sensor Temperature from 800 to 200°F.

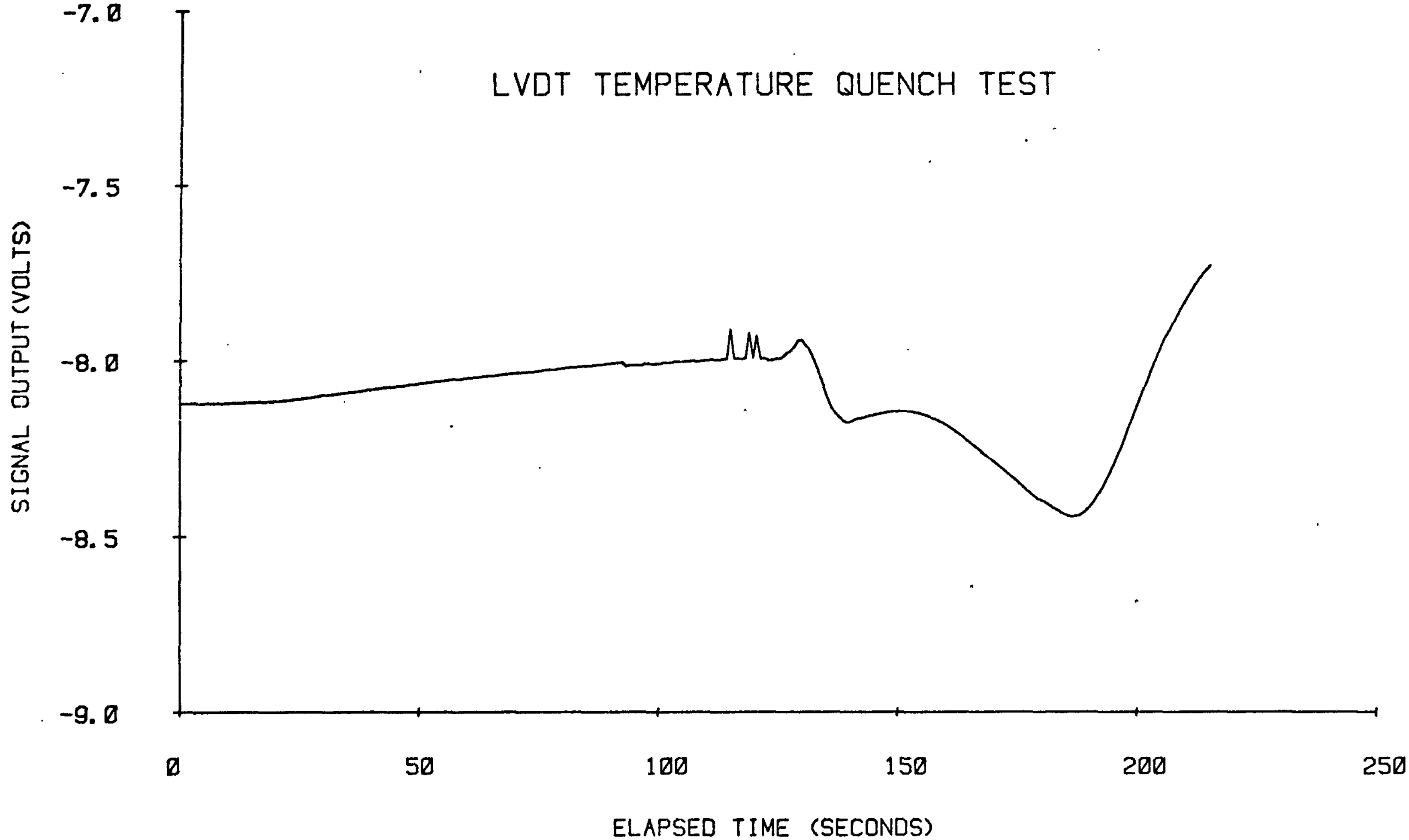

FIGURE 6.23. Time Sequence of Signal Output for Temperature Quench of Figure 6.22.