U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards

NBS Technical Note 1227

Force Calibration at the National Bureau of Standards

Richard A. Mitchell

National Bureau of Standards

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[2] Some divisions within the center are located at Boulder, CO 80303.
[3] Located at Boulder, CO, with some elements at Gaithersburg, MD.

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FORCE CALIBRATION AT THE NATIONAL BUREAU OF STANDARDS

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Force calibration and force measurement services available at the National Bureau of Standards (NBS) are described. Direct deadweight calibrations of force sensors are performed in both compression and tension up to one million lbf (4.4 MN). Comparison calibrations relative to force sensor transfer standards are performed in compression up to 12 million lbf (53 MN). In addition to force calibrations, the following tests are performed to further characterize force sensors: temperature sensitivity, pressure sensitivity, creep, and eccentric load sensitivity. Tests prescribed by the International Organization of Legal Metrology (OIML) for the classification of load cells used in electronic weighing systems are performed in compression for load capacities between about 26 klbf (116 kN) and 109 klbf (485 kN). The capabilities and limitations of the calibration and test facilities are briefly described.

Key Words: Comparison force calibration; creep; deadweight force calibration; eccentric load sensitivity; force calibration; force measurement; force sensor; NBS force calibration; OIML load cell test; pressure sensitivity; temperature sensitivity.

1. INTRODUCTION

This document describes the force calibration and test services that are available at the National Bureau of Standards (NBS). Although it is written for the general technical community, it is intended particularly as a guide to users and prospective users of the NBS services. The capabilities and limitations of the force calibration and test facilities are described. Inquiries are invited in cases where additional information is needed.

In this document the generic term "force sensor" is used to represent a wide variety of force measuring instruments and systems. This includes, but is not necessarily limited to, instruments and systems that are variously referred to by names such as load cell, proving ring, force gage, force link, force transducer, load ring, ring dynamometer, compression dynamometer, tension dynamometer, and crane scale. The important defining characteristic is that these instruments or systems produce an output that is approximately proportional to an applied force.

A very important distinction about this NBS calibration service is that it provides a <u>force</u> calibration. If the calibrated force sensor is used as a load cell in a weighing application to measure mass, the force sensor functions as the spring element of the weighing system. It is incumbent upon the user to make the appropriate corrections for the local gravity field and for air buoyancy.

2. DEADWEIGHT CALIBRATION

Tension and compression force calibrations over the range from 10 lbf (44 N) to 1000 klbf (4.4 MN) are performed in the six NBS deadweight machines described in Table 1.

Table 1 - NBS deadweight machines

Capacity, klbf	1000	300	112	25.3	6.1	0.5
(kN)	(4448)	(1334)	(498)	(113)	(27)	(2.2)
Minimum load, klbf	50	10	3	0.2	0.1	0.01
(kN)	(222)	(44)	(13)	(0.89)	(0.44)	(0.044)
Minimum increment, klbf	50	10	1	0.05	0.05	0.005
(kN)	(222)	(44)	(4.4)	(0.44)	(0.22)	(0.22)
Compression setup space:						
Vertical, m	1.98	1.65	1.02	0.76	0.61	0.25
Horizontal, m	0.86	0.91	0.71	0.50	0.47	0.29
Tension setup space:						
Vertical, m	4.45	2.49	2.16	0.91	0.76	0.56
Horizontal, m	1.17	0.91	0.71	0.66	0.64	0.29

2.1 Operational Characteristics of NBS Deadweight Machines

<u>1000-klbf (4.45-MN) Machine</u> - Although this is the largest NBS deadweight machine, it is also the simplest in design and operation (Fig. 1). The machine applies twenty equal force increments of 50 klbf (222 kN). The force increments are applied one-at-a-time as the lifting frame is raised by the hydraulic jack. Consequently, the weights are always applied and removed sequentially. For example, to apply and remove 350 klbf (1.55 MN) the necessary sequence is 0, 50, 100, 150, 200, 250, 300, 350, 300, 250, 200, 150, 100, 50, 0 klbf.

<u>300-klbf (1.33-MN) Machine</u> - This machine (Fig. 2) is similar in design and operation to the million-pound-force machine except for the fact that it has weights of three different sizes. There are three 30-klbf (133-kN) weights, four 20-klbf (89-kN) weights, and thirteen 10-klbf (44-kN) weights. The weights are arranged to enable one to apply sequentially ten equal-increment test forces over the three ranges: 100, 200, and 300 klbf (0.44, 0.89, and 1.33 MN). Some of the larger increments necessarily consist of two or three weights applied sequentially.

<u>112-klbf (498-kN) Machine</u> - This machine (Fig. 3) has one stack of ten 10-klbf (44-kN) weights and a second stack of nine 1-klbf (4.4-kN) weights. The larger weights are applied as in the two larger machines, one-at-a-time in a fixed sequence, as the lifting frame is raised by a hydraulic jack. The smaller weights are applied, one-at-a-time in a fixed sequence, as they are lowered onto the loading frame by screw jacks. The weight applied to the force sensor being calibrated is the sum of the weight applied from the two stacks plus the 3-klbf (13-kN) weight of the loading frame. This arrangement enables one to apply any multiple of 1 klbf (4.4 kN) between 3 klbf (13 kN) and 112 klbf (498 kN). However, a particular loading sequence may require that the previous load be partially removed before the next larger load is applied. For example, to increase the load from 7 klbf (31 kN) to 14 klbf (62 kN), the load must first be reduced to 4 klbf (18 kN).

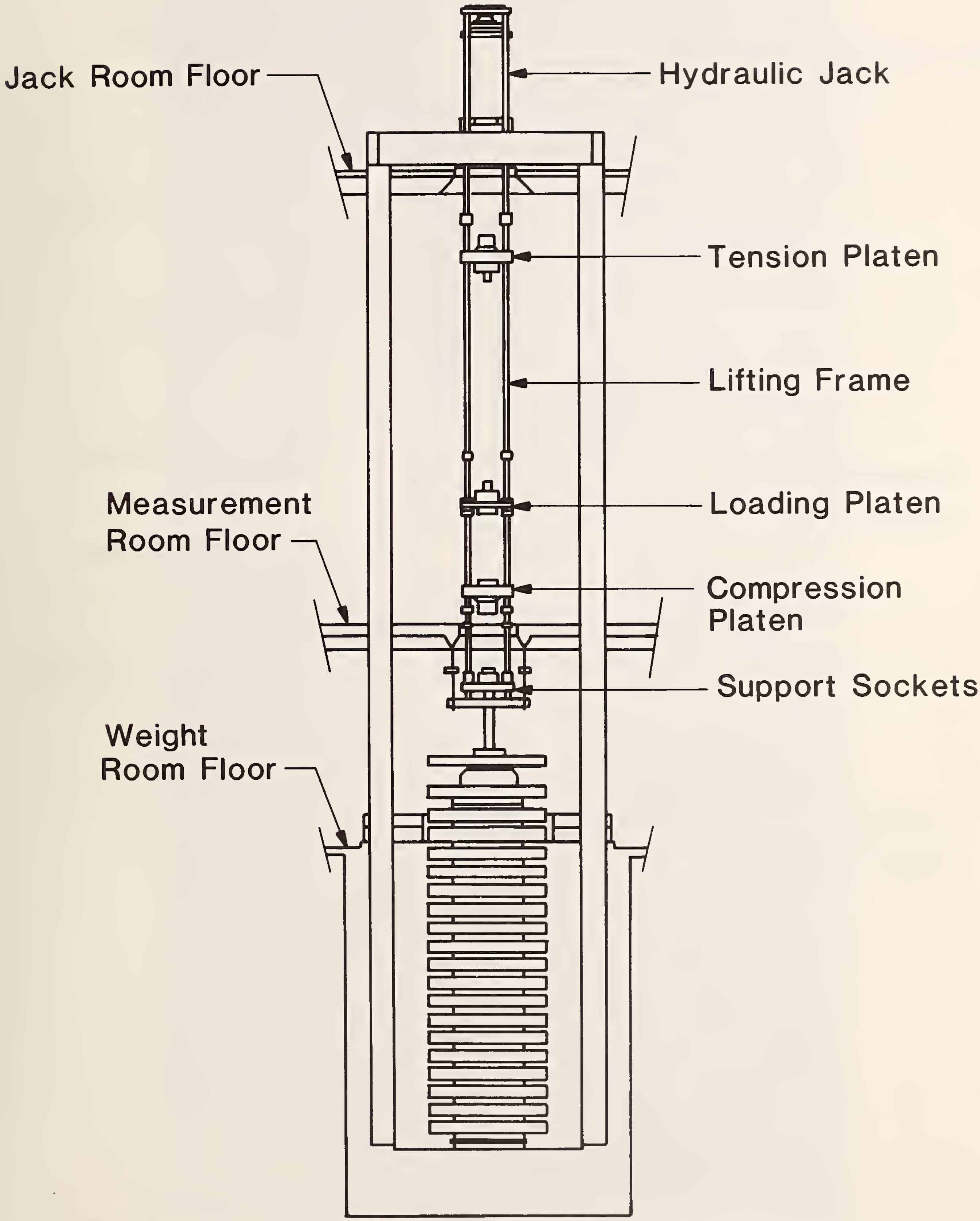

Figure 1. One-million-lbf (4.4-MN) deadweight machine.

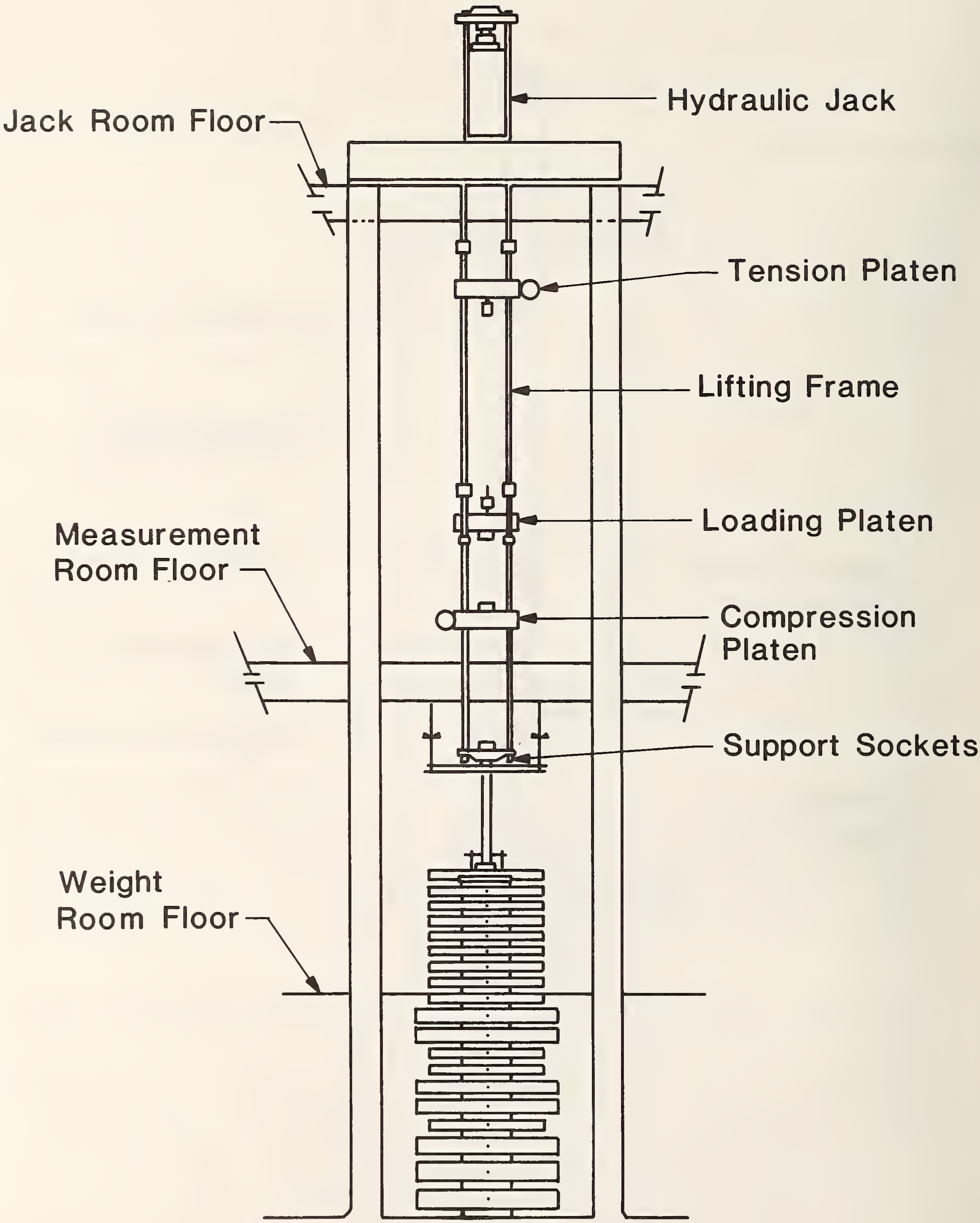

Figure 2. 300-klbf (1.3-MN) deadweight machine.

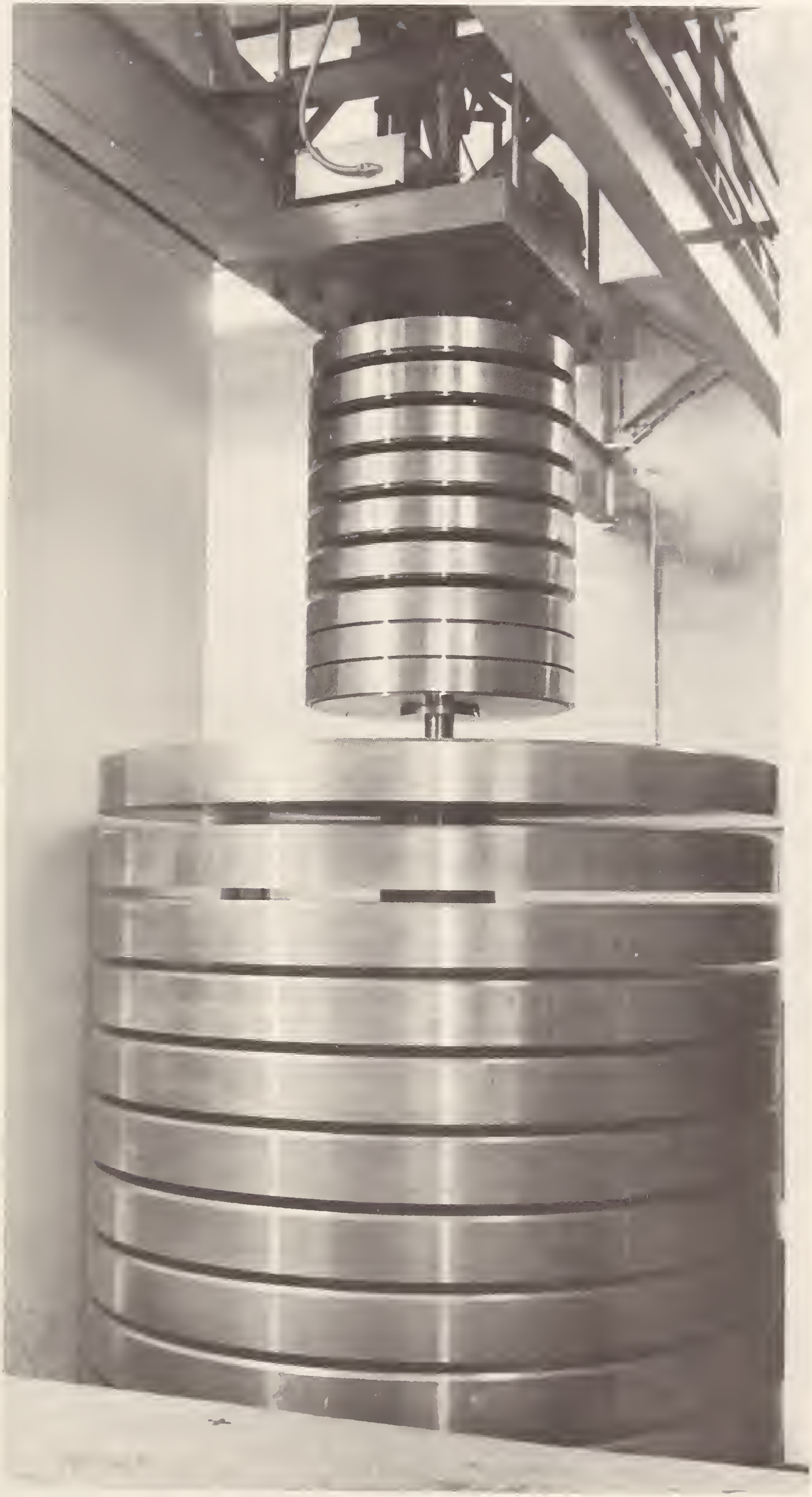

Figure 3. The two weight stacks of the 112-klbf (498-kN) deadweight machine.

25.3-klbf (113-kN) Machine - Figure 4 illustrates schematically the operating principles of this machine. Each weight, when not being used to generate an applied force, is supported by coil springs. When a weight is selected for a force application the supporting springs are compressed by the hydraulic cylinders, thus lowering the weight to a preset position. When the lifting frame is raised by the screw jacks, all of the weights that have been selected and lowered are picked up by the loading frame. The weight applied to the force sensor is the sum of the weights selected plus the weight of the loading frame. An operational limitation of this machine is that the lifting frame must be lowered sufficiently to return the applied force to zero before a different combination of weights is applied. Therefore, tests to determine the hysteresis characteristics of a force sensor cannot be performed with this machine.

A set of small supplemental weights is available that can be added manually to the loading frame to give nominal kilogram-force values for the summation of the pound-force weights and the supplemental weights.

6.1-klbf (27-kN) Machine - Figure 4 also illustrates schematically the operating principles of this machine. The method of weight selection and force application, as well as the operational limitation that the applied force must be returned to zero before the application of a different force, are the same as those of the 25.3-klbf (113-kN) machine. This machine has one set of weights that generates nominal pound-force loads and a second set of smaller weights that, when added to the larger weights, results in nominal kilogram-force values. The kilogram-force option can be switch-selected at the machine console.

500-lbf (2.2-kN) Machine - Although this machine is functionally similar to the next two larger machines (Fig. 4), it is fully manually operated. Each weight, when not being used to apply a force, is supported on two steel bars. Before applying a load, the loading frame and all weights are first raised by a manually operated worm-gear mechanism. The support bars are then manually removed from beneath the selected weights. When the loading frame is then lowered, the selected weights remain on the loading frame and are applied to the force sensor while the other weights are rested on their support bars. This machine has the operational limitation that the applied force must be returned to zero before the application of a different force.

2.2 Uncertainty of Applied Deadweight Forces

The masses of the weights of the six NBS deadweight machines have been adjusted to apply vertical forces in nominal pound-force or kilogram-force increments. The vertical force exerted by a weight is given by the formula

$$\text{Force} = \frac{Mg}{9.80665}\left(1 - \frac{d}{D}\right)$$

in which

M = mass of the weight,
g = local acceleration due to gravity, m/s^2,
d = air density, and
D = density of the weight.

If the mass of the weight is in pounds, the force is in pounds-force; if the mass is in kilograms, the force is in kilograms-force.

The weights of the three larger machines are made of AISI 410 stainless steel having a density of 7.72 g/cm^3; those of the three smaller machines are made

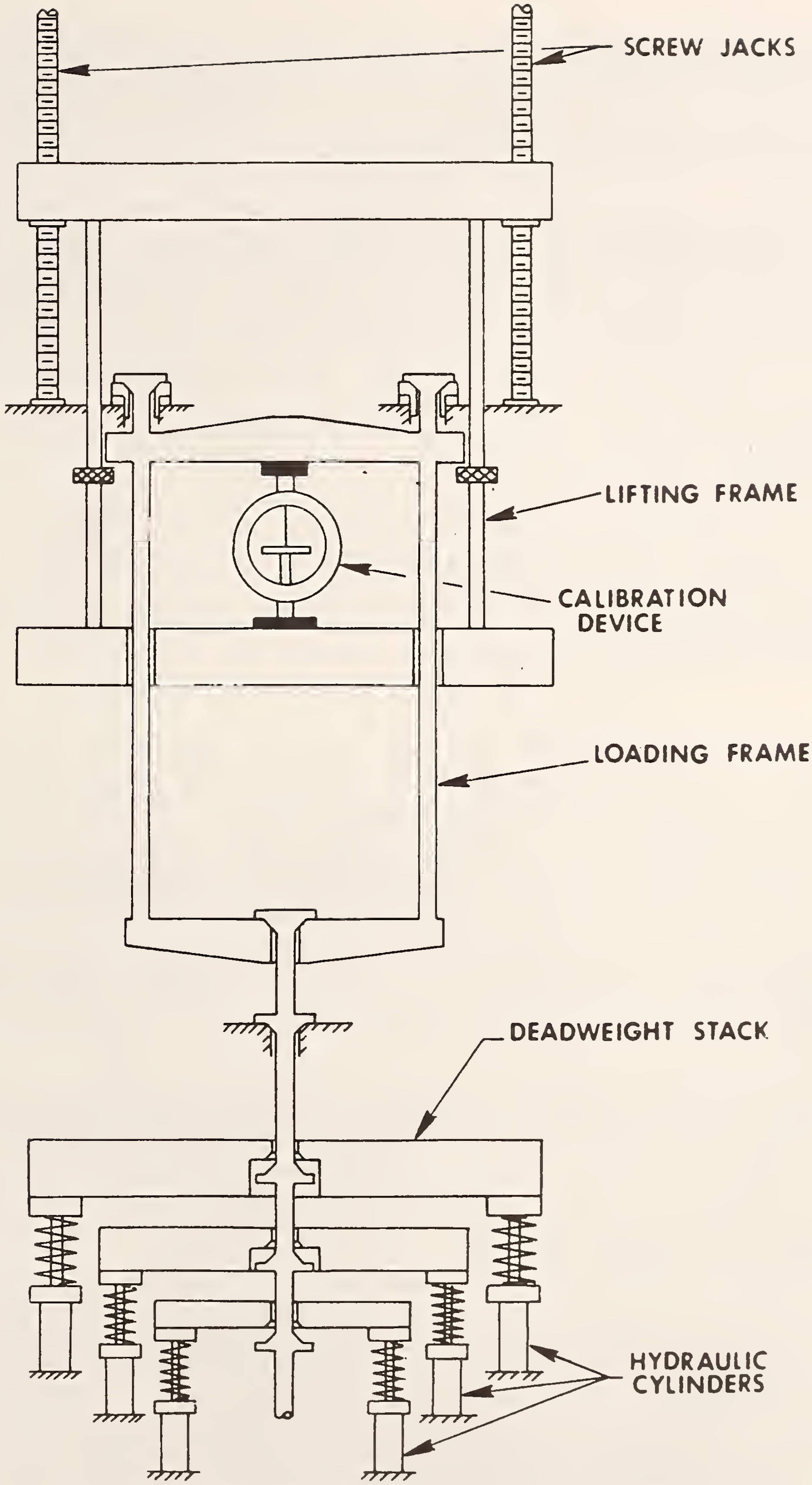

Figure 4. Schematic drawing of the 25.3-klbf (113-kN) and 6.1-klbf (27-kN) deadweight machines.

AISI 302 stainless steel having a density of 7.89 g/cm^3. The masses of the weights were adjusted for an assumed air density of 1.17×10^{-3} g/cm^3. It is estimated that the maximum difference between the actual air density in the laboratory and the assumed air density would result in a difference in applied force of no greater than 0.0005 percent.

The weights were adjusted for the local acceleration due to gravity at a point near the center of gravity of each weight stack. These local gravity values were based on a direct determination of gravity at one location in the Force Laboratory (Ref. 1), with corrections made for the differences in elevation between the weight stacks and the site of the gravity determination.

Each weight was adjusted to apply a force that differed from its nominal force value by less than 0.0005 percent. The mass of each weight, so adjusted, was then determined by substitution methods, working up from the NBS standard kilogram.

The estimated total uncertainty of the vertical component of force applied by any of the six NBS deadweight machines is 0.002 percent. If corrections were made for the actual air density during a calibration and for the actual adjusted mass of each weight, the uncertainty of the applied force could be reduced to 0.001 percent.

2.3 Force Calibration Procedures

An NBS deadweight force calibration usually includes at least 30 force applications, with the applied loads selected to represent approximately every 10 percent of the calibration range. The forces are applied in two or more calibration runs, with the force sensor rotated to a different orientation in the machine between runs. At least some of the applied loads are repeated in different runs of the same calibration. Within these general guidelines, a broad range of standard procedures prescribed by standards writing organizations, as well as special procedures to satisfy user requirements, can be accommodated. The particular calibration procedure that is appropriate depends on the requirements of the application and the characteristics of the force sensor and sensor readout.

The standard force calibration procedures most frequently used by NBS are those included in the American Society for Testing and Materials (ASTM) Standard Practice E74 [2]. These procedures are prescribed by ASTM for the calibration of either (1) force sensors that are used to calibrate testing machines or (2) force sensors that are used to calibrate other force sensors that are then used to calibrate testing machines. The same procedures are also adequate for many other applications.

Special force calibration procedures are ordinarily consistent with the minimum requirements of the general guidelines given above, but they may also include supplemental force applications or controls that are based on the requirements of the particular application of the force sensor. For example, particular loading sequences, loading rates, and waiting times may be used to more thoroughly characterize the hysteresis, time dependence, and repeatability of the force sensor. Special tests to determine other characteristics of force sensors are discussed in Sec. 4.

As known forces are applied to the force sensor, the response indicated by the sensor readout is recorded. Force sensor readouts can be functionally classified into three different types: (1) integral, (2) system, and (3) interchangeable. All three readout types are used extensively at NBS. An integral readout is an integral part of the force sensor, for example the dial micrometer of a proving ring. A system readout is a particular electrical or hydraulic instrument that is both calibrated and used in combination with a particular force sensor; the combination is referred to as a force measurement system and the calibration of the combination is referred to as a system calibration. An interchangeable readout is an instrument that is first calibrated independent of a force sensor and then used to measure the response of the force sensor, for example a dc voltage-ratio readout instrument that can be calibrated by a four-terminal network of stable electrical resistors.

2.4 Data Analysis

A polynomial curve is usually fitted to the force-versus-response calibration data. The curve most frequently used is of the form

$$\text{Response} = A + B\,(\text{Force}) + C\,(\text{Force})^2$$

in which A, B, and C are constant coefficients that are estimated by the method of least squares. An estimate of the standard deviation of the pooled calibration data relative to the fitted curve is computed by the formula

$$s = \left[\frac{d_1^2 + d_2^2 + d_3^2 + \ldots + d_n^2}{(n - m)}\right]^{1/2}$$

in which d_1, d_2, etc. = differences between the curve and the n observed response values, and
m = number of coefficients of the fitted curve.

Figure 5 is a plot of the results from such a curve fit for the compression calibration of a 100 klbf (445 kN) proving ring force sensor. The fitted calibration curve is represented by the horizontal zero axis and the data points indicate deviations from the fitted curve, in percent of capacity-load output. The dashed horizontal lines indicate the resolution of the output. Although this analysis is adequate for data that are distributed as randomly as those shown in Fig. 5, a more general analysis is needed to represent the non-random components of the response of many force sensors.

A new statistical analysis of force calibration data is being developed at NBS [3], but it has not yet been implemented for routine use in calibration reports. It makes use of statistical tests for significance to determine the degree of polynomial that best fits the data. Confidence intervals are computed for the sensor response predicted by the fitted polynomial. Figure 6 shows computed 95 percent confidence intervals, relative to a second degree polynomial fit, for the compression calibration of a 6-klbf (27-kN) strain gage force sensor. Between-run (zero offset and load proportional) and model (serpentine) error components are evident in the plot. The analysis estimates the separate contributions of these systematic error components as well as the random error.

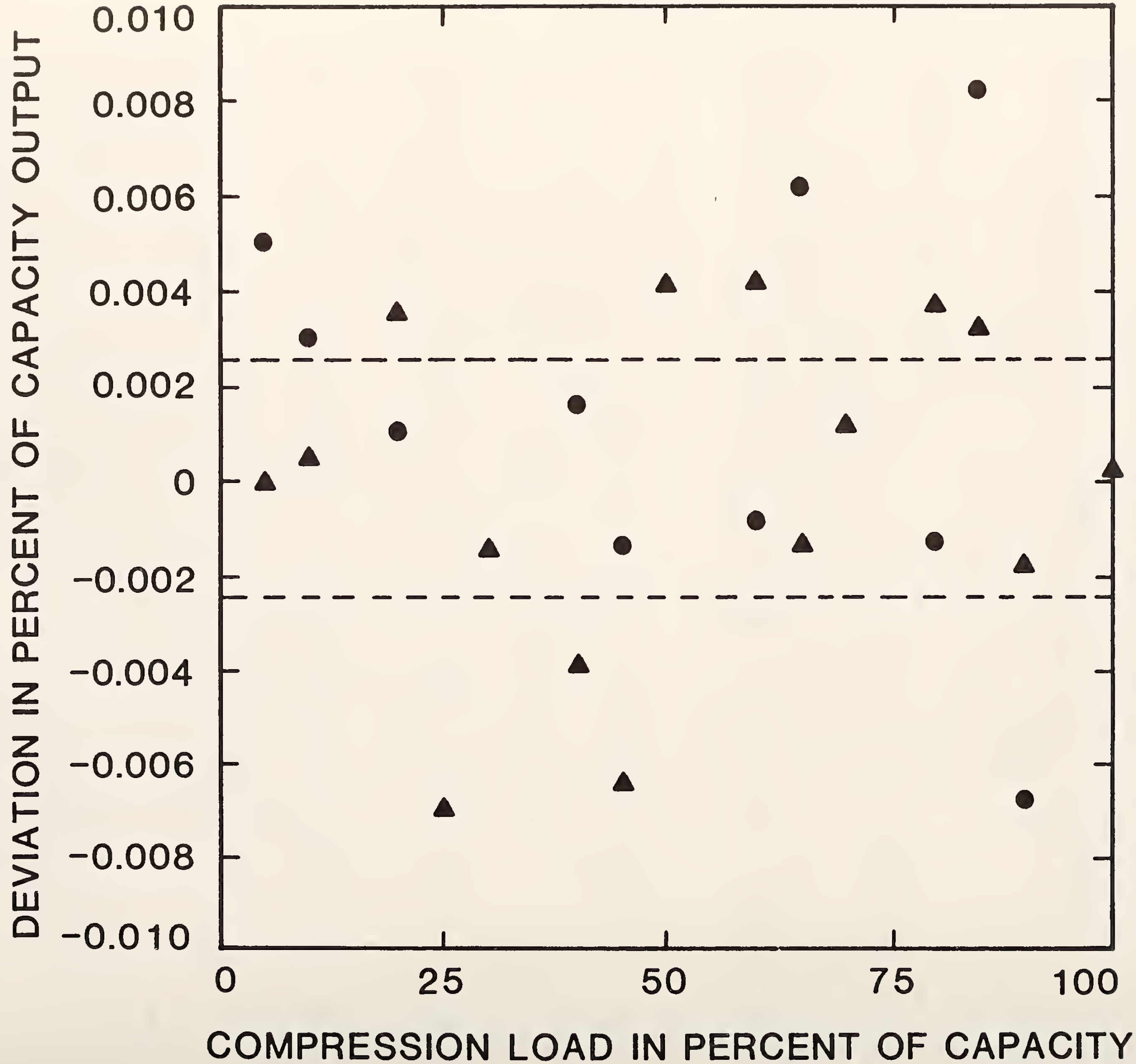

Figure 5. Deviation from the fitted calibration curve versus applied force, from the compression calibration of a 100 klbf (445 kN) proving ring force sensor.

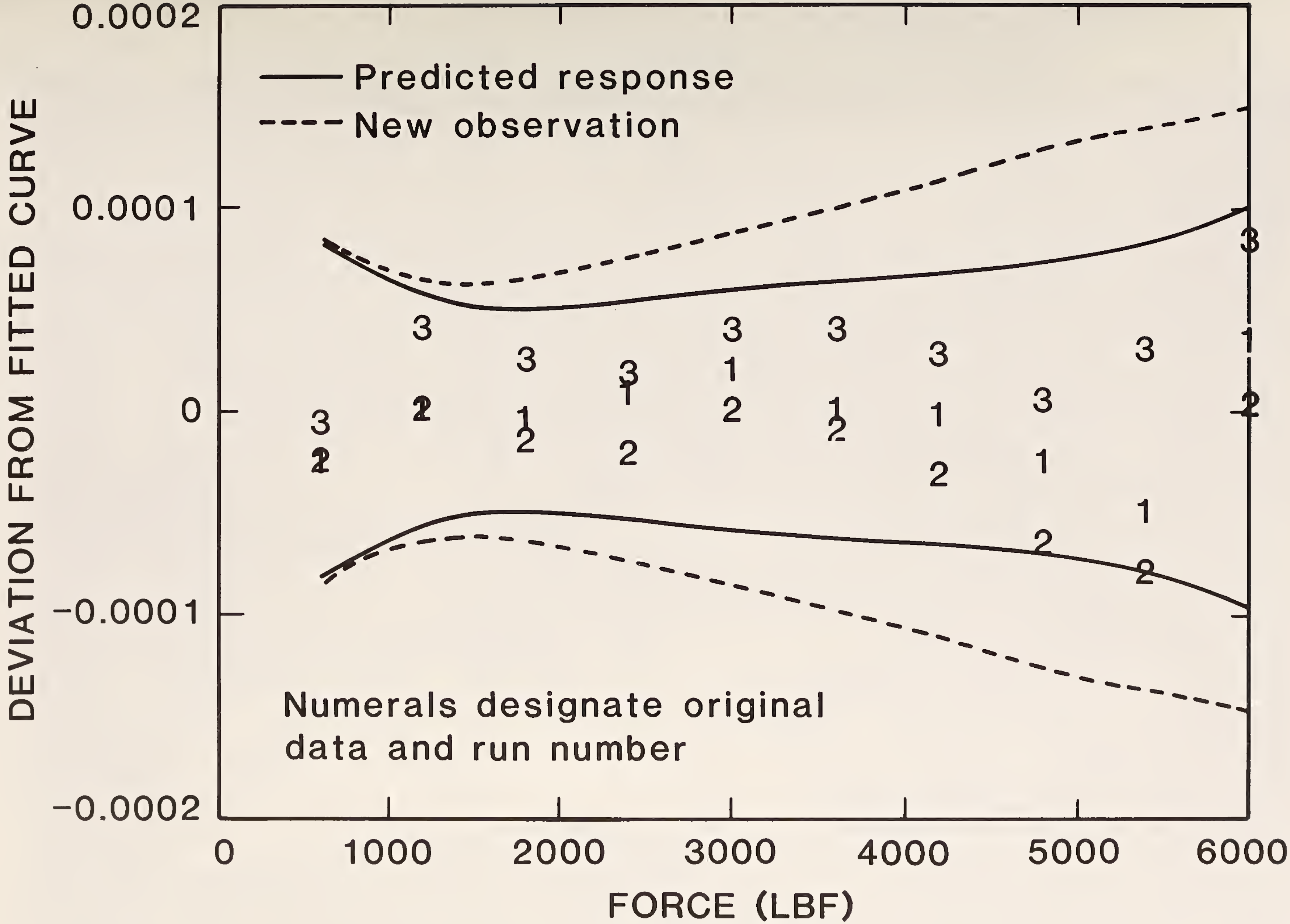

Figure 6. Deviation from the fitted calibration curve, relative to capacity output, versus applied force, from the compression calibration of a 6-klbf (27-kN) strain gage force sensor. Curves indicate the pointwise 95 percent confidence intervals.

An alternative data analysis, described in Ref. 2, is used in the calibration of so called "limited load devices," force sensors whose response characteristics do not justify interpolation of measurements at force magnitudes other than those applied in the calibration. In this analysis, the response data for each of the repeated calibration forces are averaged to give the predicted response of the force sensor.

2.5 Systematic Errors

Systematic errors evident in deadweight calibrations are ordinarily much greater than the estimated 0.002 percent uncertainty of the applied vertical deadweight force given above (Sec. 2.2). Most deadweight calibrations performed at NBS have an estimated standard deviation of the pooled data relative to a fitted calibration curve in the range 0.002 to 0.02 percent of full scale output. The apparent systematic error, indicated by the non-random structure of the data (Fig. 6), is often greater than the apparent random error. The two major sources of systematic error are usually mechanical misalignment and load-time effects. Complex mechanical interactions between the force sensor and the deadweight machine, due to small mechanical misalignment of the sensor and the machine, can cause significant bending, shear, and torsional loads to act in combination with the precisely known vertical force. Also, the response of the force sensor is inherently dependent on the loading sequence, the loading rate, and the duration and stability of the load. These sources of calibration error are discussed in Refs. 4, 5, and 6. Of course, the same types of error are present, to some degree, when the calibrated force sensor is used to measure force in a different setup. Reference 7 reports a round robin study of the calibration of a set of four force sensors at NBS and at 27 other laboratories. The results give an indication of the range of performance that might be obtained with the force sensors, loading machines, and procedures used.

3. COMPARISON FORCE CALIBRATION

Compression force calibrations up to a capacity of 12 million lbf (53 MN) are done by comparison with NBS transfer standard strain gage force sensors. These comparison calibrations are done in the compression section of the NBS 12-million-lbf (53-MN) capacity universal testing machine described in Ref. 8. Figure 7 shows the setup for the calibration of a 3-million-lbf (13-MN) strain gage force sensor by comparison with three NBS 1-million-lbf (4.4-MN) transfer standards loaded in parallel. Each of the 1-million-lbf (4.4-MN) transfer standards has been calibrated in compression in the NBS 1-million-lbf (4.4-MN) deadweight machine. NBS has a set of four 3-million-lbf (13-MN) transfer standard strain gage force sensors that are each calibrated in compression by comparison with three NBS 1-million-lbf (4.4-MN) transfer standards. To calibrate in compression above 3 million lbf (13 MN) either three or four of the NBS 3-million-lbf (13-MN) transfer standards are loaded in parallel in a setup similar to that shown in Fig. 7.

The 12-million-lbf (53-MN) universal testing machine applies the calibration force with a hydraulic ram and senses the applied force with an annular-ring hydraulic capsule equipped with a pressure sensor. The applied force is controlled by manually operated hydraulic flow-control valves. With this method of force control, it is not possible to apply and hold constant a precise force as is done in a deadweight calibration. The usual procedure is to approximate a

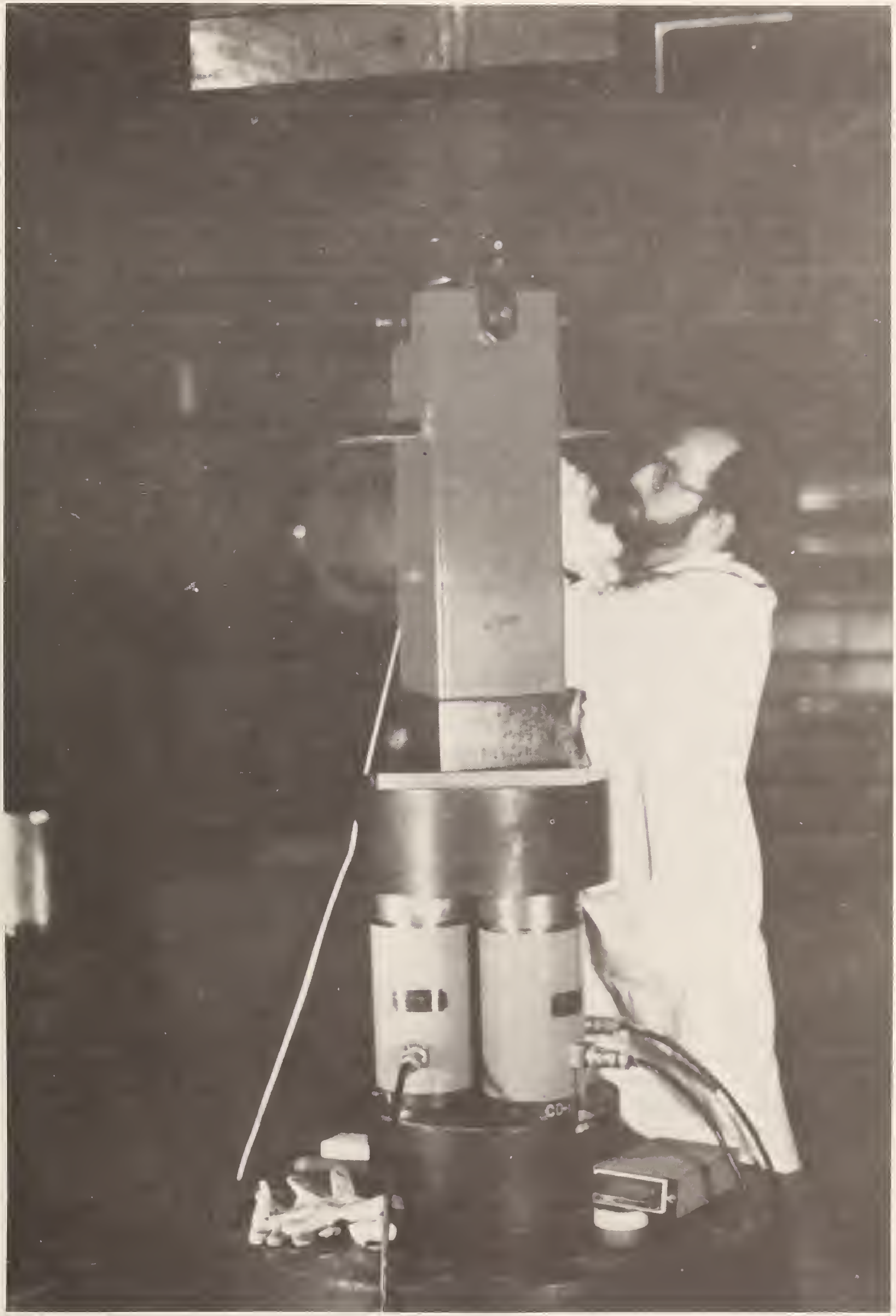

Figure 7. Setup for the comparison calibration of a 3-million-lbf (13-MN) strain gage force sensor.

target force by making the comparison calibration measurements as the hydraulically applied force slowly increases through the target force value as indicated by the dial of the universal testing machine. The readouts from all of the force sensors in the setup (Fig. 7) are recorded simultaneously. To facilitate this, the readout instruments used with the NBS transfer standards are electrically interconnected so that simultaneous readings can be obtained by operating a single freeze switch.

The applied calibration force is assumed to be the sum of the forces indicated by the NBS transfer standards that are loaded in parallel (Fig. 7). To investigate the validity of this assumption, a setup equivalent to that shown in Fig. 7 was made in the compression section of the NBS 1-million-lbf (4.4-MN) deadweight machine. Repeated calibration runs up to 1 million lbf (4.4 MN) were then performed with one or more of the smaller transfer standards rotated and/or moved slightly in a radial direction between runs to simulate the normal variations that might be expected in multiple-standard setups. The average of the differences between the applied deadweight force and the sum of the forces indicated by the three parallel 1-million-lbf (4.4-MN) transfer standards was 84 lbf (374 N).

Estimates of the uncertainties in the forces applied in comparison calibrations are computed by combining in quadrature the estimated uncertainties contributed by each of the three or four transfer standards that are loaded in parallel. The uncertainty of each of the 1-million-lbf (4.4-MN) transfer standards is estimated to be 2.4 times the standard deviation of the pooled data from the deadweight calibration of that transfer standard, as prescribed by ASTM E74 (Ref. 2). The uncertainty of each of the 3-million-lbf (13-MN) transfer standards is estimated to be 2.4 times the standard deviation of the pooled data from its comparison calibration plus the estimated uncertainty of the loads applied during its calibration. Based on repeated calibrations of the transfer standards over several years, the estimated uncertainties in the forces applied in comparison calibrations are:

To 3000 klbf (13 MN) using three of the smaller standards -- 0.3 klbf (1.3 kN)
To 9000 klbf (40 MN) using three of the larger standards -- 1.3 klbf (5.8 kN)
To 12000 klbf (53 MN) using four of the larger standards -- 1.6 klbf (7.1 kN).

4. FORCE SENSOR CHARACTERIZATION TESTS

Determinations of force sensor characteristics other than the calibration curve are needed for many applications. The NBS Force Laboratory can perform temperature sensitivity, pressure sensitivity, creep, eccentric load sensitivity, and pattern evaluation tests over certain ranges as described below.

4.1 Temperature Sensitivity Test

Two methods are available at NBS for controlling the test temperature in order to determine the temperature sensitivity of a force sensor: the constant-temperature room and the constant-temperature chamber. In the first method the temperature of the entire laboratory room is varied. In the second method the force sensor is placed inside a temperature chamber that is installed in a deadweight machine.

The measurement rooms of all six NBS deadweight machines can be adjusted up or down several degrees Celsius and held at a constant temperature. Thus, the temperature sensitivity over a moderate temperature range can be determined, for tensile or compressive applied force, over the force range from 10 lbf (44 N) to 1000 klbf (4.45 MN).

The NBS temperature chamber has a range of -15 °C to 50 °C. However, it can only be used in compression and, as it is presently equipped, it can only be used over the force range from 100 lbf (445 N) to 112 klbf (498 kN). The inside dimensions of the chamber are 36 cm diameter by 43 cm height. Within these limitations, the constant-temperature chamber method is much more efficient than the constant-temperature room method. Figure 8 shows the insulated temperature chamber installed for a test in the 112-klbf (498-kN) deadweight machine. Other equipment used in the test, shown left-to-right in Fig. 8, are a constant-temperature liquid bath that controls the chamber temperature, an ac power line conditioner for removing electrical transients (underneath the bath), a four-terminal resistance network used to calibrate the dc readout instrument for a strain gage force sensor, the readout instrument for a strain gage force sensor, the deadweight machine control console, a desktop computer used to monitor the readout instrument and thermocouples located inside the chamber, and a temperature data scanner. During this test the maximum temperature difference between the top and bottom of the force sensor was less than 0.5 °C over a test temperature range of -10 °C to 40 °C.

4.2 Pressure Sensitivity Test

Force sensors that are hermetically sealed can have a significant sensitivity to changes in ambient air pressure. Intuitively, one would expect that the pressure sensitivity would be approximately constant throughout the loading range of the force sensor. The system shown in Fig. 9 is used to determine the pressure sensitivity of unloaded or lightly loaded force sensors over the atmospheric range, from 710 mm Hg (95 kPa) to 785 mm Hg (105 kPa). The pressure chamber is 38 cm in diameter by 71 cm in height which allows enough room to apply small tare weights to the force sensor being tested. The vacuum pump and gas supply provide a continuous range of ambient pressure above and below laboratory ambient pressure. Pressure is regulated by the manual momentary valve (visible in Fig. 9 attached to the side of the pressure chamber) and read by the dial gage absolute pressure sensor.

4.3 Creep Test

Drift in the output signal of a force sensor while it is subjected to a constant applied force, commonly called creep, can be a critical characteristic in many applications. The creep characteristics of force sensors over the force range from 10 lbf (44 N) to 1000 klbf (4.4 MN) can be determined in the NBS deadweight machines (Ref. 9). Where it is practical the force can be applied in one step. For example, a 50 klbf (222 kN) creep test can be performed by applying in one step the initial force increment of the 1000-klbf (4.4-MN) deadweight machine. Creep tests can be performed at laboratory room temperature or in the temperature chamber (Sec. 4.1). Figure 10 illustrates the importance of ambient temperature in a creep test.

4.4 Eccentric Load Sensitivity Test

Force sensors are ordinarily designed with a symmetry that is intended to make them relatively insensitive to load eccentricity. In general, however, there is a residual eccentric load sensitivity due to imperfections in machining,

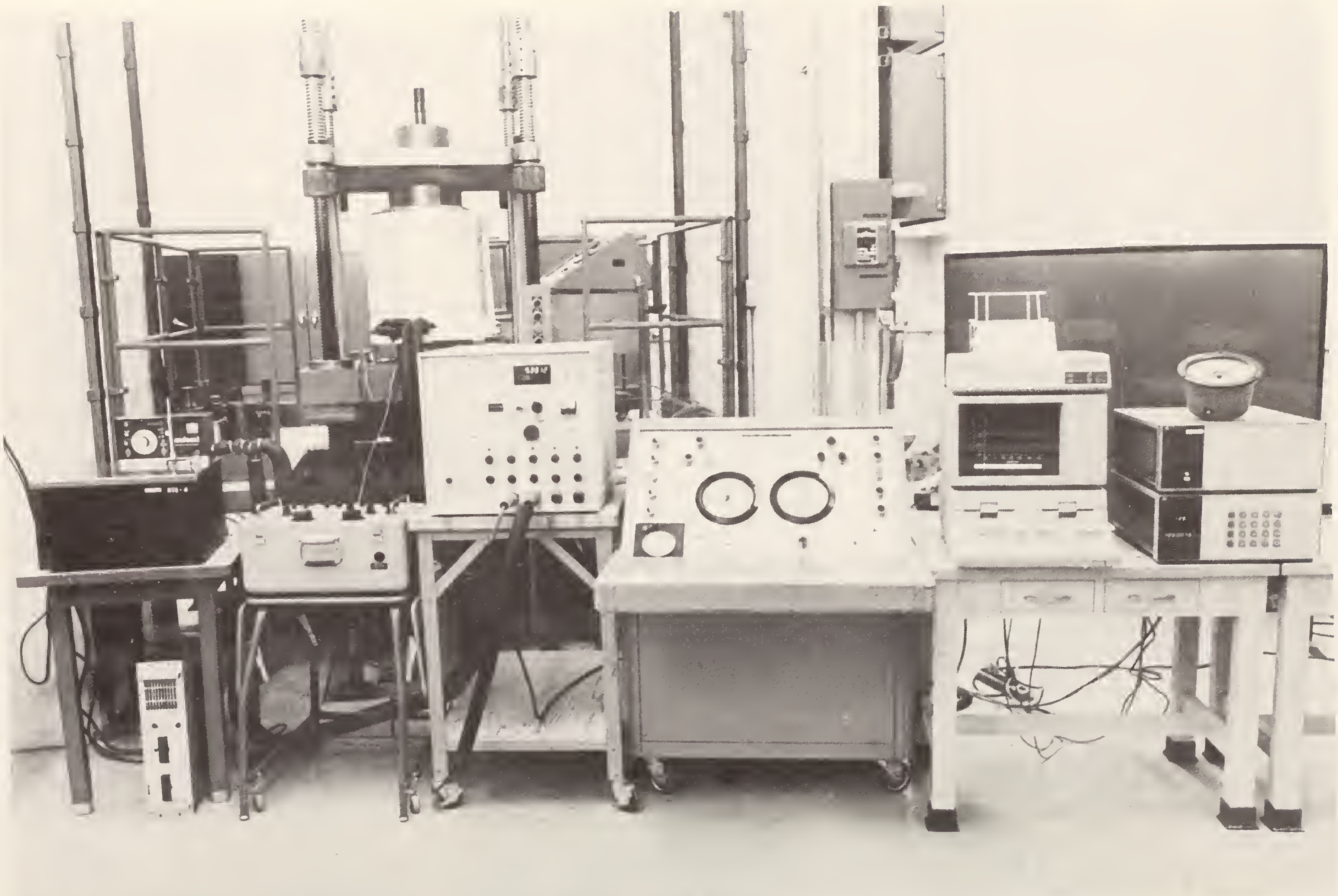

Figure 8. Temperature sensitivity test setup. The instruments are identified in the text.

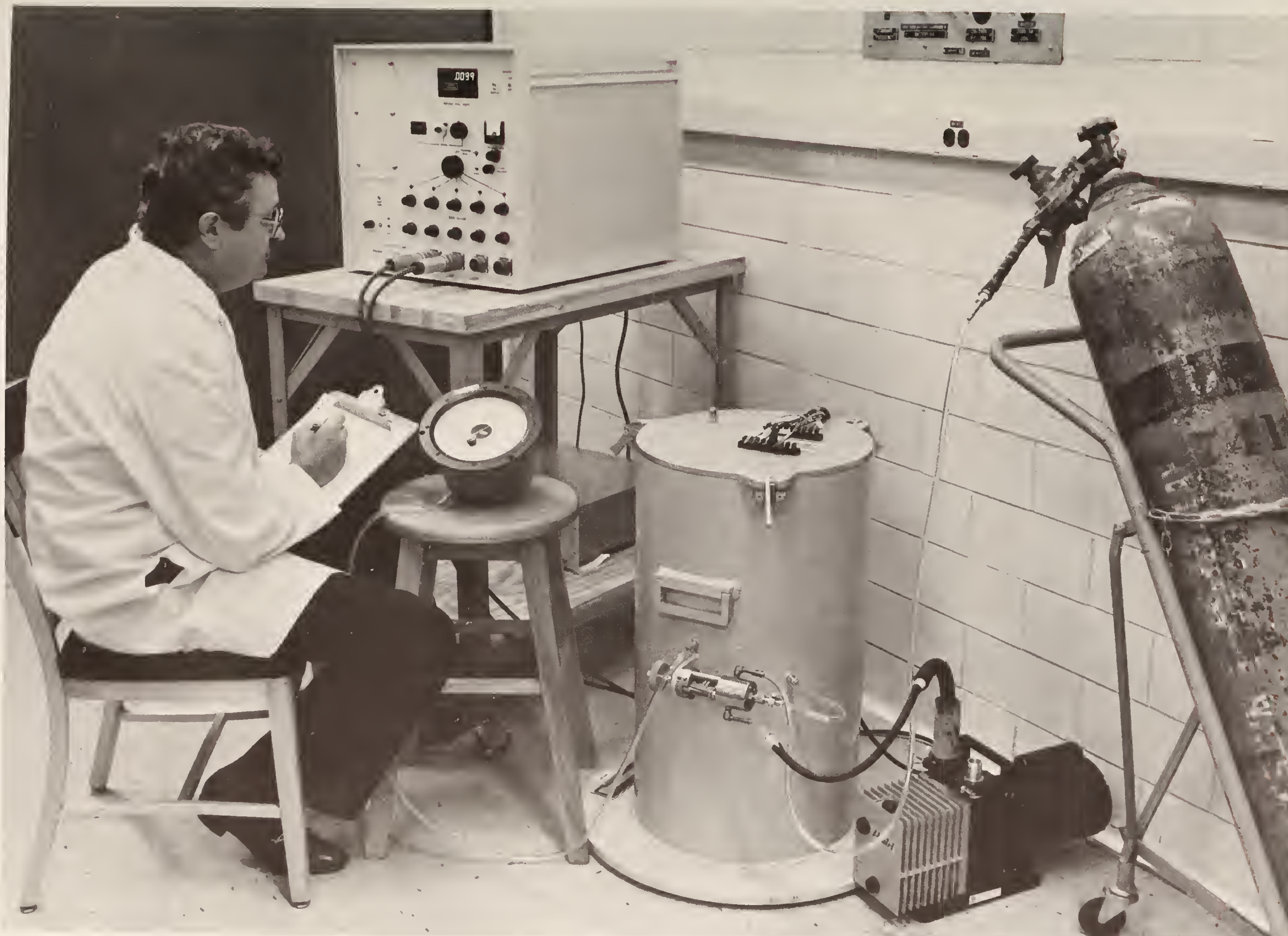

Figure 9. Pressure sensitivity test system. The instruments are identified in the text.

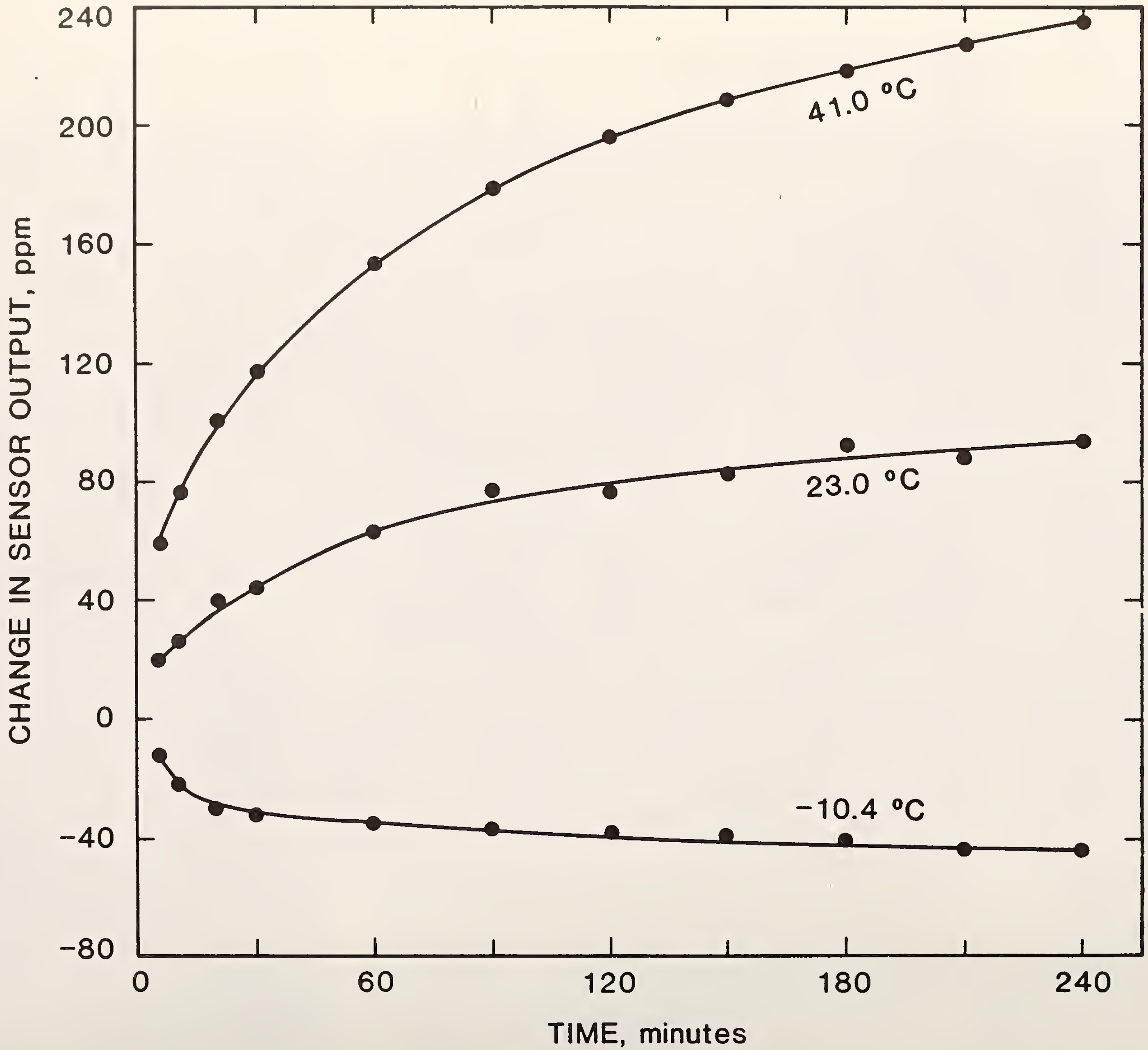

Figure 10. Creep response of a 50-klbf (222-kN) strain gage force sensor loaded in compression at three different temperatures.

assembly, gage location, etc. that may be significant. The eccentric load sensitivity of universal (tension and compression) force sensors that are loaded in compression can be measured in the NBS deadweight machines by the use of special eccentric loading fixtures. The test determines this sensitivity, as a percentage of full scale output, per millimeter of load eccentricity. Figure 11 shows the results of a test of a 5-klbf (22-kN) capacity sensor having two different force sensing electrical bridges. In this test a vertical compressive load was applied at a 2-mm eccentricity and the eccentric loading fixture was rotated in 60-deg. angular steps. These results indicate that one bridge has about four times the eccentric load sensitivity of the other bridge and that the axes of maximum sensitivity differ by about 90 deg. In some cases the eccentric load sensitivity test can also be used to calibrate the transverse bending moment bridges of multi-axis force-moment sensors. Reference 10 describes the test in greater detail and gives the results of tests on five different sensors.

4.5 Pattern Evaluation Tests

The International Organization of Legal Metrology (OIML) has adopted a standard (Ref. 11) for the pattern evaluation testing of load cells (force sensors) used in electronic weighing systems. The (U.S.) National Conference of Weights and Measures has revised its standard (Ref. 12) to be in harmony with the OIML requirements. The OIML standard prescribes deadweight loading tests for linearity, repeatability, hysteresis, and creep over the temperature range −10 to 40 °C and a test for pressure sensitivity at room temperature. The loading tests require the application of a sequence of five or more deadweight load increments following the application of an initial minimum deadweight (tare) load. These loading tests can be performed, in compression, in the 112-klbf (498-kN) deadweight machine. However, because of the operational characteristic of this machine (Sec. 2.1) it is suitable for performing these tests only on load cells of capacity between about 26 klbf (116 kN) and 109 klbf (485 kN). Plans are being developed to extend the NBS test capability to cover a greater range of load capacities, in tension as well as compression.

5. CONCLUSION

Force calibration and force measurement services available at NBS have been described. Detailed procedures for obtaining these services are given in Ref. 13. The fee schedule for deadweight force calibration is published in Ref. 14. The fees for comparison force calibrations and for force sensor characterization tests are computed for each job.

Inquires about the available services, either by mail or telephone, are welcomed. Personal visits to the laboratory can also be arranged, by scheduling in advance. Prior consultation, either by mail, telephone, or visit, are particularly encouraged for first-time users of these services.

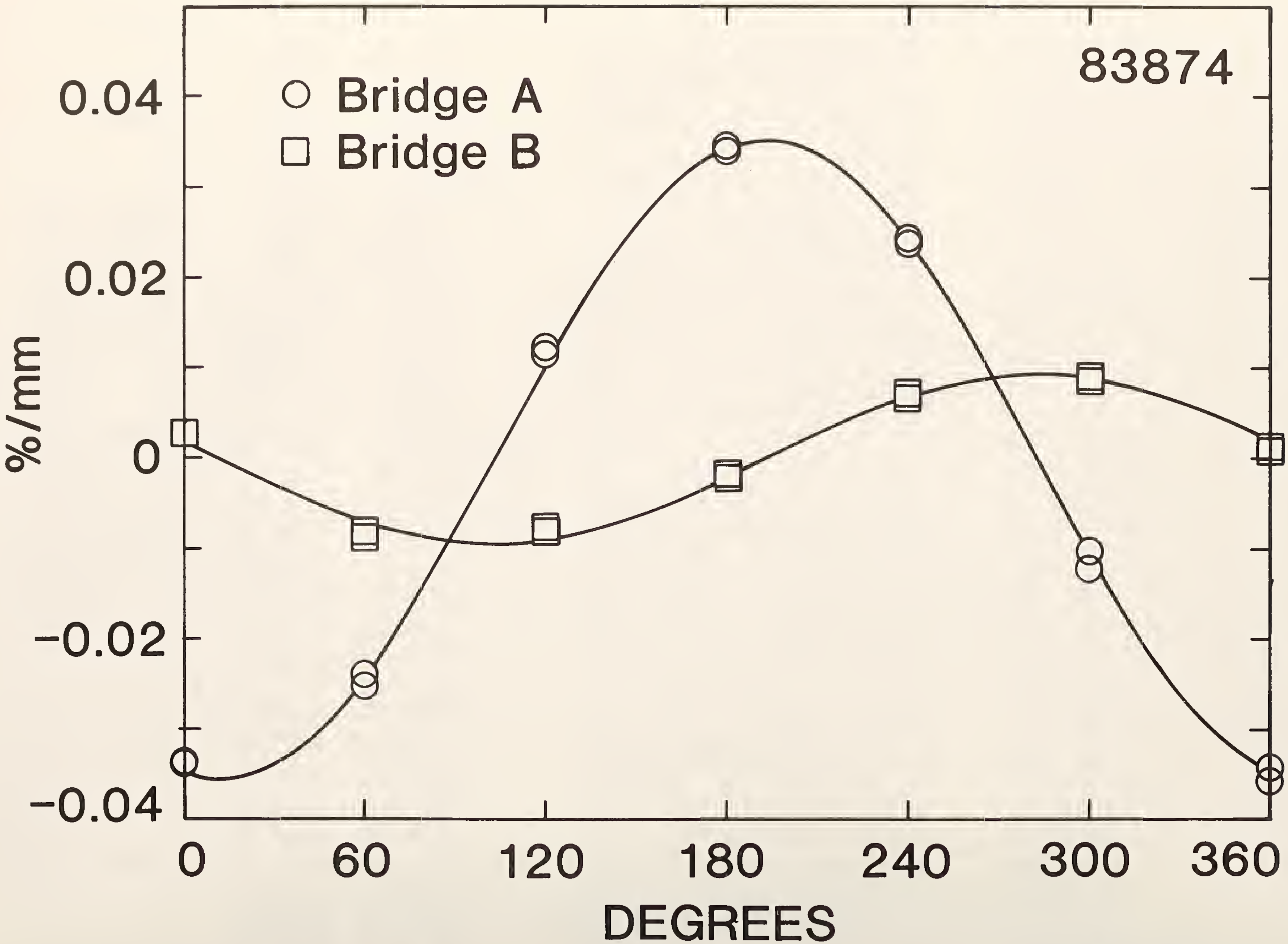

Figure 11. Eccentric load sensitivity of the two measurement bridges of a 5-klbf (22-kN) strain gage force sensor. Deviation from full scale output, in percent of full scale output per millimeter of load eccentricity, is plotted versus angular orientation of the eccentric loading fixture.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Force calibration and force measurement services available at the National Bureau of Standards (NBS) are described. Direct deadweight calibration of force sensors are performed in both compression and tension up to one million lbf (4.4 MN). Comparison calibrations relative to force sensor transfer standards are performed in compression up to 12 million lbf (53 MN). In addition to force calibrations, the following tests are performed to further characterize force sensors: temperature sensitivity, pressure sensitivity, creep, and eccentric load sensitivity. Tests prescribed by the International Organization of Legal Metrology (OIML) for the classification of load cells used in electronic weighing systems are performed in compression for load capacities between about 26 klbf (116 kN) and 109 klbf (485 kN). The capabilities and limitations of the calibration and test facilities are briefly described.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Comparison force calibration; creep; deadweight force calibration; eccentric load sensitivity; force calibration; force measurement; force sensor; NBS force calibration; OIML load cell test; pressure sensitivity; temperature sensitivity.

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