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IMPROVED MASS-MEASUREMENT ACCURACY
USING A
PNB LOAD CELL SCALE

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ABSTRACT

The PNB Load Cell Scale is a Preloaded, Narrow-Band calibration mass comparator. It consists of (1) a frame and servo-mechanism that maintains a preload tension on the load cell until the load an unknown mass is sensed, and (2) a null-balance digital instrument that suppresses the cell response associated with the preload thereby improving the precision, and accuracy of the measurements. Ideally, the objects used to set the preload should be replica mass standards that closely approximate the density and mass of the unknowns. The advantages of the PNB scale are an expanded output signal over the range of interest which increases both the sensitivity and resolution, and minimizes the transient effects associated with loading and unloading of load cells. An area of immediate and practical application of this technique to nuclear material safeguards is the weighing of UF_6 cylinders where in-house mass standards are currently available and where the mass values are typically assigned on the basis of comparison weighings. Several prototypical versions of the PNB scale have been assembled at the U.S. National Bureau of Standards. A description of the instrumentation, principles of measurements, and applications are presented in this paper.

1. Introduction

Weighing is a comparative process by which the values assigned to a known object (mass standard) are used to assign mass values to an unknown. The instrument used to make the comparison in essence compares, either directly or indirectly, the net vertical forces acting on the known or some appropriate substitute, and the unknown, as each is suspended from or supported by an appropriate sensing element. The net verticle force has two components, the gravitational force acting on the object under study, which is by far the largest component, and the buoyant force of the air immediately surrounding that object. All other factors being the same for two weighings, equality in the net verticle forces acting on the objects implies equality in mass.

The scale user must select from a variety of instruments one which will adequately make the above comparison relative to his particular measurement requirements. The selection is usually a judgement based on factors such as performance specifications, initial cost, maintenance costs, and ease of operation with respect to physical operation of the instrument and data processing.

The scale manufacturer devotes his efforts toward reducing the systematic effects inherent in a particular design to a point commensurate with the requirements of the majority of the users. Typically manufacturers and users alike use some form of certification* procedure to verify that the initial and continuing performance of an instrument is in accordance with specifications.

Difficulties arise when the user's requirments are more stringent than the stated performance specifications for generally available equipment. Assuming that the stated requirements are indeed realistic, the resolution of the problems requires a more detailed understanding of mass measurement process and a more sophisticated weighing approach than that outlined above.

There have been significant advances in weighing technology over the past several decades. These advances have not only improved the performance of the available instruments but have also simplified the measurement procedures required for a direct reading mode of operation. With a direct reading instrument there is very nearly a one-to-one correspondence between the instrument indication and the mass of the object used to test the instrument. Discrepancies, if any, are usually those associated with the manner in which the buoyant effect of the air is handled. In practice, only differences in mass can be measured. That is, given a mass standard of known value, the instrument provides a quantitative measure of the difference between the standard and an unknown. Thus, the value assigned to the unknown is the mass of the standard plus the measured difference. Typically, as the sensitivity increases, the on-scale range is substantially reduced.

Advances in weighing technology came with the recognition that it was not necessary to compare directly the forces acting on the standard and the unknown. The same data can be obtained with far less complication by comparing the forces acting on the standard and the unknown with a reference force which is stable over the time interval required for the comparison. The result is the current generation of substitution and top-loading weighing equipment.

When large masses are concerned, the situation is more complex because of the time and effort involved in the handling and stacking of many large reference weights. With few exceptions, one must rely on the constancy of the instrument. In the case of the weighbeam with a sliding poise for example, given a set of mass standards of known value, one can adjust or verify the one-to-one correspondence for discrete setting of the poise along the beam. This however is a costly operation. Handling problems associated with large weights severely complicate making a direct comparison of the forces acting on the unknown and the standard. In this paper we examine how uses of substitution weighing and a pre-loaded, load-cell scale introduce into the area of large mass measurements those principles which have been successfully used in the development of small mass instruments.

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*Certification is used here in the context of that delineated in Reference 1. It is a series of specific tests in which the instrument indication is compared with the values of known mass standards as they are weighed on a particular instrument. An analysis of the results is the basis for a decision to (a) certify the scale for general use over a specified time interval, or (b) overhaul and readjust the instrument, and retest.

2. Substitution Weighing

The double substitution weighing method requires a minimum of two mass standards, A and B, with known mass values M(A) and M(B). For a complete description of the method see References 2 and 3. The mass of these standards should be such that:

$$A < U < (A + B) \quad \text{or} \quad U < A < (U + B)$$

where U is the unknown. Ideally, A should be near but slightly lighter than U; B is a small weight that defines the weighing window. The four weighing steps, taken in the order listed, are:

$$A \rightarrow R1$$

$$U \rightarrow R2$$

$$U + B \rightarrow R3$$

$$A + B \rightarrow R4,$$

where R1 through R4 are the associated instrument responses. The weight W(U) is then computed as:

$$W(U) = W(A) + W(B)(R1 - R2 - R3 + R4) /(R1 - 3R2 + 3R3 - R4)$$

according to an equation based on least squares (Reference 4). Knowing the displacement volumes and the air density, one can compute M(U) relative to M(A) and M(B) by following the prescribed procedures. See Reference 5. The series of four weighings can be repeated as many times as necessary to assure that the calculated average, $M(\bar{U})$, and error variance, $Var(M(\bar{U}))$, meet the measurement accuracy requirements. Note first that the reference force need only to be stable over the time interval for the four measurements. The sensitivity weight B calibrates the instrument indicating scale as a part of the sequence. Further, if A and U have essentially the same displacement volumes, there is no buoyant force correction. In a situation where appropriate reference standards are available and a large number of similar items are to be weighed, substitution weighing is feasible as a production weighing technique.

3. Inherent Problems with Load Cell Measurements

Ongoing work at NBS on the use of load cells as sensors in force measurement systems is documented in References 6 through 8. See also Reference 9. Characteristics which cause difficulties in the calibration and application of load cells include creep, non-linearity, hysteresis, and load misalignment.

Load cell creep is defined as the change in response observed after the initial response to a force increment. When a load is applied to a load cell there is an initial deformation of the constituent stressed material, followed by a delayed creep deformation of the material. There is an initial change in temperature associated with the deformation followed by another temperature change as the elements approach a new thermal equilibrium state. These changes are not permanent changes in the load cell characteristics.

The NBS creep tests were all done at one temperature. Petik[9] reports results that show significant differences in response for tests conducted at different temperatures including creep in opposite directions at temperatures that differed by 24°C.

While the factors contributing to creep are complex, in general the magnitude is roughly proportional to the force increment, and the creep rate decreases exponentially with time. For a given load cell, the creep characteristic is stable and repeatable at a given temperature. Under the action of the preload force, the PNB scale reaches a steady state creep condition subject only to a small increment associated with the on-scale range or measuring window.

Generally, the load-cell response is not a linear function of the load. The departure from linearity however, seldom exceeds 3% of the full load response. In most circumstances, the departure from linearity at mid point of a sub-interval decreases substantially as the sub-interval width decreases. Since the width of the measuring window of the PNB scale is made small, the effect of non-linearity is eliminated and with it the need for a correction equation.

Hystersis refers to the condition where load cell response is affected by the direction in which the load increments are applied. That is, the response for ascending load increments differs from the response at the same loads as the increments are removed. The magnitude of the effect depends upon the sum of the force increments applied before load reversal. Over the measuring window of the PNB load cell scale, the hystersis effect is negligible.

Load misalignments introduce non-axial load components on the force sensor which produce significant error signals in the load cell response. Load misalignments tend to produce erratic responses that in general do not behave in a predictable manner and therefore cannot be readily characterized and corrected for.

The load cell response to a given applied force can be considered associated with the axial component of the applied force, and one associated with the non-axial components. Small changes in the interface between the load cell and the other elements of the structure forming the assembly can introduce a variability in the loading configuration which is observable in the response.

One corrective approach is to rigidly mount the load cell in the structure and to calibrate in situ. Here one must accept the residual variability associated with small structural deflections. Alternatively, one can effectively put bounds on the magnitude of the nonaxial components by interposing flexures between the load cell and the adjacent elements. In a tension mounting, the loading configuration is precisely defined by the flexures, with the maximum bending moment being established by the stiffness of the flexure. An example of a load cell system that was designed to assure axial load alignment is described in Reference 10.

Experience has shown that better results are obtained when the load cell is used under tension rather than under compression, and that load cell measurements made with due precaution to assure good accuracy can be time consuming when compared with weighbeam-scale measurements. The reduced performance of load cells under compression is probably a contributing factor to the problems experienced in the operation of load-cell weigh tanks.

4. The PNB Load Cell Scale

In 1965, a mass comparator system based on nearly constant loading of a bonded, strain-gage load cell was constructed by Gilmore Industries for the Department of the Army[11]. This system, with capacities of 1000 to 50000 lb. was portable and was designed for in situ calibration of weights used in certain large dead weight force generators. The dead weight force generators were, in turn, to be used to calibrate force measuring systems. Both the performance and the portability of the system were tested at NBS. The design concept was to maintain the cell at nearly constant load during the periods it would normally be unloaded, and to amplify only that part of the response signal associated with a narrow measurement window in the neighborhood of the preload. The result is sensitivity, precision, and accuracy not ordinarily attained with a load cell.

A detailed drawing of this system is shown in Figure 1. The load sensing component of the system is comprised of a commercially available load cell mounted between a hydraulic cylinder and a compression truss and separated from them by two flexures. The lifting bail and load receiving element are attached to heavy duty plates against which the preload force is applied. The preload force is generated by an annular hydraulic cylinder acting on the lower plate (preload stop) and on a combination cylindrical shroud and compression truss that transmits the force to the upper plate.

The above unit was suspended from a hydraulic cylinder, which in turn, was suspended from a crane hook. This cylinder and associated limit switches controlled both the lifting rate and the amount of lift during the transfer of the objects to be weighed.

Not shown in Figure 1 are the hydraulic unit and the electronic cabinet. In operation, a standard was suspended from the system for a period of time to allow stabilization of the response signal. The pre-load force was set relative to this signal. During the exchange of weights, the preload force did not vary in excess of 1% of the set value. The amplified response over a 5 lb. measurement window was plotted graphically as a function of time. The process standard deviation at the test points (50000 lb., 30000 lb., and 10000 lb.) did not exceed 2 ppm.

5. NBS Prototype Mass Comparators

In order to meet in-house requirements for use in calibrating a 378 liter (100 gal.) volumetric test measure, NBS in 1978 fabricated the 225 kilogram mass comparator shown in Figure 2. The NBS Prototype uses the force exerted by a coil spring to maintain about 90 percent of the load during the interchange of objects. This is accomplished by suspending the cell through a coil spring, allowing the load to compress the spring, and then adjusting the surrounding frame to prevent removal of more than 10 percent of the spring force. After initial adjustment, nominally equal masses can be compared.

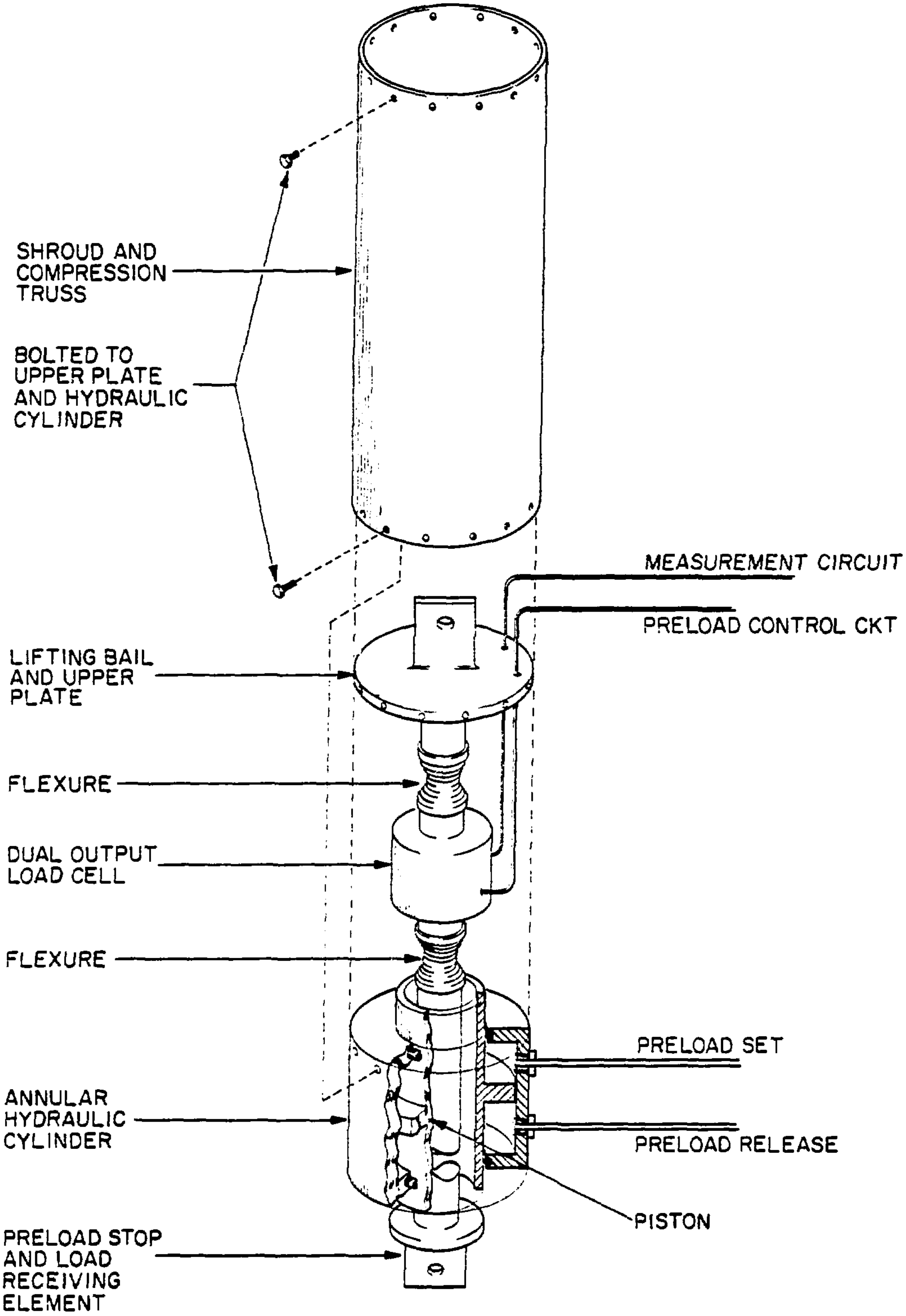

FIGURE 1. DETAIL OF A PNB LOAD CELL SCALE

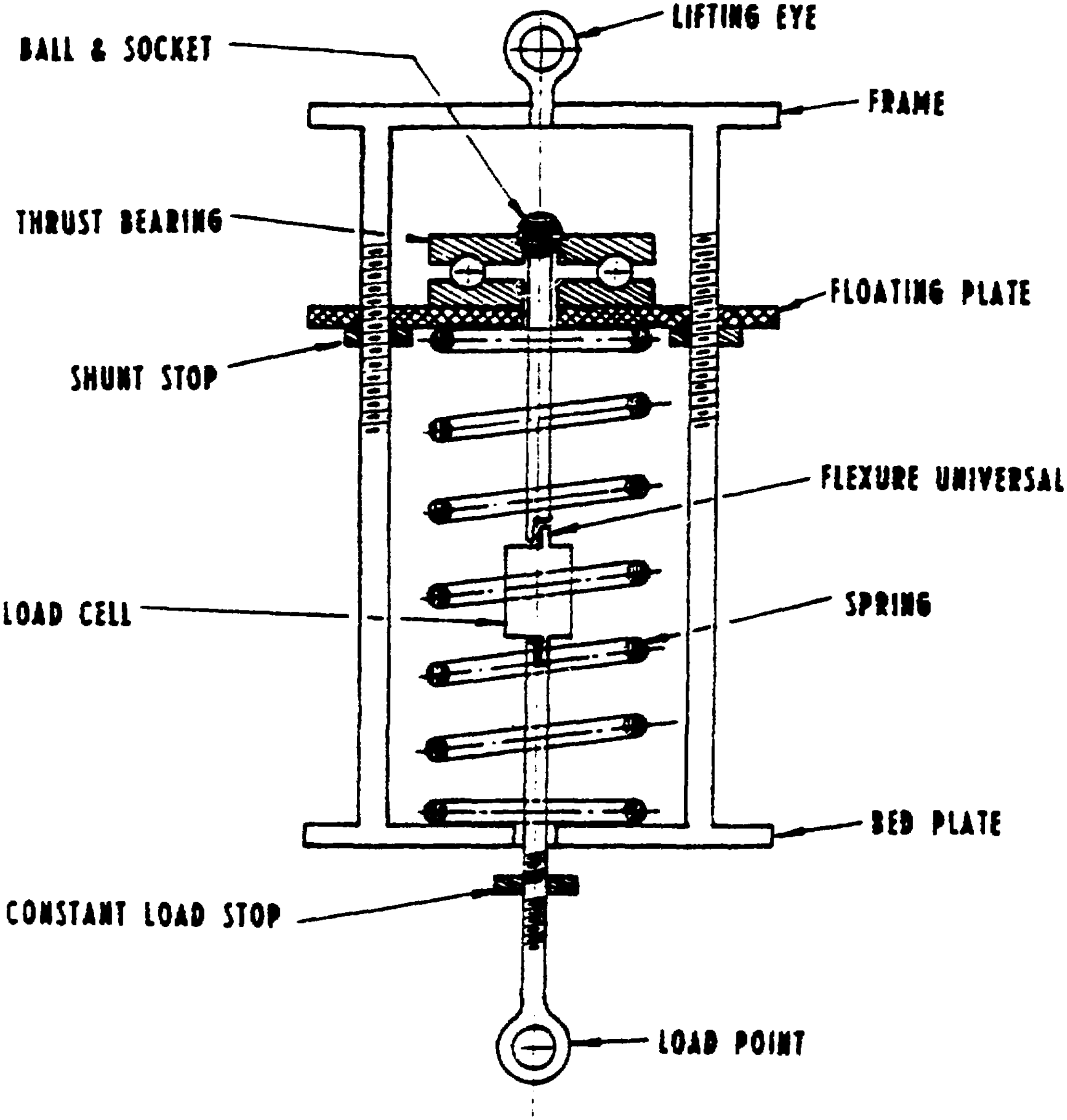

FIGURE 2. DETAIL OF 225-Kg LOAD CELL SCALE

The lifting eye carries the frame and is connected to a hydraulic lifter that can be suspended from a building structural member or A-frame. The rigid frame receives the forces exerted by the objects to be compared.

The open coil compression spring rests upon the lower plate and is centered around a passageway. On the upper end of the springs rests a floating plate with its passageway likewise centered. Horizontal motion of the floating plate is restricted by vertical rods that are part of the frame. The rods do not, however, impede vertical motion of the spring and plate.

Resting on top of the floating plate are a thrust bearing and ball-and-socket assembly. The ball-and-socket permits gross vertical misalignment of the cell and frame during initial assembly. Whereas the bearing allows the spring to rotate during compression and extension, it also removes torque from the cell during the loading cycle as well.

Adjustable shunt stops are set to halt vertical motion of the floating plate just before full loading is reached, thus providing a rigid suspension of the cell. When the load is removed, slight vertical motion of the spring and cell is permitted before reaching the constant load stop. This stop is adjusted to provide about 90 percent of full load to the cell when the load is removed.

In addition to the above components, a hydraulic lifting mechanism is required as well as a weight transport system. Dollies and tracks provide excellent weight handling up to 1000 kg for this device. A conventional load cell indicator is used to display the load cell output signal. Figure 3 shows schematically the complete weighing system.

To make full use of the mass comparator, careful attention should be paid to its support and loading. A stiff supporting structure for the comparator is required. Slow, uniform loading is accomplished with a hydraulic lifter (see Fig. 3). This is to minimize the mechanical shock from improper loading which is known to degrade load cell performance. Also by indexing the position of the object to be loaded, with respect to the load point, reproducible load position can be obtained thereby minimizing the loading error.

As mentioned previously, the comparator was used successfully to determine the capacity of a 378 ℓ (100 gal) test measure. The results are summarized in Reference 12.

A 30-kilogram capacity high precision mass comparator was built at NBS in 1980.[13] The 30-kg comparator differs significantly in design from the 225-kg version in several ways. The instrument is self-supporting and is provided with a built-in weight exchanger as shown in Figure 4. This feature not only loads the cell without shock but also aligns the weight in the center of the weighing pan. The cell itself is supported by four parallel springs in tension rather than a single spring in compression as before. Finally, the flexure universals above and below the cell are replaced with gimballed joints fabricated from ball bearing assemblies. The load cell, which incorporates a resistance bridge, has a capacity of 45 kg (100 lb.). A schematic view of the load cell and spring assembly is shown in Figure 5.

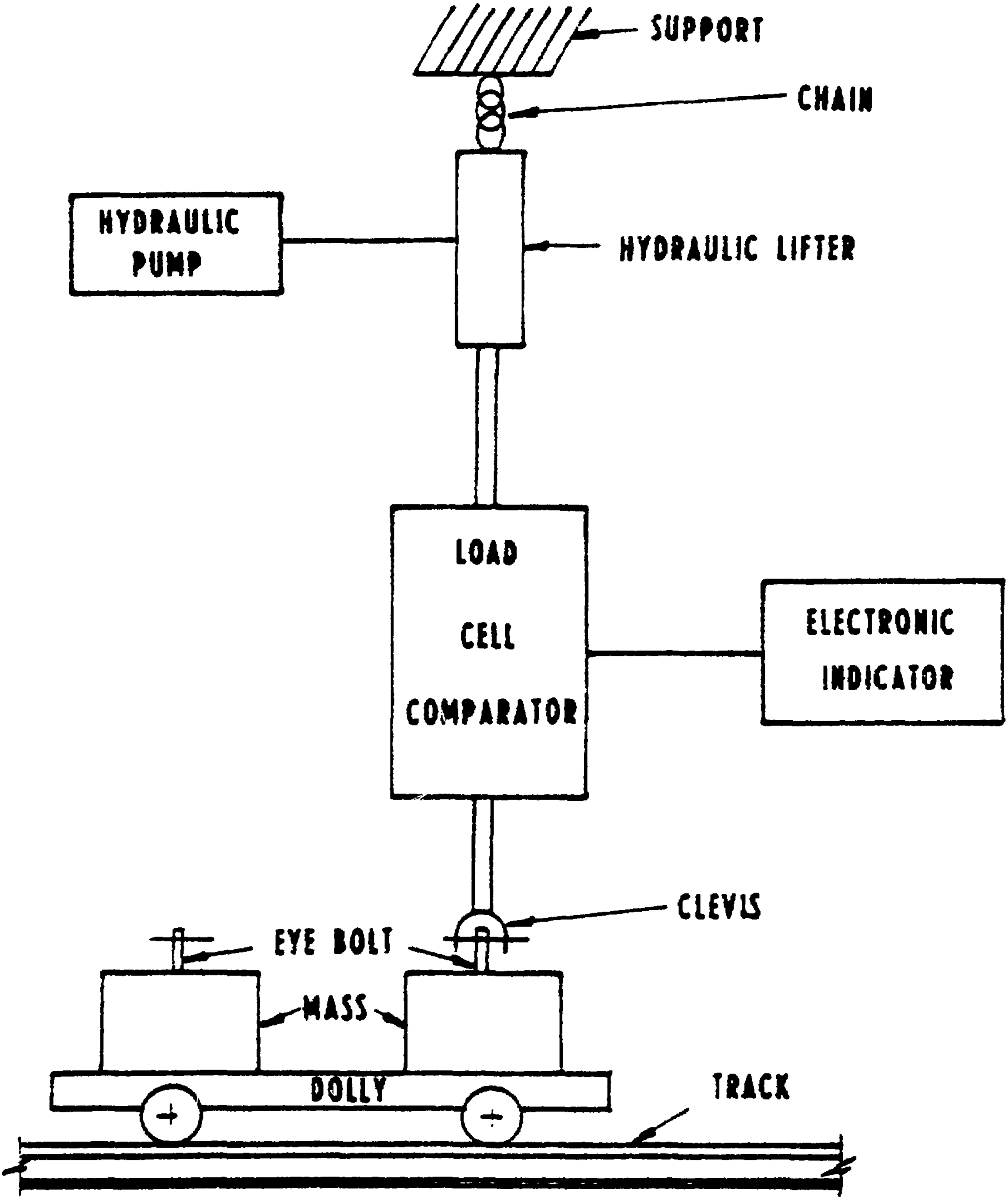

FIGURE 3. SCHEMATIC OF 225-KG WEIGHING SYSTEM

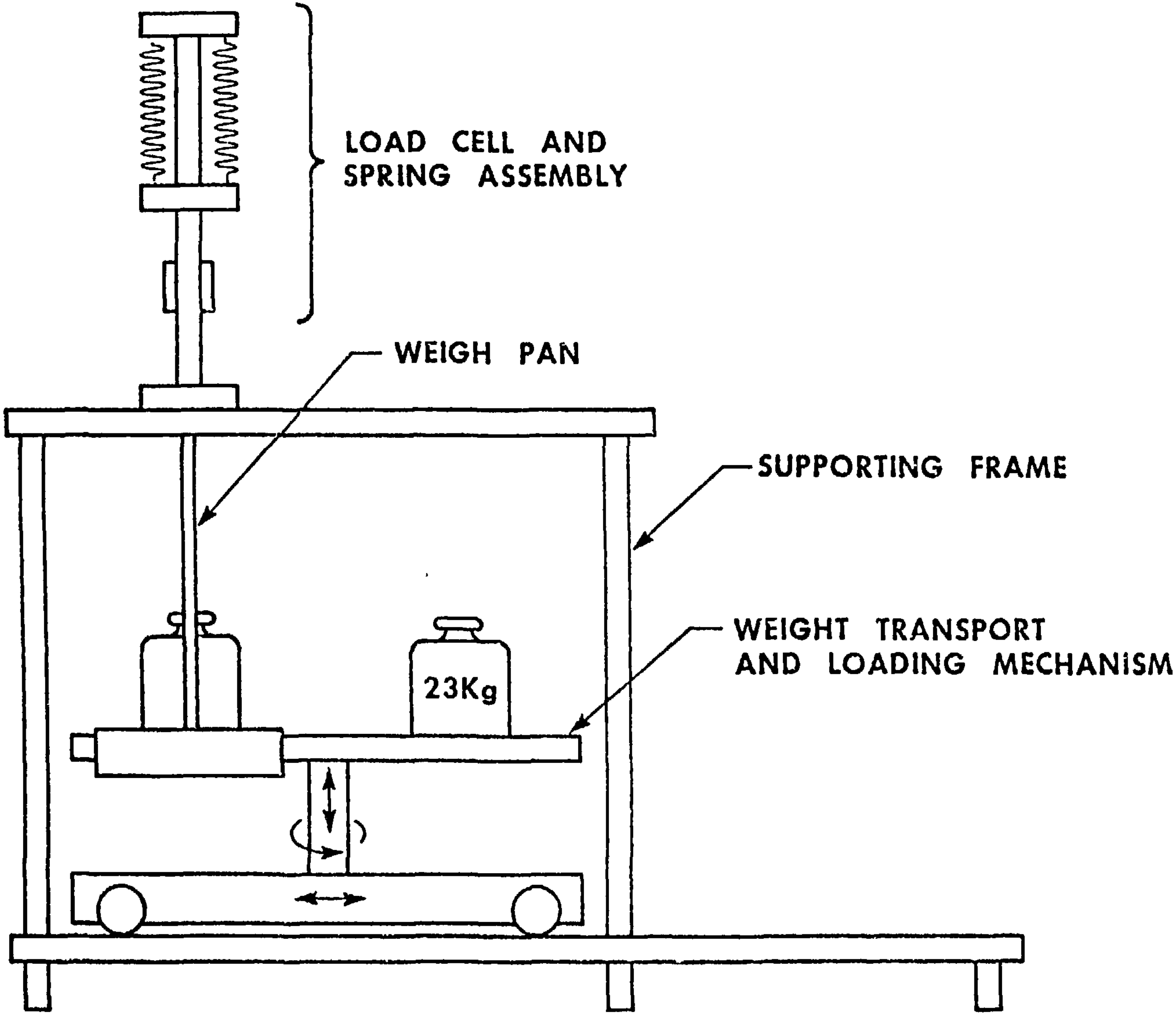

FIGURE 4. SCHEMATIC OF 30-Kg WEIGHING SYSTEM

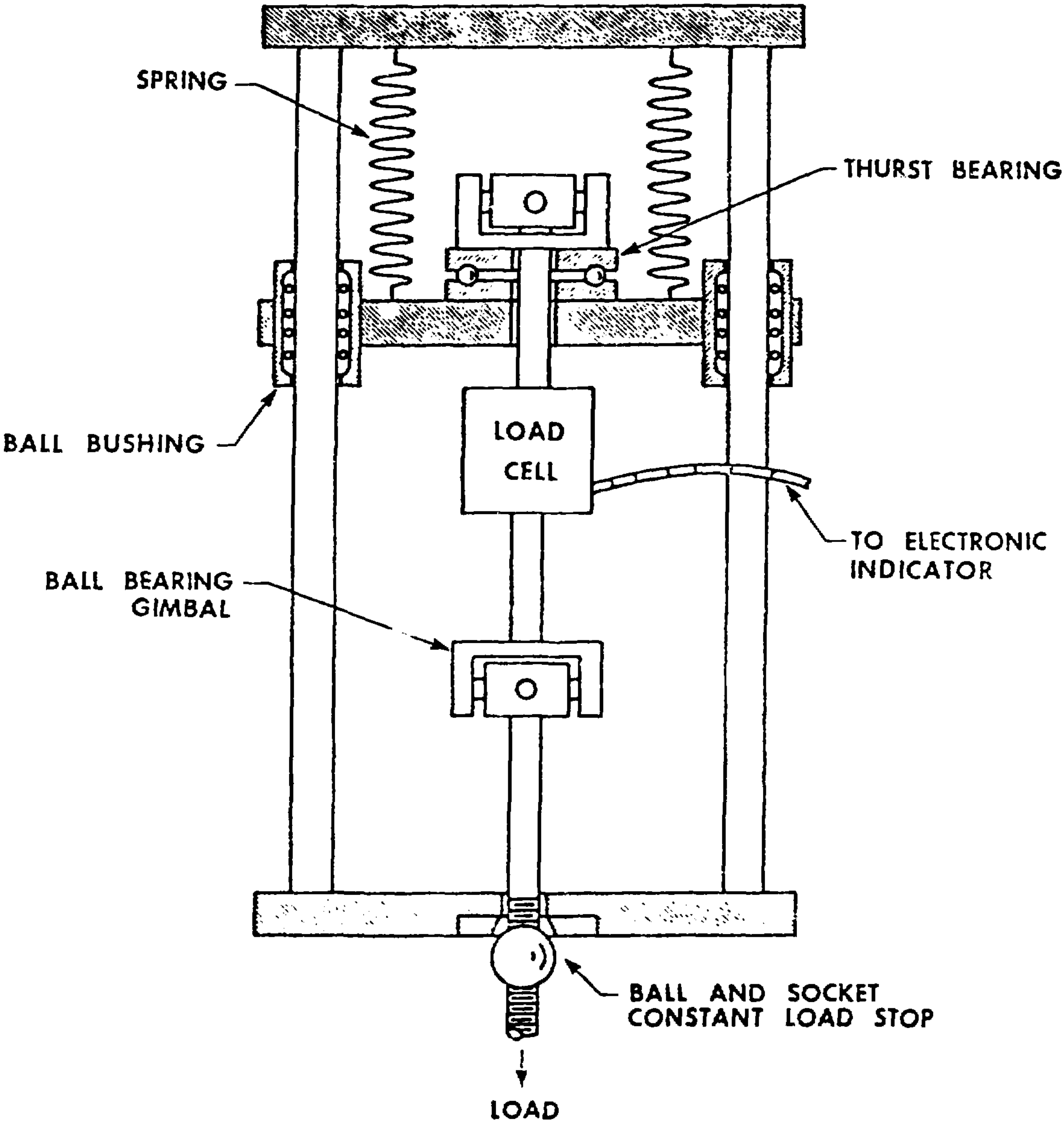

FIGURE 5. DETAIL OF 30-Kg LOAD CELL SCALE

It is noteworthy to report one major operational change in the use of the comparator. Unlike the previous instrument, the springs are used to support the load cell during the weighing mode whereas before a mechanical shunt intervened and supported the cell. This method of supporting the cell appears to improve the isolation from ambient vibration. In addition nearly 100% of the load is maintained on the cell at all times.

The indicating electronics for this instrument were developed at NBS.[14] The circuit is designed to amplify the cell response signal over a range defined by the pre-load response and a defined measurement window. The circuit includes features which enhance the measurement of low level electrical signals. The output signal is that observed on a conventional digital voltmeter. Additional output is available via the detector's internal amplifier which is used to drive a high-impendance strip chart recorder for recording the observations.

This system, initially developed for the Office of Weights and Measures at NBS, is now located at Texas Weights and Measures Laboratory at Austin, Texas.

6. Weighings Based on Preloading, Replica Mass Standards, and Substitution Weighings

Preloading of a PNB scale minimizes a number of weighing errors which are exponentially time-dependent. By mounting the load cell between two flexures in a tension mode, the bending moments associated with non-axial loading are controlled. The use of double substitution weighing methods automatically compensates for linear drift and the time interval required for the four measurements. The availability of stable electronic circuits permits the user not only to set the width of the measuring window but also to position that window over the capacity of interest. This results in weighing accuracies of large objects heretofore available only at national laboratories.

A replica mass standard (RMS) is a facsimile of a production object that has been completely characterized with respect to its mass and displaced volume by NBS. An in-house standard is a facsimile of a production object whose mass value has been determined relative to that assigned to an RMS. Establishing the mass values for in-house standards is currently a tedious and time consuming task. A portable PNB scale to accompany the RMS standard would greatly simplify this task and would reduce interruptions of production activities.

It is easy to envision the extension of the usage to production weighing. Preloading the PNC scale with the value of an in-house standard that closely approximates the weight of the objects to be weighed on a daily basis effectively converts it into a null-balance measurement system.

If a small desktop computer is available for data acquisition, then buoyancy corrections, choice of reporting unit, etc., can be included in the software programs. The results are ease of operation, speed, and accuracy not routinely obtainable with existing large capacity weighing systems.

7. Future Applications

The area of most promise for the immediate use of a PNB Load Cell Scale is in the weighing of 30B cylinders at those facilities that now have, or are soon to acquire, in-house standards that have been characterized using the NRC-DOE replica mass standards calibrated by NBS under the UF_6 INMM-ANSI sponsored measurement assurance program.

Because U.S. scale manufacturers are reluctant to bid on large systems to be built to customer specifications, nuclear material plant operators have a choice of buying the components and doing the development work themselves to assure the weighing specifications are achieved, or to go to foreign manufacturers whose response to service and scale maintainability may not be prompt enough for plant operation.

In the future, the PNB scale concept will become more and more attractive to the plant operators because of reduced operating cost, lower capital cost than large capacity weighbeam scales, ease of operation, and attainability of high accuracy with routine operation.

Handling UF_6 cylinders is labor intensive, in particular for those plants in which UF_6 cylinders are weighed on a platform scale, either indoors or outside. Normal transfer and movement of UF_6 cylinders involves high operating costs which escalate quickly with the size of the inventory. The more cylinders there are on inventory, the larger the storage area and, hence, the greater the distance involved in moving the cylinder to and from a fixed position scale. The PNB load cell scale can be made portable and therefore could be brought to the cylinder storage area where each cylinder can be weighed in place.

Just as the U.S. Army's missile program and the NBS calibration accuracy requirements created needs for new concepts in weighing, so also are the safeguards requirements affecting DOE or licensee plant operators. Although the techniques described here are not new, recent improvement in the electronics and ingenuity in developing the pre-load force have made possible the development of a system which routinely and predictably produces high accuracy weighings. The same techniques are being used to develop systems with capacities up to 10000 lb. The technology exist to extend the servo hydraulic preloads to 50000 lbs. and beyond.

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