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Studies of Calibration Procedures for Load Cells and Proving Rings as Weighing Devices

Gordon B. Anderson

Physical Measurements Section
Calibration Laboratory
White Sands Missile Range, New Mexico 88070

and

Robert C. Raybold

Institute for Basic Standards
National Bureau of Standards
Washington, D.C. 20234

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STUDIES OF CALIBRATION PROCEDURES FOR LOAD CELLS AND PROVING RINGS AS WEIGHING DEVICES

BY

GORDON B. ANDERSON
Physical Measurements Section
Calibration Laboratory
White Sands Missile Range, New Mexico 88070

AND

ROBERT C. RAYBOLD
Institute for Basic Standards
National Bureau of Standards
Washington, D. C. 20234

ABSTRACT

Elastic devices such as load cells and proving rings, when used with comparison measurement techniques, yield uncertainties orders of magnitude smaller than generally accepted. Their use, in direct reading application, is affected by numerous characteristics of materials, as well as the techniques of application and interpretation of data. This paper is intended to present progress made in the evaluation of calibration techniques, to the end that such transducers may be used with a predictable uncertainty in direct reading applications. Attempts are being made to formulate calibration procedures which are consistent with application procedures. The confusion existing in the derivation and application of practical force units is considered sufficient justification for a brief discussion of forces derived from mass standards and gravitational acceleration.

Key words: Calibration, force, weighing, load cells, proving rings, transducers, uncertainty.

INTRODUCTION

A basic precept in metrology is to strive for comparison or difference measurement. By these techniques, maximum integrity is maintained by the use of relatively simple measurement techniques. These techniques have withstood the test of time, and when applied to elastic weighing devices, the results have been illuminating and gratifying.

Load cells, as a general class of instruments, suffer from numerous and serious limitations, unless the measurement is designed so as to minimize their limitations and maximize such advantages as a simplicity of construction, installation and repeatability of electrical and mechanical response characteristics.

The precision capabilities of quality load cells, when used for comparison measurements, have been adequately established. For several years the White Sands Missile Range (WSMR) Calibration Laboratory has given field support to various projects in the determination of missile weight and center of gravity. Project requirements for mass determinations with uncertainties (systematic error plus three times the standard deviation of random errors) on the order of 0.05% were met satisfactorily under field conditions by the use of substitution techniques. The WSMR Calibration Laboratory in its early days, was part of an instrumentation group, and the use of these techniques was a natural extension of the electrical measurement techniques in daily use. As early as 1958, these techniques were being applied to the design of fixtures for center of gravity determinations. [1]*. Data presented at the 1964 Large Mass Symposium, held at the National Bureau of Standards (NBS), indicated that standard deviations on the order of 5 ppm are practically obtainable with "off-the-shelf" hardware. Subsequently, measurements performed at various other installations indicate that such standard deviations are practically obtainable under seemingly impossible environmental conditions, when due care is given to the measurement process.

As a result of knowledge and experience gained from these tests, the WSMR Calibration Laboratory specification for the "second generation" mass comparator was prepared. The availability of large masses of known accuracy is rather limited, and NBS was requested to perform the acceptance tests. The results substantiate the ability of load cells to perform as comparators with standard deviations approaching 1 ppm.

Serious reflection on measurement data obtained immediately raised the age old question, "How good is this device when used as a direct reading instrument?". Current production systems claimed "direct reading accuracies" approaching 0.02%. When given serious thought, such performance could impugn the capabilities of force standards in current use. [2]. Thus, to make use of the direct reading capabilities of current production load cells, it was thought that a calibration procedure should be developed which would take all possible advantage of design and mimimize the effects generally accepted as limitations. It was originally planned to present in one paper a summary of calibration data, the result of evaluation of characteristics such as loading history, loading rate, creep, hysteresis, temperature coefficient, temperature gradient, linearity, repeatability, sensitivity, effect of tare, etc. It soon became apparent that this was a chore of more than considerable magnitude. The decision was made, as time and material resources permit, to make use of routine calibration data, to accumulate calibration history, to establish long term stability by study

*The numbers in brackets refer to similarly-numbered references at the end of this paper.

of accumulated data, to verify the validity of the electrical measurements, to establish uniform methods for treatment of the data, and to study temperature and pressure effects.

Such an effort seems to be a hopeless task for even the most simple mechanism, on close examination, becomes a complexity. A load cell, basically, is a simple mechanism, but when one attempts to explain its behavior in detail it is immediately obvious that many processes are involved, some of which are at best little understood, more usually misunderstood. To identify, control and measure each of these would require a tremendously large and complex research and development effort. Even if such efforts were fruitful, there is no assurance that knowledge gained would increase our ability to measure with these devices. No matter how much valid theory and associated measure are incorporated into the design, the problem always remains of determining the constant of the instrument. This is the essence of the calibration process.

Thus, we feel that a study of the theory of design of transducers would be of doubtful value. This is better left to the purists. We need to develop better measurement techniques and to determine how this device as a system responds to a given set of conditions, so that a meaningful calibration is produced. The fact that man, after more than 100 years study, has been unable to explain the behavior of common engineering materials is not sufficient justification to ignore their capabilities for practical application. This is not to say that the purist is without a rightful place in instrument technology, but only to say that we should not subsititue his hoped for creation of an idealized instrument for our efforts to improve utilization of the tools he has already provided us.

To study force transducers for direct reading application, four major requirements were considered.

a. A precision loading machine with considerable versatility, to enable us to study the effects of various loading schedules, loading rates, tare loads, etc.

b. Flexural isolation, to minimize the effects of non-axial loading, and to provide the ability to "make fixed" or make repeatable any misalignment present.

c. Transducer instrumentation with sufficient stability, resolution and linearity to study transducer response without constantly making "instrument" corrections.

d. Uniformity in the treatment of data.

Industry has developed, and we have acquired equipment to satisfy the requirements of a, b, and c. Data reduction procedures are formulated and being updated constantly.

The dead weight loading machines are designed so that load increments of less than 0.5% of capacity are available. Weights may be applied in any order, and at a number of different controlled loading rates. The loading may proceed from one mode to the other (tension or compression) without disturbing the alignment of the load cell. Tare weight in compression is essentially zero, while the tare weight in tension is kept below 0.3% at 1000 pounds. By means of the mass comparator, the machine is verified in its normal operating configuration. Standard weights of known differences are incorporated into the machine, so that all forces generated are directly compared, removing any uncertainty due to position in the machine.

All calibrations are performed using flexural insolation so that, as far as is practical, no transverse loading exists. The instrumentation used is of ratio, or millivolt per volt (mV/V) type. The standard deviation of these indicators (available competitively) is on the order of 10 ppm.

The verification of the read-outs themselves has pointed out the need for better electrical calibration techniques. One result has been the procurement of a network on which any selected ratio is verifiable within an uncertainty (three times standard deviation for random error plus systematic error) of 50 ppm and stability is such that the ratio remains constant within 20 ppm for any one year period. Investigation is continuing to improve our ability to precisely establish ratios, and such a network appears to have good application in the transfer of ratios among laboratories. Another side issue evolving from these tests is the use of mV/V indicators and the mass comparator for intercomparing standard resistors. First efforts appear to have promise, and standard deviation of a few parts in 10^7 seem practical.

GRAVITY AND FORCE

Gravitation is generally described as being the mutual action between masses, by virtue of which every mass tends towards every other mass with a force (F) varying directly as the product of the two masses ($\underline{m}_1 \underline{m}_2$), and inversely as the square of the distance ($\underline{d}$) between their centers of mass. That is:

$$F \propto \frac{\underline{m}_1 \underline{m}_2}{\underline{d}^2}$$

$$F = \frac{k\underline{m}_1 \underline{m}_2}{\underline{d}^2}$$

where $\underline{k}$ is a constant of proportionality. For a given pair of masses, this is usually written as:

$$F = \frac{G\underline{m}_1 \underline{m}_2}{\underline{d}^2}$$

where G is the Universal Gravitation Constant. This is an observable relationship and the value of G can be determined experimentally. The latest determination, by Heyl [3, 4], yields the value $6.670 \times 10^{-11} \text{Nm}^2/\text{kg}^2$. [1] The extremely small magnitude of G indicates that small forces exist between bodies on the earth's surface. However, a fairly large force exists between the earth and a body near the earth's surface, due to the magnitude of the earth's mass ($\underline{m}_e$). In describing this force, equation 3 is usually written as:

$$F = \frac{G\underline{m}_e \underline{m}}{R_e^2}$$

where R_e is the radius of the earth.

This force produces an acceleration E (due to gravity) that is

$$E = \frac{F}{\underline{m}} = \frac{G\underline{m}_e}{R_e^2}$$

In the International System of Units (SI), this acceleration has units of

$$E = \frac{(\text{Nm}^2\text{kg}^{-2})\,(\text{kg})}{\text{m}^2} = \text{m/s}^2$$

1. Newtons (N), meter (m), kilogram (kg)

where s is seconds. Therefore, to describe the force of attraction between the earth and a mass subjected to the earth's gravitational field, equation 4 may be written as:

$$F = \underline{k}\ (\underline{m}E)$$

Based on the assumption that the earth is a non-rotating sphere of uniform density, substitution of numerical values for $\underline{m}_e$, G and R_e will yield a value for the acceleration of

$$E \approx \frac{5.975 \times 10^{24}\text{kg} \times 6.670 \times 10^{-11}\text{Nm}^2\text{kg}^{-2}}{(6.371 \times 10^6\text{m})^2}$$

$$E \approx 9.819 \text{ N/kg}$$

For gross calculation, such a procedure is sufficient. However, this value differs considerably from the value usually associated with local gravity ($\underline{g}$) due to the fact that the earth is not symetrical, homogeneous, or non-rotating. The effect of the centrifugal force due to the earth's rotation is approximately 0.034 m/s^2 (sea level, zero latitude) and due to the difference in polar and equatorial radii is approximately m/s^2. Non-spherical distribution of the earth's mass accounts for approximately half of this amount so that the total variation in $\underline{g}$ is approximately 0.05 m/s^2. This method of computing local acceleration due to gravity should not be used in precise force measurements.

Values of $\underline{g}$ calculated by the above procedure differ from the values obtained by the International Gravity Formula (HEISKANEN, 1938). Corrections normally applied to the latter are:

a. Free air correction (inverse square law)

b. Bouguer Correction (to free air correction)

c. Topographic Correction, (non-uniformity of terrain)

Observed values of $\underline{g}$ differ from both of the above, and additionally are usually corrected to sea level values by applying a and b above. Generally, there are differences between theoretical values obtained by the International Gravity Formula and those obtained from reduced observations. These differences are called free air anomalies and are usually charted as shown in Fig. 1. For practical applications to physical problems, the user should know which value he is using (theoretical or observed), and what corrections are pertinent to his use.

By applying all known corrections and using refinements to Kater's pendulum, the 1906 measurement at Potsdam yielded the value of 9.81274 m/s^2 for the acceleration due to gravity at that station. By observing changes in period, pendulums were used to transfer this value to other stations throughout the world. A base station for the United States was established in Washington, D. C. in 1891 by the United States Coast and Geodetic Survey which serves as the base for all U. S. Pendulum stations.

FORCE UNITS

When dealing with bodies of finite mass, having velocities which are small as compared to the velocity of light, the concept of force implies an agent or a property capable of producing a change in momentum. When force is thus defined, then force is a derived quantity and is the product of a mass and acceleration (a). The product (ma) is taken as a measure of the force and when we write $F = k\,(ma)$, k is an arbitrary constant which defines the size of the particular force unit used, different choices of k giving different sizes of force units. A simple choice would be $k = 1$, so that unit acceleration times unit mass produces unit force.

In tne International System of Units, the name of the force unit is the newton. One newton will accelerate a one kilogram mass one foot per second per second.

In the English System of Units, the name of the force unit is the poundal (pdl). One poundal will accelerate a one pound mass one foot per second per second.

The newton and the poundal are usually referred to as "absolute" force units. Unlike the kilogram force and the pound force (as generally used, where one uses force equals mass) their effect on an object is independent of position in the universe. Absolute force units always have the physical dimensions of (Mass x Length)/Time^2 symbolically $F = MLT^{-2}$.

The practical engineering system of units, for very practical reasons, equates force and mass, and force is reported in mass units. For structural engineering work this is a convenience. Although dimensionally unsatisfactory, there is no serious error because a design factor ranging from two to ten is immediately applied as a safety factor. In this system of units, force is taken to be numerically equal to mass ($F = m$), the implication being that a force of one pound will accelerate a one pound mass g ft/s^2 (where g is local gravity). This is a convenient system of units because weight is obtained directly in mass units, that is, x force units will accelerate y mass units x/y acceleration units. However, when the unit of force is the pound and the unit of mass is the pound, k cannot be equal to 1. If a force is to accelerate a one pound mass g ft/s^2, then it is obvious that the units are numerically in the ratio:

$$\frac{\text{poundal}}{\text{pound (force)}} \qquad \frac{1}{g}$$

or, 1 pound (force) = g poundals. The pound force is g times larger than the poundal, and this requires the product (ma) to be multiplied by the factor $1/g$. (Some texts introduce a mass unit, the slug, which is numerically g pounds mass. The results, however, are the same.)

As our technology advanced, the need for the precise comparison of force measurements increased. The variation in the observed value of g over tne earth's surface created confusion as there was no common reference of acceleration. In 1901 the International Conference of Weights and Measures defined the standard value of g as being 9.80665 m/s^2 approximately 32.1739 ft/s^2. (The 1958 definition of the inch makes this value approximately 32.17404 ft/s^2). Also in the past years, since engineering applications of force measurements did not require that consideration be given to variations in tne acceleration due to gravity, buoyant forces were of no consequence. However in aero-space applications the relationship of force and mass becomes critical and demands more exacting measurements; so to more precisely describe tne relations among force, mass and acceleration, Newton's Second Law for a static case is written as

$$F = k\,(m\ \rho v)\,a \qquad (1)$$

where

F is force

$\underline{m}$ is mass

$\rho\underline{v}$ is a correction for buoyancy

$\underline{a}$ is acceleration

$\underline{k}$ is a dimensionless constant, its numerical value being dependent on the choice of units for F, $\underline{m}$, and $\underline{a}$.

In the International System of Units (SI), the unit of force is the newton and equation (1) is written as:

$$F = \underline{k}\ (\underline{m} - \rho\underline{v})\underline{a} \quad (2)$$

where $\underline{m}$ is mass in kilograms; ρ is the density of the air in kilograms per cubic meter; $\underline{v}$ is the volume of the mass in cubic meters; $\underline{a}$ is the acceleration to which the mass is subjected, in meters per second per second; and $\underline{k} = 1$.

In the British Engineering System of Units, the unit of force is the pound force (lbf) and equation 1 is written as:

$$F = \underline{k}\ (\underline{m} - \rho\underline{v})\underline{a} \quad (3)$$

where $\underline{m}$ is mass in pounds (lb); ρ is the density of air in pounds per cubic foot; $\underline{v}$ is the volume of the mass standard in cubic feet; $\underline{a}$ is the acceleration to which the mass is subjected, in feet per second per second, and $\underline{k} = 1/32.17404$.

The acceleration in the above equation when due to the earth's gravitational field is usually determined by comparison measurements, and the reported value is based on the Potsdam system. It is generally agreed that the Potsdam value of 9.81274 m/s^2 is high by about 0.00013 m/s^2. [5]

The policy of the NBS is to use the International System of Units "except when their use would obviously impair communications or reduce the usefulness of a report to the primary recipients". The choice of units, as discussed above, should be left to each laboratory as its particular needs require; however, for the purpose of intercomparisons among laboratories, the use of the International Units is recommended.

To clarify the concepts discussed above, it may be well to discuss in detail a typical calibration of an elastic device, such as a high quality spring scale. For convenience, suppose a mass of 1 kg whose volume is computed to be 120 cm^3, is supported in air of density $1.0 \times 10^{-3} g/cm^3$ and the acceleration due to gravity is taken as 9.79108 m/s^2.

The derived force would be, from equation (2):

$$\begin{aligned} F &= \underline{k}\ (\underline{m}\ \rho\underline{v})\underline{a} \\ &\approx 1(1.000000 - 1.0 \times 10^{-6} \times 120)(9.79108) \\ &\approx (0.99988)(9.79108)\ m/s^2 \\ &\approx 9.78991 \text{ newtons} \end{aligned}$$

The pointer should now be made to coincide with 9.78991 on the scale, and the adjusting screw sealed. The scale will now correctly read force, irrespective of location, as long as the constant of the instrument does not change.

Suppose that the 1 kg mass were replaced by an object of unknown mass and that the scale now indicates 9.63025 N, or

$$9.63025 = (\underline{ma}) - (\rho \underline{v}\ \underline{a})$$

The indicated force is seen to be the sum of two forces, one due to ($\underline{ma}$) acting downward and one due to ($\rho \underline{v}\ \underline{a}$) acting upward.

Now, the user must know what measurement he is trying to make. The instrument has properly indicated the net downward force. This is the usual commercial connotation of weighing. If the user wishes to identify the mass of the unknown object, whose volume is computed to be 240 cm^3, equation (2) can be written as:

$$\underline{ma} = F + (\rho \underline{v})\ \underline{a}$$

$$\underline{ma} \approx 9.63025 + (\rho \underline{v})\ \underline{a}$$

or

$$\underline{m} \approx \frac{9.63025}{9.79108}\ kg + 240 \times 10^{-6}$$

$$\approx (0.983574 + 0.000240) = .983814\ kg$$

Now suppose that this same object and the scale were transferred to a location where the air density is 1.15×10^{-3} g/cm^3 and the acceleration due to gravity is reckoned at 9.80320 m/s^2. As before, one would write:

$$F = \underline{k}\ (\underline{m} - \rho \underline{V})\ \underline{a}$$

$$\approx (0.983814 - 1.15 \times 10^{-6} \times 240)(9.80320)$$

$$\approx 9.641820 \text{ newtons}$$

It is clearly seen that this mass of 0.983814 kg produces a different force when subjected to a different acceleration.

Again, if the mass were not known, since the resulting force has been measured, the mass is computed as before:

$$F = \underline{k}(\underline{m} - \rho \underline{v})\ \underline{a}$$

or

$$9.641820 = \underline{ma} - \rho \underline{v}\ \underline{a}$$

$$\underline{ma} = 9.641820 + 0.000276\underline{a}$$

$$m = \frac{9.641820}{9.80320} + 0.000276$$

$$\approx 0.983538 + 0.000276$$

$$\approx 0.983814\ kg$$

Finally, suppose that this force indicator were now transported to a location where the air density is 1.15×10^{-3} g/cm^3, and the acceleration due to gravity is 9.80320 m/s^2, an object of unknown mass, whose volume is 60 cm^3, is supported as in the previous example and causes the scale to indicate 8.32720 newtons. Then as before:

$$F = \underline{k}\ (\underline{m} - \rho \underline{v})\ \underline{a}$$

or

$$8.32720 \approx (\underline{m}\ \rho \underline{V})\ \underline{a}$$

The situation is identical to the one in the previous example; this object weighs 8.32720 newtons. The mass of the unknown is computed as before; that is

$$\underline{m} = \frac{8.32720}{9.80320} + 1.15 \times 60 \times 10^{-6}$$

$$\approx 0.849436 + 0.000069 = 0.849506 \text{ kg}$$

The past practice of the National Bureau of Standards has been to issue calibration reports relating instrument readings to applied mass, the derived force being the product of mass standards and the acceleration due to gravity at the Industrial Building at NBS Washington, D. C.

The results were not stated as pounds force, and it was tacitly assumed that the user was aware of this fact. As an example, when a 10,000 pound mass was applied as load, some users concluded that the derived force was 10,000 pounds, when actually the derived force was approximately 9993 pounds force. Failure to properly account for this difference admitted a systematic error of approximately 0.07%[2] into all measurements so referenced.

Systems of units and units of measure are a convenience to the user, and we find no fault with any system when properly used. Due to custom and convenience, the pound force remains as the practical unit of force. The above procedures are applicable, however, regardless of the unit of measure and if these procedures are used, we will have a common basis upon which to discuss basic concepts, and the calibration of force measuring instruments.

The procedure adopted by the WSMR Calibration Laboratory is to report the transducer's indicated output in dial divisions or mV/V per pound of applied force, the force derived being $\underline{k}\ (\underline{m} - \rho \underline{v})\underline{a}$. This is reported in SI and English units, as per equation (3).

CALIBRATION PHILOSOPHY

There are numerous instances of similarity of behavior among distinctly different classes of instruments. The similarity between the load cell and the D'Arsonval Movement, dating from 1882, is an example. A list of all factors affecting performance would be lengthy and also of doubtful value to the calibration. The effect of many of these factors can be minimized by good design, but they are not calibrated directly. They are indicators [6] of performance, and the calibration of the instrument

2. 0.06% gravity correction plus 0.01% buoyancy correction

will include their effect, under the conditions existing at that time. By observance of good principle in design, craftmanship in construction, and care in use, such an instrument may be made direct reading to perhaps 0.05% in static applications, and perhaps 2% in dynamic applications.[3] To obtain this uncertainty, it is not necessary (or possible) to identify and calibrate separately each of the indicants. What is required is a calibration which will reveal the operation of the instrument under a particular set of conditions. To take maximum advantage of the capabilities of the instrument, the user should be assured that the calibration process is consistent with the requirements of his particular application. As an example, the usual D'Arsonval movement responds to the average value of a rectified sine wave. Most users want an indication of the root mean squared value, so the instrument maker scribes the scale accordingly. Now the user need not worry as to why the meter will properly indicate the root mean squared value, although an understanding of why may save some embarrassment, but it is not required for the instrument to operate properly. As the waveform departs from a sinusoid, the indication will also depart from the calibration, and unless a proper instrument constant is determined, the user will again be subject to embarrassment. However, the instrument can be calibrated for this condition of use, but not until the user communicates with the calibrator.

The same situation exists in the application and calibration of a load cell. The user must have knowledge of its behavior under a particular set of conditions. General performance criteria may be established for load cells as a class of instruments and as a means of standardization. This, of course, is an economic consideration and one of ever increasing importance. The aero-space industry is of such diversity that it is altogether proper that the formulation and promulgation of standardized design and performance criteria be the responsibility of an organization such as the Instrument Society of America (ISA). Recommended Practice Guide for Specifications and Tests for Strain Gage Force Transducers for Aero-Space Testing (RP 37.8) of sub-committee 8A of ISA is representative of this, and the calibration data contained in the present report is submitted in the light of specific measurement requirements, rather than attempting to cover a multitude of requirements. It is submitted with the hope that it may augment the RP 37.8 in the Formulation of Performance Requirements (Sec 4), Acceptance Tests and Calibrations (Sec 5), and Qualification Tests (Sec 6).

As has been previously stated, the effects of hysteresis and metal creep are generally believed to be the major factors controlling load cell performance. This may well be true, but the usual measurement process would be hard put to separate these effects, and could probably not separate the two together from the effects of creep (or relaxation) in the bond, creep in the gage, temperature compensation of the gage, modulus compensation of the column, and various thermal, mechanical, electrical, or other effects which lack identification. Fortunately, it is not required that we have knowledge of other than the magnitude of the combined effects, under a given set of conditions, to produce a meaningful calibration.

Figure 2 represents data recently obtained with a load cell which has been in service for over twelve years. At the time of purchase, typical specifications were for linearity and hysteresis not to exceed 0.1% of full scale. No indication of repeatability or long term stability was given by the seller and usually there was no such requirement stated by the user.

3. It is interesting to note the superior performance of the same instrument when used in a comparison measurement.

Probably the most valuable calibration data obtainable would be similar to that shown in Figure 2. The graph shows the loading cycle and the output of the transducer.

After repeated application of the load prior to the recording of the data, the load cell appears to take a set somewhat similar to the behavior of a single crystal that is stressed beyond the proportional limit. The fact that the change in output as a function of time may be either positive or negative is not surprising. The change, as pointed out previously, does not stem from any one known cause, but is further evidence of a composite of complexities. The concept of a negative creep in metals is contrary to observed fact. Possible causes are overshoot in the load, overshoot in the instrumentation, thermal effects in gage and modulus compensation, or relaxation in the bond.

These data were obtained with a mV recorder at the galvanometer terminals of a mV/V indicator. The load cell was of 2 mV/V output and 6000 lbf capacity. The recorder sensitivity was adjusted to be 1 inch deflection for 3 oz at 6000 lbf or approximately 1/30,000.

Data displayed in this manner readily give an indication of the number of cycles, under a specified set of conditions, required to obtain a given precision. Also, such a display gives an indication of the time required for stability of output at zero and at load, and time required for the span to stabilize with a particular loading history. [7].

It must be emphasized that such data does not necessarily represent any particular group or class of load cells, but is representative of one load cell, with some particular history, and then only under a particular set of conditions of excitation voltage, loading rate, temperature, etc. This is believed to be representative of what can be determined for any load cell, if one is willing to take the necessary care in calibration. What remains to be done is for the user to design his application procedures in such a manner that a meaningful calibration <u>can</u> be accomplished.

PRELIMINARY CALIBRATION STUDIES

Since January 1965, WSMR Calibration Laboratory has selected data from 75 calibrations of 21 transducers, 17 of which were calibrated both in tension and compression. Each load cell was calibrated at 11 load points, some with 10 and others with 5 observations at a given load. (An observation is defined as a complete load cycle from zero to load back to zero load). From the analysis of these data the following conclusions are drawn:

A. Exercise of the load cell (on the order of 10 times) at 110% capacity, will establish a stable loop and indicate performance hysteresis.

B. The first two observations generally show a significantly large variation and are not included in the computations of the calibration report.

C. After the deletion of the first two observations, four or more observations are needed to indicate the variability of the measurement.

This preliminary study also included a 10,000 lbf proving ring and an electronic readout that was calibrated in compression by NBS on October 29, 1959 and subsequently three times by WSMR Calibration Laboratory. The calibration data, after adjustment of NBS data for the 0.07% systematic error, are shown in Table 1. The largest change in calibration was approximately 0.06% of full scale or 6 lbf. An interesting fact is that the uncertainty of a calibration point based on the random errors of a single calibration was about 0.012% of full scale or 1.2 lbf. The tabular data shown in Table 1 are the average of repeated observations in dial divisions adjusted both for instrument (zero) drift and temperature corrections as given by the manufacturer.

REPORT OF CALIBRATION

After the loading cycle is established, the transducer is flexed by 10 times to 110% of range. Information is recorded for 6 observations at a load point in the following order:

a. The instrument reading at zero load (indicator zero is offset upscale to be able to observe zero drift).

b. The instrument reading at load.

c. Ambient temperature and pressure.

d. The instrument reading at zero load.

Corrected dial divisions are computed from the following equation:

$$Y_{ij} = X_{ij} - \frac{Z_i + Z_{i+1}}{2}$$

where

Y_{ij} is corrected loaded reading

X_{ij} is observed loaded reading

Z_i is zero reading before load

Z_{i+1} is zero reading after load

i is the observation number

j is the load point number

The first page of the report of calibration, as shown in Table 2, is the general calibration information, such as manufacturers serial number, bridge impedance, bridge voltage, time cycle, loading rate, the corrected dial divisions and temperature during the observation.

In computing the applied pounds force (lbf) the following equations and conditions are used at WSMR Calibration laboratory:

$$F_j = \underline{k}(\underline{m}_j - \rho\underline{v}_j)\underline{a}$$

where

F_j is pounds force at load j

$\underline{k}$ is 1/32.17404

$\underline{m}_j$ is mass of load j in pounds

ρ is average density at WSMR 0.06 lb/ft^3

$\underline{v}_j$ is volume of $\underline{m}_j$ [$\underline{m}_j$ times 0.002 ft^3/lb]

and $\underline{a}$ is acceleration due to gravity at WSMR Calibration Laboratory [32.12296 ft/s^2].

The data were analyzed by the method of least squares with the following functional form:

$$d_e = \alpha F_e$$

where

d_e is the corrected dial divisions for the e^{th} observation

α is the least squares coefficient

F_e is the force in pounds at a given observation e

where e is a number representing the order in which the data were taken.

The deviations of the least squares fit and the observed data are plotted in Figure 3. This procedure is used to analyze the departure of the transducer's output from linearity.

Tables 3 and 4 are the final report of calibration and explanation of the use of the calibration data. The reported dial divisions are derived from the average of the last four (or more) readings at a given load point. The pooled standard deviation is computed from the deviations about this average.

At the present time the data are not adjusted for temperature or pressure effects on the transducer. It is recognized that corrections for variabilities from these sources may be necessary to correlate results obtained in an environment substantially different from that of the calibration facility.

Plots such as shown in Figure 3 are used to find patterns in the deviations and may also be used to determine functional relationships which better describe the output of the load cell being calibrated. Preliminary studies indicate that a second degree equation of the following form will generally describe the output of a transducer within the precision of the measurement process.

$$d_e = \alpha F_e + \beta F_e^2$$

where α and β are the coefficients determined by least squares. An alternate method of fitting the data would be to use a straight line plus a function of the deviations from a straight line.

Such computations are tedious when done by hand methods. But these procedures are straightforward by machine methods. All computations in this study were done using Omnitab [8].

Data reduction procedures are being constantly updated, and a general purpose computer program is available to those interested.

THE FUTURE

Progress made in the development of a calibration procedure for load cells which are to be used in missile weighing applications has been reported herein. Much remains to be done, such as:

a. Comparison of loading schedules.

b. Response to various loading rates.

c. Effects of change of mode.

d. Effects of temperature.

e. Effects of temperature differential.

f. Effects of pressure.

g. Prediction of long term stability.

Equipment is now under procurement which will provide controlled changes in temperature and pressure, so that we will obtain temperature and pressure sensitivity data.

For field weighing applications, special jigs have been procured which will allow for flexing of the load cells, the load being controlled by hydraulic means. It is hoped that time permits an evaluation of these jigs in the near future. The advantages of such techniques in aero-space testing are obvious. In this study we have purposely avoided the quasi-dynamic and dynamic applications, not because they are less important, but because of the greater complexity of equipment and techniques required to produce a meaningful calibration.

ACKNOWLEDGMENT

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REFERENCES

1. Donald M. Button, Gilmore Industries, "A Method of Design for a Center of Gravity Determination System". (Unpublished Report)

2. R. J. Carleton, "Precision High Capacity Force Standards", ISA Preprint No. 36, New York, 1960.

3. Paul R. Heyl, "A Redetermination of the Constant of Gravitation", Journal of Research, National Bureau of Standards, Vol. 5, 1930, pp 1243-1290.

4. Paul R. Heyl and Peter Chrzanowski, "A New Determination of the Constant of Gravitation", Journal of Research, National Bureau of Standards, Vol. 29, 1942, pp 1-31.

5. Kenneth I. Daugherty, J. Donald Define, Geophysical Studies Section, Geo-Sciences Branch, Aeronautical Chart and Information Center, "Comparison of Methods for Determining the Earth's Normal External Gravitational Field", presented at the XIII General Assembly of the International Union of Geodesy and Geophysics, Berkeley, California, August 1963.

6. Russell L. Ackoff, "Scientific Method, Optimizing Applied Research Decisions", John Wiley & Sons, Inc., New York, 1962.

7. Hilding E. Almer, "Elastic Devices as Mass Comparators", National Bureau of Standards, (Unpublished).

8. J. Hilsenrath, G. G. Ziegler, C. G. Messina, P. J. Walsh and R. J. Herbold, "OMNITAB", NBS Handbook 101, U. S. Government Printing Office, Washington, D. C.

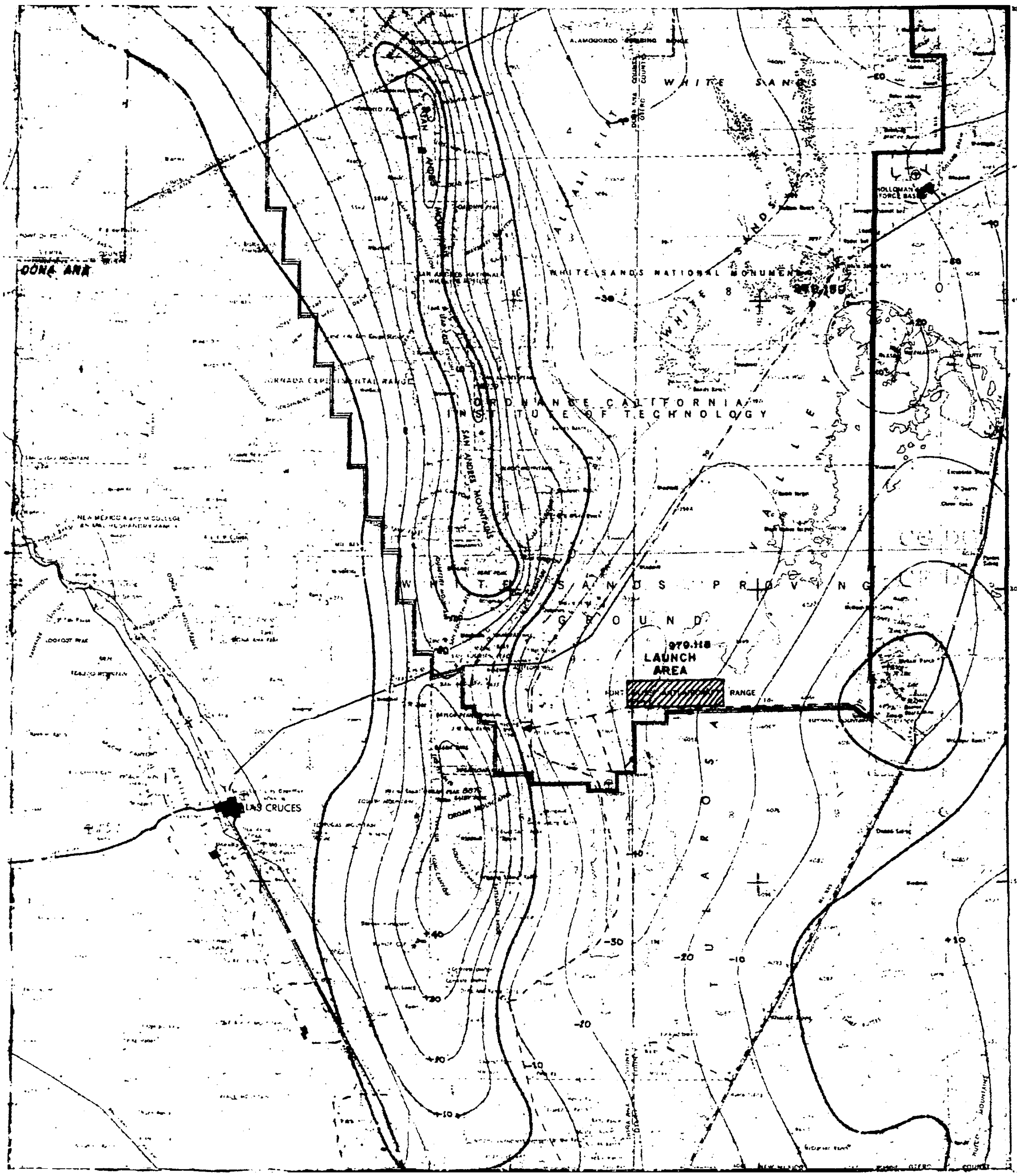

Figure I. Gravity Anomalies, W.S.M.R.

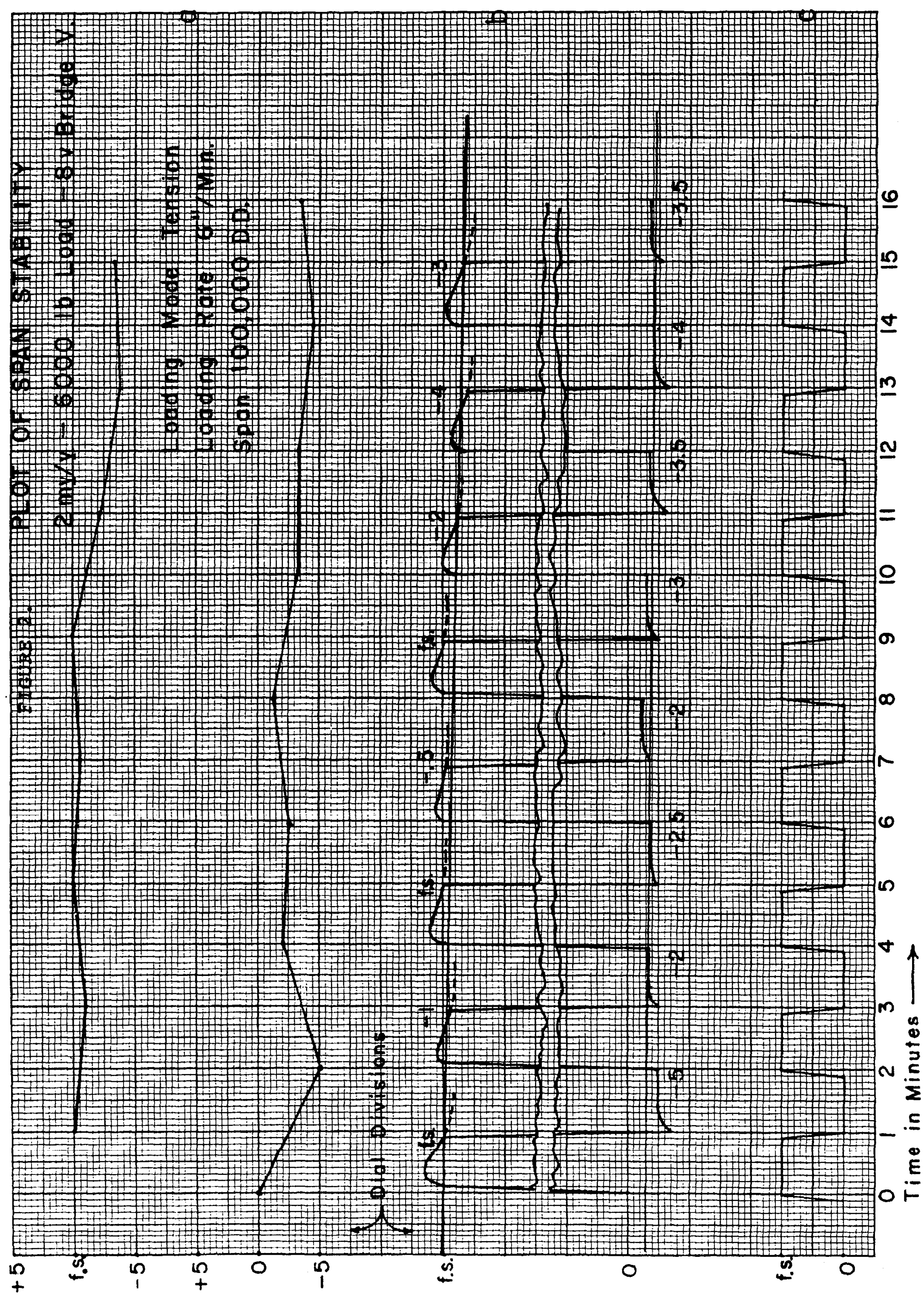

FIGURE 2.
PLOT OF SPAN STABILITY
2 mv/v – 6000 lb Load – 8 v Bridge V.
Loading Mode Tension
Loading Rate 6"/Min.
Span 100,000 D.D.
Dial Divisions
Time in Minutes
a
b
c

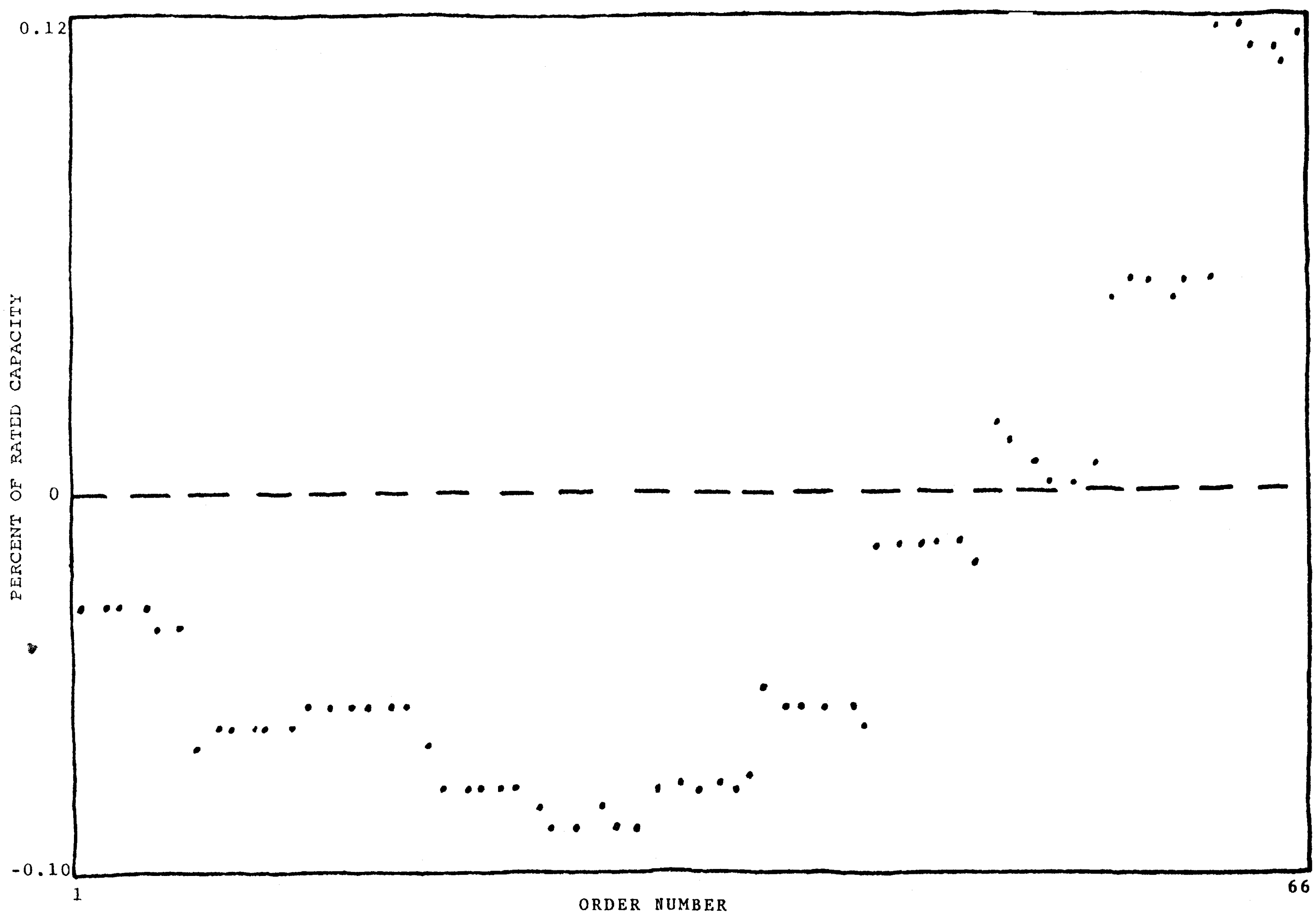

FIGURE 3. DEVIATION FROM $d = \alpha F$

TABLE 1

CALIBRATION OF A PROVING RING IN COMPRESSION

	Dial Divisions			
Load (lbf)	10-29-59	1-21-65	3-15-65	4-27-65
998.29	74.81	74.80	74.91	74.86
1996.58	149.86	149.81	149.90	149.93
2994.88	225.23	225.01	225.30	225.32
3993.17	300.85	300.57	300.90	300.91
4991.46	376.65	376.38	376.72	376.82
5989.75	452.76	452.49	452.87	452.97
6988.05	529.17	529.16	529.17	529.35
7986.34	605.78	605.82	605.88	605.98
8984.63	682.70	682.79	682.90	683.05
9982.92	759.91	759.96	760.17	760.36
10981.22	-	-	837.81	837.89

Nomenclature : Load Cell Mfgr:
S/N: Model: 10K
Mode: Tension Interval:on 2 Min. - off 2 Min.
Tare Weight:33.12 lb Loading Rate:6 in/min.
Bridge Impedence:120 ohms Bridge Voltage: 10V
Calibrated for:WSMR Calibration Laboratory Date 4-26-65

	Load 1		Load 2		Load 3	
Reading	D.D.	Temp.	D.D.	Temp	D.D.	Temp.
1	3002.3	71.2	7009.7	71.8	11031.8	72.3
2	3003.9	71.3	7012.3	71.8	11031.3	72.3
3	3004.0	71.4	7012.5	71.9	11030.9	72.3
4	3003.8	71.4	7011.9	72.0	11031.3	72.4
5	3003.0	71.4	7012.3	72.0	11031.4	72.5
6	3003.0	71.6	7012.2	72.2	11031.8	72.6
	Load 4		Load 5		Load 6	
1	15044.7	72.3	19055.8	73.0	23084.8	73.4
2	15042.1	72.3	19054.5	73.0	23083.6	73.4
3	15042.0	72.3	19054.3	73.1	23084.0	73.4
4	15042.5	72.4	19056.2	73.1	23083.1	73.4
5	15042.4	72.4	19054.6	73.2	23082.3	73.5
6	15042.0	72.6	19055.1	73.2	23082.9	73.5
	Load 7		Load 8		Load 9	
1	27102.7	73.6	31131.7	74.0	35159.3	74.4
2	27102.1	73.7	31132.0	74.0	35158.2	74.4
3	27101.9	73.7	31132.6	74.1	35157.4	74.4
4	27102.1	73.8	31132.1	74.1	35154.6	74.4
5	27102.0	73.8	31131.7	74.2	35155.5	74.4
6	27099.9	73.9	31131.0	74.3	35156.8	74.6
	Load 10		Load 11			
1	39188.0	71.1	43233.4	71.7		
2	39189.3	71.2	43232.7	71.8		
3	39188.4	71.2	43231.5	71.8		
4	39187.0	71.3	43232.1	71.9		
5	39188.5	71.4	43229.9	71.9		
6	39189.9	71.4	43232.3	72.0		

The report of calibration is based on the last four observations.

Table 2 REPORT OF CALIBRATION

Report of Calibration
Load Cell

S/N 10K

Mass (lb)	lbf	D.D.	lbf/D.D.
750	748.72	3003.5	0.2493
1750	1747.02	7012.2	0.2492
2750	2745.30	11036.3	0.2487
3750	3743.60	15042.2	0.2488
4750	4741.50	19055.0	0.2488
5750	5745.17	23083.0	0.2486
6750	6738.48	27101.4	0.2486
7750	7736.77	31131.8	0.2485
8750	8735.07	35156.0	0.2484
9750	9733.35	39300.3	0.2476
10750	10731.64	43231.4	0.2482

English Units $F = \underline{k}\ (m - \rho\underline{v})\underline{a}$
where

F is force in pounds force (lbf)

m is mass in pounds

ρ is air density in pounds per cubic foot

$\underline{v}$ is volume in cubic feet

$\underline{a}$ is acceleration in ft/sec/sec (a at place of use)

$\underline{k} = 1/32.17404$

To obtain force in pounds force, multiply pounds force /D.D. from table (interpolating as necessary) and multiply by D.D. observed.

To obtain mass in pounds, multiply lbf/D.D. from table (interpolating as necessary) times DD observed and multiply by the ratio of 32.17404 to acceleration at place of use. Compute $\rho\underline{v}$ and add to mass as computed above.

3 sigma (lbf) = 0.5

Three sigma is an estimate of the overall uncertainty of a point using three standard deviations based on 33 degrees of freedom as a limit to the effect of random errors of measurement, the magnitude of systematic errors from known sources are negligible.

Table 3 REPORT OF CALIBRATION (ENGLISH SYSTEM)