Kirk-Othmer Encyclopedia of Chemical Technology.

WEIGHING AND PROPORTIONING

Weighing is the operation of determining the mass of any material as represented by one or more objects or by a quantity of bulk material. Proportioning is the control, by weighing, of relative quantities of two or more ingredients according to a specific recipe in order to make a mixed product, or to prepare the ingredients for use in a chemical process.

It is likely that volumetric measures were used for quantity determination when commodities were first bartered; however, it has been established with certainty that weighing scales or balances have been in use for at least 7,000 years (1). Measuring by weight instead of by volume eliminates some very considerable inaccuracies from, for example, changes in specific gravity of liquids with temperature, or changes in density of solids owing to voids.

Mass is a fundamental physical property of matter; the mass of an object does not change with its location on the earth. Mass is what is measured in the act of weighing, and scales are calibrated to read in units of mass, eg, kilograms. The terms weight and weighing are used somewhat loosely in this connection, in that weight is a measure of the gravitational force of the earth acting on a mass. Thus, weight depends on the location of the scale relative to the equator and on its altitude. It is common practice to calibrate scales *in situ* using mass standards (test weights); hence, for practical purposes scales actually determine mass.

The terms *balance* and *scale* are currently used to describe weighing machines of various forms. The word balance comes from the Latin term *libra bilanx. Libra* means scale and *bilanx* means two pans; thus *libra bilanx* means scale with two pans (2). Over the centuries *bilanx* evolved into balance. Balance still refers to sensitive weighing devices with two pans (Fig. 1), although it is also used in a more general sense to refer to any very sensitive laboratory weighing device. The word scale comes from the old Norse word *skal*, which means bowl, and it was originally used to describe the pan of a balance (2). Scale today (ca 1997) is used to describe general-purpose weighing machines found in industrial and retail applications.

Some common industrial weighing applications include the following:

- Verifying quantities of incoming raw materials
- Controlling ingredients to the proper proportions
- Putting the product into packages of uniform weight, either by packaging directly on a scale or by using a scale to check the performance of filling equipment
- Weighing outgoing shipments for purposes of billing and determination of transportation charges
- Weighing interdepartmental material transfers for accounting purposes
- Controlling the rate of material flow to various pieces of equipment such as grinders or kilns

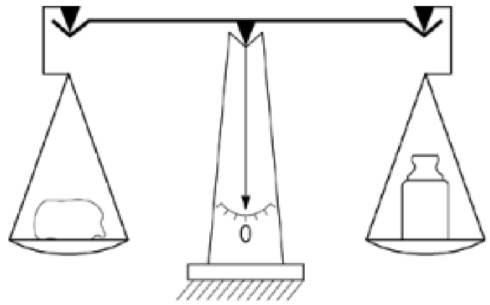

Fig. 1. Balance.

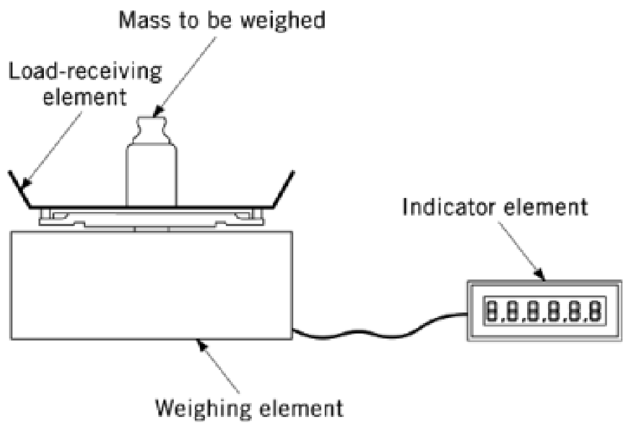

Fig. 2. Basic elements of a scale.

1. Weighing Principles

There are many types of scales using many different principles of operation. There are, however, three distinct elements which can be identified regardless of the principle of operation (Fig. 2).

The load-receiving element supports the load during the weighing operation. It may take the form of a scoop, platter, deck, rail, hopper, belt conveyor, or any other configuration appropriate to the material being weighed.

The weighing element supports the load-receiving element. It produces a signal proportional to the load and sends this signal to the indicator element. The weighing element can take many forms. It could, for example, be a mechanical lever system sending a force, a hydraulic load cell sending fluid pressure, or a strain gauge load cell sending an electrical signal.

The indicator element measures the signal from the weighing element, and converts it into a readable form. It may be any of several different types, eg, the graduated beam of Figure 3, a Bourdon tube pressure gauge, or a numeric display device. Today (ca 1997), with the increase in automation, the indicator element may not display the weight but may instead transmit it electronically to a controller.

The principal weighing technologies in use currently are mechanical, hydraulic, strain-gauge, electromagnetic force compensation, and nuclear.

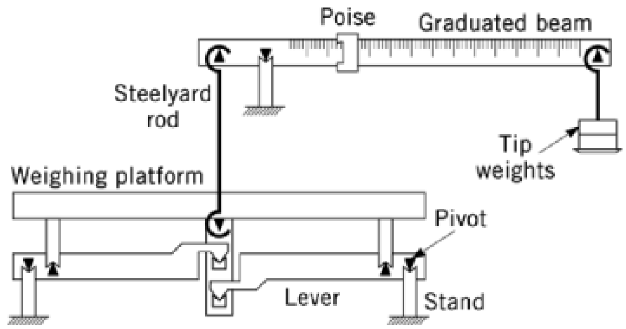

Fig. 3. Mechanical beam scale.

2. Mechanical

Mechanical scales, measure a load either by comparing it with a known weight or by measuring the distortion of a spring caused by the load. With the even-balance type shown in Figure 1, the load is measured by direct comparison with known weights. With beam scales (Fig. 3), the force resulting from the load on the platform is reduced to a more manageable magnitude by the multiple of the lever system. It is then measured by the position of a known weight, or poise, on a graduated beam. A scale with a graduated beam and poise weight is often referred to as a Roman or steelyard scale; it was developed by the Romans and remains in limited production today (1). In operation, the poise is moved by hand until the beam balances in a horizontal position, at which point the weight can be read directly from the beam. To extend the capacity of the scale without a loss of resolution, many beam scales also use tip weights that can be placed on a hanger at the tip of the beam. For instance, a 500 kg scale could have a beam graduated from 0 to 50 kg in 0.2 kg divisions, and be supplied with a combination of tip weights which in total can counterbalance 450 kg; note, with a scale multiple of 100, a tip weight of 100 kg would actually weigh 1 kg. With this scale, any load up to 500 kg can be weighed with 0.2 kg divisions. With the poise at 50 kg, tip weights are added until the beam moves down, then the poise is moved back until the beam balances. The weight is the sum of the tip weights and that indicated on the beam.

Automatic indicating scales eliminate the manual operation of placing tip weights and positioning a poise on a graduated beam. In spring-type automatic indicating scales, the steelyard rod is connected to a spring whose deflection is indicated by a pointer against a graduated scale. A dashpot is required to dampen the oscillations of this type of scale.

The primary advantages of mechanical scales are that they are relatively inexpensive in smaller capacities; they do not need electrical power, enhancing their portability; and they do not need to be protected from power line transients or lightning strikes.

Their disadvantages include diminished performance owing to normal wear, damage from corrosives, or buildup of dirt and debris; excessive vibration that may cause damage and render them difficult to read; the fact that for larger sizes the installation is relatively complicated and expensive; their slow speed of operation; and the fact that they do not lend themselves to automation. In order to take advantage of the data collection and automation possibilities afforded by electronics, many older scales have been converted to operate with electronic indicating elements through insertion of a strain-gauge-type load cell in the steelyard rod.

2.1. Hydraulic

A hydraulic scale measures weight by supporting the load receiver on the piston of a hydraulic load cell (Fig. 4) and measuring the resulting hydraulic pressure with a Bourdon tube or similar device. Many weighing

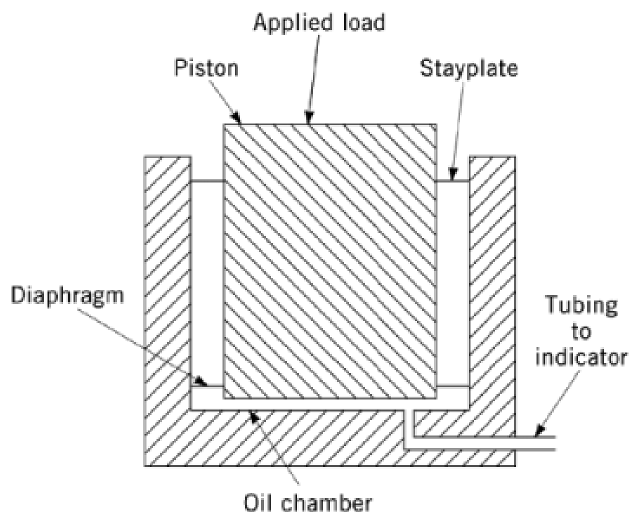

Fig. 4. Hydraulic load cell.

operations require that the load be supported at three or more points, requiring the use of three or more hydraulic load cells. The individual hydraulic pressures developed by these cells must be converted back to forces for summing and measurement; this is often accomplished using strain-gauge load cells. The hydraulic equipment performs the same function as a mechanical lever system in reducing the load to an easily measured force.

The advantages of a hydraulic scale are immunity from electrical transients and lightning damage, that vibration can be controlled by damping, and that downward travel of the platform or weighing container is relatively small. The disadvantages include the fact that additional equipment, either mechanical or electrical, is required to sum the individual cell outputs in multiple-cell applications, or for control or data acquisition purposes; the fact that the speed of operation is dependent on temperature, ie, as a result of variations in the viscosity of the hydraulic fluid; and the fact that there is a danger of contamination from leaking hydraulic fluid.

2.2. Strain-Gauge Load Cells

The majority of industrial scales today use strain-gauge load cells as the weighing element. The strain-gauge load cell is a device which, when a force is applied to it, gives an electrical output proportional to the applied load.

Figure 5 shows a typical metallic foil strain gauge. It consists of an etched grid of very thin foil attached to a thin insulating backing material. The gauges are bonded firmly to a surface that prevents buckling. When stretched or compressed along the grid lines, the resistance measured between the ends of the grid (solder pads) increases in the case of the former and decreases in the case of the latter.

The central mechanism of a load cell is the spring element that supports the load, and it is designed to have areas of both tensile and compressive strain suitable for application of strain gauges. Spring elements come in a wide variety of designs, such that choice among them is often dictated by their capacity or the method used in supporting the scale. Figure 6 shows a typical spring element for a moment-insensitive load cell that would be used in a small platform scale. Typically, four gauges are applied in such a way that two are in compression and two in tension (C and T, respectively, in Fig. 6) as the spring element is loaded.

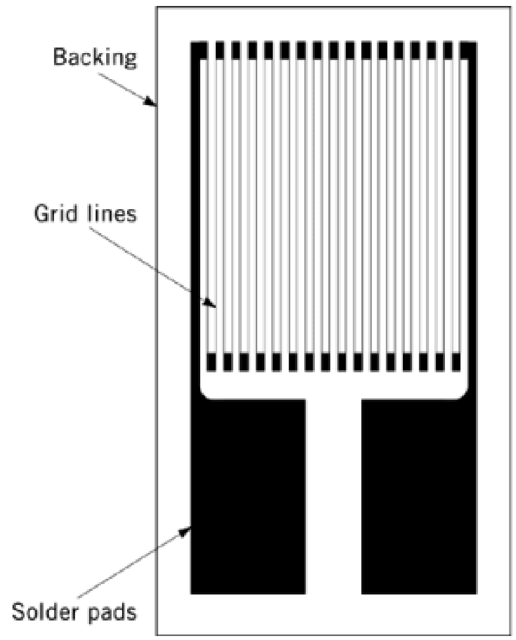

Fig. 5. Foil strain gauge.

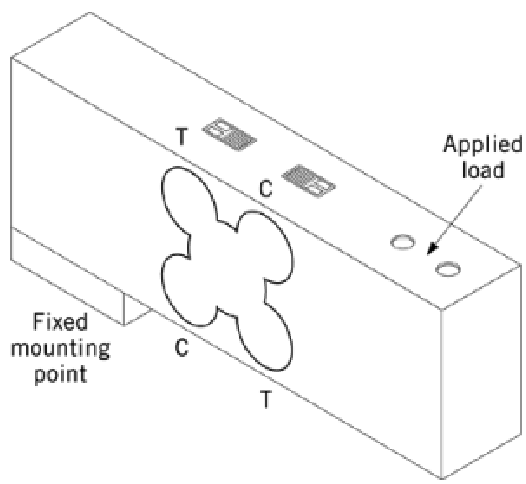

Fig. 6. Load cell spring element. C, gauges in compression; T, gauges in tension.

The four gauges are wired together to form a Wheatstone bridge (3), as shown in Figure 7. An input voltage (typically 10 V dc) is applied as shown, and the resulting output voltage is measured across points A and B. When no load is applied to the cell, all gauge resistances are the same; the bridge is said to be balanced, and the voltage difference between points A and B is zero. As load is applied to the cell, the resistance of the tension gauges increases, whereas that of the compression gauges decreases. The bridge becomes unbalanced, and a voltage difference appears across points A and B. As load continues to increase, the output increases linearly to 20 mV typically at rated capacity.

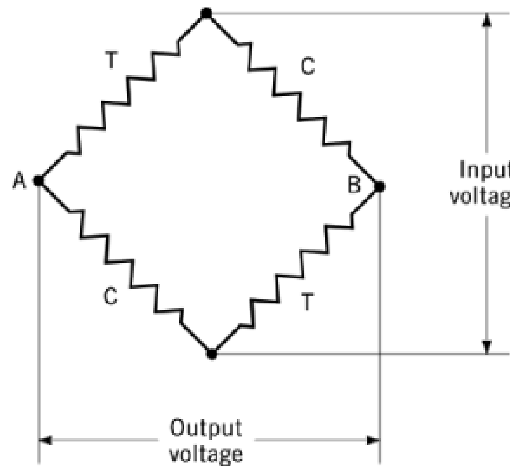

Fig. 7. Wheatstone bridge (see Fig. 6).

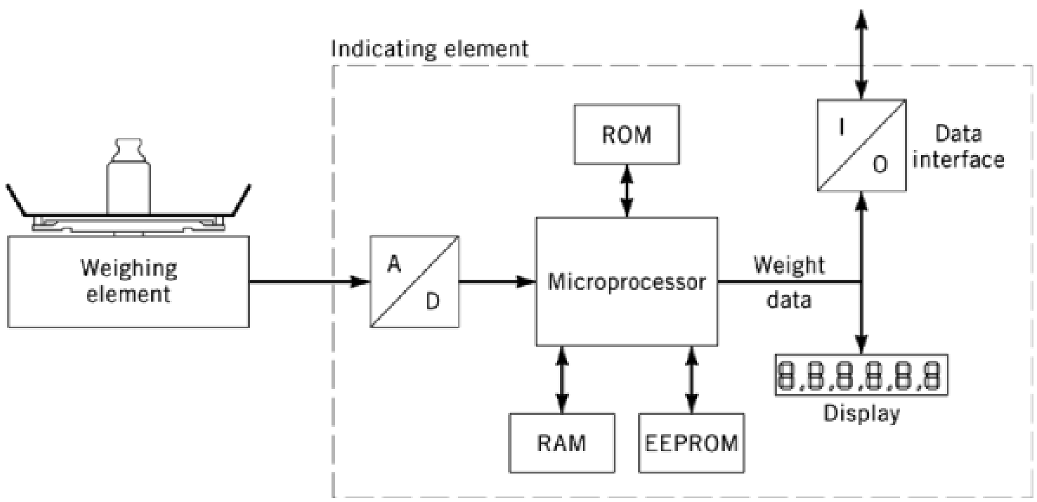

Fig. 8. Basic components of an electronic scale.

Figure 8 shows the basic components of an electronic scale based on strain-gauge load cells. A power supply (not shown, but usually housed in the indicator) provides operating power for the indicator and the input voltage for the load cell. The analogue signal produced by the load cell is sensed by the analogue-to-digital (A/D) converter, which sends digital weight information to the digital computer. The digital computer comprises the microprocessor, the working storage (RAM), a permanent memory (EEPROM) for storing calibration data, and the program memory (ROM). The computer filters the raw digital signal and processes it into calibrated weight for the display. The weight is also available at the data interface, from which it can be transmitted to any external device. Also, the indicator can be remotely controlled via the data interface; this is an important feature in systems applications.

The advantages of scales based on strain gauge load cells are as follows:

Minimal deflection of the platform or weighing container

A large selection of load cells is available in a variety of configurations and materials with capacities from 0.5 kg to 100 t or more

Ease of installation; load cells can be used individually or connected in parallel for multiple load-cell applications

The weighing and indicating elements may be incorporated into a single housing (as in the case of many bench and retail scales) or the indicating element may be remotely mounted

Versatility; the scale components can be purchased individually and used to create custom configurations

Availability of a wide range of accessories for data acquisition or process control

Some disadvantages include the following:

A very low output voltage from the load cell, commonly 1 μV per displayed division, makes the signal susceptible to noise and degradation (particularly over long distances)

Environmental factors such as temperature, humidity, moisture, and Electromagnetic Interference (EMI) or Radio Frequency Interference (RFI) can affect performance if insufficient care is exercised in designing the scale

Load-cell performance is limited by properties such as nonlinearity, hysteresis, and creep, which are inherent to the particular design or spring element material.

Analogue compensations for temperature effects are required in production

Load-cell mountings must be designed in such a way as to minimize the effects of extraneous forces

Electrical power is required, along with power-line transient protection

Analogue load cells have remained fundamentally unchanged for over 50 years, but they have been improved greatly in their performance and reliability. Since the mid-1980s, digital load cells have been gaining acceptance in certain applications. A digital load cell has a strain-gauged spring element as described herein, but its output is a robust digital signal. Figure 9 shows a cross section of a typical digital load cell used in truck-scale applications. It consists of a pin-type spring element that is compressed when loaded. The element is surrounded by an enclosure that is welded in place to provide a hermetic seal. The gauges are wired to a printed circuit board which includes an A/D converter and microprocessor; the digital output is through a hermetically sealed connector.

The advantages of digital load cells compared to analogue are:

The signal is less susceptible to noise and degradation; this factor is particularly important where long cable runs are necessary

Because a microprocessor is built into each cell, compensations for nonlinearity, hysteresis, creep, and temperature fluctuations can be performed digitally to achieve greater consistency and accuracy; also, temperature effects on the A/D are automatically compensated for

Outputs can be matched digitally to eliminate laborious corner trimming when installing a scale or when replacing a load cell

The indicating element can address each cell independently to display individual load cell weights, or for troubleshooting individual cells.

2.3. Electromagnetic Force Compensation

Precision balances traditionally were of the form illustrated in Figure 1. These were very finely made, with agate pivots and bearings and were often housed in an enclosure of glass and highly polished hard wood. Today, the

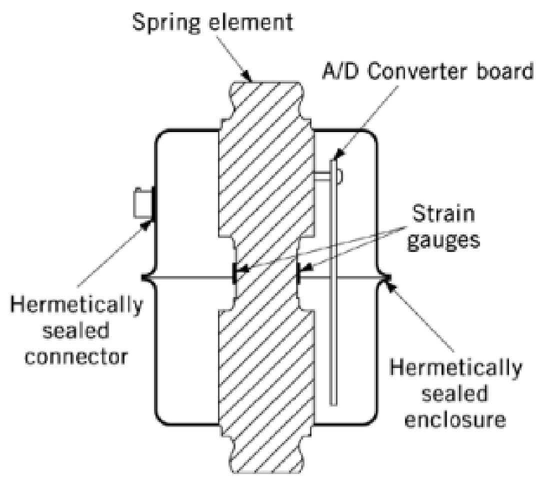

Fig. 9. Digital load cell.

principle of electromagnetic force compensation (EMFC), also referred to as magnetic force restoration (MFR), is used where extremely high accuracy is required. The fundamental principle of an EMFC balance is that the load added to the pan of the balance is maintained at the same vertical height by varying the current supplied to an electrodynamic converter that supports the pan; the current required is proportional to the load in the pan.

Figure 10 shows a cross section of the weighing cell of a typical EMFC balance. The pan (item 1) is rigidly attached to the hanger (item 2), which is held rigid in a horizontal plane by the parallel guides (item 3). The parallel guides attach to the hanger and fixed chassis (item 4) through the flexures (item 5). This parallelogram arrangement allows the pan and hanger to move freely in the vertical direction, although restraining them completely in the horizontal plane. The hanger is supported in the vertical direction by the lever (item 6); they are attached through the flexible link (item 7). The lever pivots freely at the pivot point (item 8) and has a position indicator (item 9) attached at its free end. The position sensor (item 10) senses the position of the lever, and controls the electrodynamic converter (a device which can convert electrical current into a mechanical force). The electrodynamic converter consists of a permanent magnet (item 11) which produces a uniform magnetic field in the air gap (item 12) between its poles and the coil (item 13) that is positioned in the air gap and attached to the lever. Current flowing in the coil produces a downward force on the lever (4); the position sensor controls the current to maintain the lever at its null position. When a load is added to the pan, the lever deflects. This is sensed by the position sensor, which adjusts the current to the coil such that the lever returns to the null position once again. This current is proportional to the load and is the means by which the mass is determined.

The electronics for a balance based on EMFC technology is very similar to that shown in Figure 8 for a strain-gauge-based scale, with the exception that the weighing element consists of the EMFC cell described herein, together with the circuitry to control the current flow to the compensation coil. Also, the signal sent to the A/D converter is not a voltage, but rather only the current necessary to return the lever to its null position. For balances, the weighing and indicating elements are usually integrated into the same housing.

Because of the extreme accuracy expected of many of these products, some include internal test weights which can be used to recalibrate regularly and to adjust for nonlinearity. Some balances monitor changing conditions and initiate the recalibration procedure as needed.

The advantages of this technology are as follows:

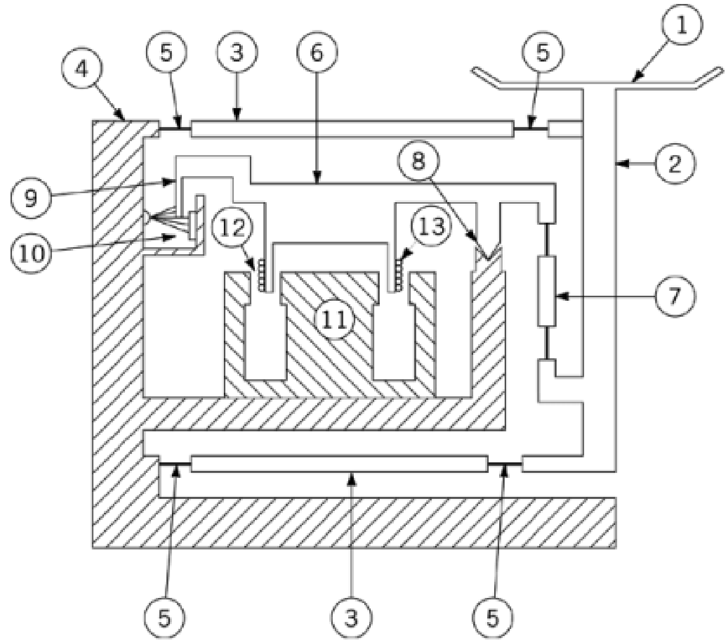

Fig. 10. Cross section of an EMFC weighing cell. Item 1, pan; 2, hanger; 3, parallel guide; 4, chassis; 5, flexure; 6, lever; 7, flexible link; 8, pivot point; 9, position indicator; 10, position sensor; 11, permanent magnet; 12, permanent magnet air gap; 13, compensation coil. See text.

Extreme accuracy is achievable; balances based on EMFC technology can have up to 50 million displayed divisions, eg, a typical semimicrobalance might have a capacity of 205 g with a division size of 0.01 mg (equivalent to 20.5×10^6 displayed divisions)
Extremely good repeatability is achievable (as required for mass comparators)
Faster operation and greater flexibility are achieved, compared to mechanical balances

The disadvantages are as follows:

Cost, particularly where the highest resolution is required
These products are very sensitive and are best used in a controlled environment
Electric power, along with suitable power line transient protection, is required
Capacity range is limited, although this can be extended through the use of lever systems

2.4. Nuclear

Mass can be determined directly by measuring changes in the absorption, reflection, or transmission of alpha- or beta-rays, which changes in proportion to the amount of material present. This method is primarily used to determine the mass of bulk material moving on a conveyor. The advantages include the following:

Simple installation
No contact with the material, no moving parts to wear out or corrode
Unaffected by changes in the tension or stiffness of the conveyor belt

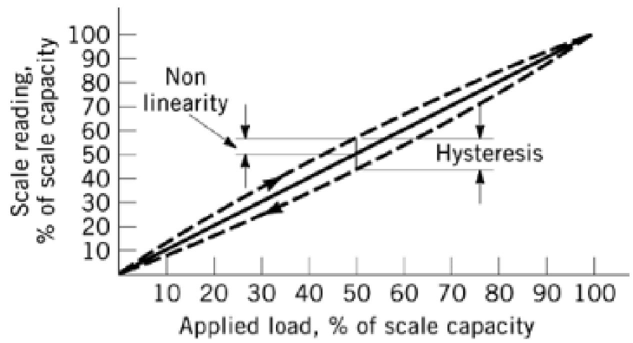

Fig. 11. Scale calibration curve (---); $\longrightarrow$, increasing load direction; $\longleftarrow$, decreasing load direction.

Direct readout and adaptability to modern controls

Some of the disadvantages are as follows:

Low accuracy, unsuitability for commercial transactions
Variations in material geometry and density affect accuracy
Requires shielding and special procedures to avoid exposure of personnel to radiation
Frequent recalibration is required to compensate for source decay over time
Electrical power and power line transient protection required

3. Commercial Regulatory Aspects and Performance Characteristics

3.1. Scale Performance

Figure 11 shows the relationship between the applied load and the scale reading. The ideal scale would have a perfectly linear relationship, as represented by the straight line, and the results from increasing and decreasing load tests would fall on this line. The two broken lines represent the typical calibration curve (greatly exaggerated); the arrows indicate increasing and decreasing load directions.

Definitions of some terms commonly used in describing scale performance follow (6, 7):

Nonlinearity: the maximum deviation from the straight line as load is applied, usually expressed as a percentage of scale capacity (see Fig. 11)

Hysteresis: the maximum difference between the increasing and decreasing load curves at a given load, expressed as a percentage of scale capacity (see Fig. 11)

Nonrepeatability: the maximum difference in scale readings when the same test load is applied repeatedly under the same conditions, expressed as a percentage of scale capacity

Creep: the change in scale reading when a load (usually scale capacity) is applied for a period of time, and all other variables are held constant; it is expressed as a percentage of applied load in a specified time period

Value of the scale division, d: the difference between two consecutive weight readings on the scale's display, expressed in units of mass, eg, if a scale display increments upwards in steps of 0.02 g, $d = 0.02$ g

Number of scale divisions: the scale capacity divided by d, eg, a scale of 5-kg capacity with a 1-g scale division has 5,000 scale divisions

Shift error: the range of results obtained when a test weight is moved around the scale platform in a specified manner (5), expressed as a percentage of scale capacity

Temperature effect on zero: the change in the scale's no-load reading with changes in ambient temperature, expressed as a percentage of scale capacity per °C, or the number of scale divisions per 5°C

Temperature effect on span: the change in a scale's calibration with changes in ambient temperature, expressed as a percentage of scale capacity per °C

Accuracy: a measure of the extent to which a scale can provide results that conform to the true value

3.2. U.S. Regulations

Weighing equipment used in commercial transactions is subject to regulation and inspection by state or local weights and measures agencies. It must comply with certain design and performance requirements, and must have a certificate of conformance issued prior to installation. *Handbook 44* issued by the National Institute of Standards and Technology is the basis for weights and measures enforcement activities in the United States (5). It covers scales used in buying or selling goods of any kind, and scales for determining the cost of services, eg, shipping and laundry charges. Although *Handbook 44* does not apply to scales used only to control processes or to measure yield or inventory, the majority of scales used comply with its requirements. Thus, *Handbook 44* provides a standardized and comprehensive basis for comparison of scales for industrial and retail applications.

Handbook 44 defines five accuracy classes for scales in terms of the value of the scale division and the number of divisions. Class I applies to precision laboratory weighing. Class II applies to laboratory weighing (precious metals, gems, and grain test scales). Class III applies to the majority of industrial and retail scales, and to all scales not specified in the other categories. Class III L applies to vehicle, livestock, railway, crane, and hopper scales. Class IIII applies to portable scales used for highway weight enforcement.

Table 1 is condensed from *Handbook 44.* It lists the number of divisions allowed for each class, eg, a Class III scale must have between 100 and 1,200 divisions. Also, for each class it lists the acceptance tolerances applicable to test load ranges expressed in divisions (d); for example, for test loads from 0 to 5,000 d, a Class II scale has an acceptance tolerance of ± 0.5 d. The least ambiguous way to specify the accuracy for an industrial or retail scale is to specify an accuracy class and the number of divisions, eg, Class III, 5,000 divisions. It must be noted that this is not the same as 1 part in 5,000, which is another method commonly used to specify accuracy; eg, a Class III 5,000 d scale is allowed a tolerance which varies from ± 0.5 d at zero to ± 2.5 d at 5,000 divisions. Calibration curves are typically plotted as in Figure 12, which shows a typical 5,000-division Class III scale. The error tunnel (stepped lines, top and bottom) is defined by the acceptance tolerances listed in Table 1. The three calibration curves belong to the same scale tested at three different temperatures. Performance must remain within the error tunnel under the combined effect of nonlinearity, hysteresis, and temperature effect on span. Other specifications, including those for temperature effect on zero, nonrepeatability, shift error, and creep may be found in *Handbook 44* (5). The acceptance tolerances in Table 1 apply to new or reconditioned equipment tested within 30 days of being put into service. After that, maintenance tolerances apply; they are twice the values listed in Table 1.

3.3. Regulation Outside the United States

Each country establishes its own weights and measures requirements. The majority of these are based on the recommendations of the Organisation Internationale de Métrologie Légale (OIML), in Paris. *R76-1* is the OIML equivalent of *Handbook 44;* it uses accuracy classes and an acceptance tolerance structure similar in many ways to Table 1 (8).

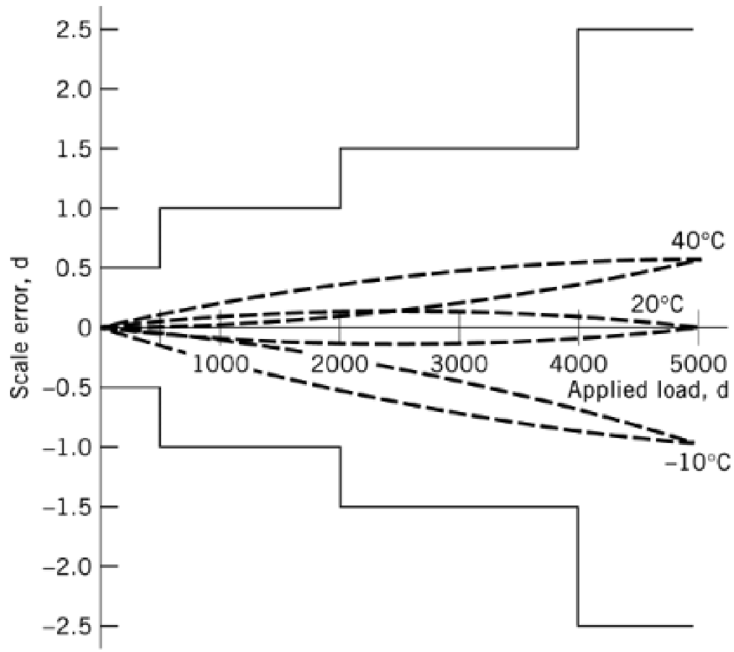

Fig. 12. Calibration curves for a *Handbook 44* Class III 5,000 d scale. See text.

Table 1. Summary of Tolerances and Number of Divisions Applicable to Accuracy Classes[a]

	All values in this table are in scale divisions				
Parameter	Class I	Class II	Class III	Class III L	Class IIII
allowed number of divisions	50, 000+	100–100,000	100–10,000	2,000–10,000	100–1,200
acceptance tolerances					
±0.5 d	0–50,000	0–5,000	0–500	0–500	0–50
±1 d	50,001–200,000	5,001–20,000	501–2,000	501–1,000	51–200
±1.5 d	200, 000+	20,001–100,000	2,001–4,000		201–400
±2.5 d			4,001–10,000		401–1,200
add 0.5 d/500 d[b]				1,001–10,000	

[a]Ref. 5.
[b]Add 0.5 d tolerance for each additional 500 d or fraction thereof.

4. Factors Affecting Weighing Accuracy

4.1. Variations in the Force Due to Gravity

The mass of an object is the quantity of matter in the object. It is a fundamental quantity that is fixed, and does not change with time, temperature, location, etc. The standard for mass is a platinum–iridium cylinder, called the International Kilogram, maintained at the International Bureau of Weights and Measures, in Sèvres, France. The mass of this cylinder is 1 kg by definition (9). All national mass standards are traceable to this artifact standard.

It is easiest to appreciate what is meant by mass indirectly, by observing the influence of forces on objects, eg, by picking up an object and sensing the effect of the earth's gravitational force acting on it, and hence "feeling" its weight.

Newton's law of gravitation states that if two particles are a distance r apart, the mutual attraction force between them can be expressed as follows (10):

$$F = \frac{6.673 \times \left(10^{-11}\right) m_0 m}{r^2} \qquad (1)$$

where F is the mutual attraction force in N, m_0 and m are the masses of the particles in kg, and r is the distance between their centers in meters. This equation can be used to calculate the attractive force between the earth and a mass, m, resting on its surface (mass of the earth is 5.976×10^{24} kg and its mean radius is $6,371 \times 10^3$ meters) as follows:

$$F = \frac{6.673 \times \left(10^{-11}\right) 5.976 \times \left(10^{24}\right)(m)}{\left(6,371 \times 10^3\right)^2} = 9.82\,(m) \qquad (2)$$

A mass, m, resting on the surface of the earth is attracted to it with a force of 9.82(m) N. Put another way, the force per kg experienced by a mass resting on the earth is 9.82 N/kg. The proportionality factor 9.82 is referred to as gravity, or *g;* it is sometimes referred to as acceleration due to gravity with the equivalent units of m/s^2 (11).

The factor g was calculated using the earth's mean radius; g actually varies with changes in location and altitude. The earth is not spherical; it bulges at the equator; ie, an object at either of the poles is actually nearer to the center of the earth. Also, the earth is rotating on its axis, and an object at the equator is subject to a small centrifugal force that is not present at the poles. For both of these reasons, g increases with increasing latitude from the equator to the poles. In addition, g decreases with increasing altitude above the earth's surface. All of these factors are taken into account in Helmert's equation for *g:*

$$g = 9.80616 - 0.025928\cos 2\phi + 0.000069\cos^2 2\phi - 3.086 \times 10^{-6}\,h \qquad (3)$$

where φ is the latitude in degrees and h is the altitude in meters. Table 2 gives the value of g at various locations.

Using an equal-arm balance (see Fig. 1), the unknown mass of an object can be determined by placing it in one pan, and adding test weights to the other until the beam balances. The result will be the same regardless of location because the object and the test weights are subject to the same value of g. Any scales that measure an unknown mass by comparing it with a known mass (with or without a lever system), will be unaffected by variations in g. However, this is not a very convenient method of weighing, and the majority of scales in use today determine the mass of an object indirectly by measuring the gravitational force acting on it. If a scale is calibrated at one location, and is used at another, the reading would change by a factor of g/g_c, where g and g_c are gravity at the point of use and calibration, respectively. If a mass weighed 5,000 kg on a force-measuring scale in Miami, Florida, it would weigh 5016 kg $(5,000 \text{ kg} \times 9.82192/9.79053)$ if weighed on the same scale in St. Michael, Alaska, a change of 0.3%. In the extreme case, a variation of 0.7% could be expected. Force-measuring scales should be recalibrated when relocated.

Some scales have a software feature whereby a certain geographical region is identified on initial configuration, and the software then makes the appropriate correction. Some high performance balances have built-in test weights for initial (and periodic) calibration.

Table 2. Values for Gravity, *g*, at Various Locations

Location	Gravity, g, N/Kg	Location	Gravity, g, N/kg
United States		*Other countries and areas*	
St. Michael, Alaska	9.82192	Arctic Red River, Canada	9.82434
Quiet Harbor, Alaska	9.81624	Vancouver, Canada	9.80949
Los Angeles	9.79595	Canal Zone, Panama	9.78243
San Francisco	9.79965	Greenwich, U.K.	9.81188
Denver	9.79609	Königsberg, Germany	9.81477
Hartford, Conn.	9.80336	Rome, Italy	9.80367
Washington, D.C.	9.80095	Monrovia, Liberia	9.78165
Key West	9.78970	Bergen, Norway	9.81922
Miami	9.79053	Stockholm, Sweden	9.81843
Honolulu	9.78591	Balia, Brazil	9.78331
St. Louis	9.80001	Kingston, Jamaica	9.78591
New York	9.80267	North or South Pole, sea level	9.83217
El Paso	9.79124	equator, sea level	9.78039
Seattle	9.80733	equator, 500 m above sea level	9.76496

Scales are sensitive to force applied in one direction only, eg, a scale with a horizontal platform is sensitive to forces applied perpendicular to the platform. Scales should be leveled before calibration and whenever they are moved; portable scales generally have a bubble level to facilitate leveling.

Slight changes in altitude can significantly affect precision balances of the force-measuring type (note that Helmert's equation for g accounts for the effects of altitude). For example, if an analytical balance is relocated from the basement to the 12th floor of the same building (a change of 48 m in altitude), and is used to weigh a mass of 250 g, the reading will be lighter by 3.8 mg on the 12th floor. Again, recalibration is required.

4.2. Moisture Content

In making very fine measurements, it might be necessary to protect a sample from the possibility of losing or absorbing moisture during the weighing operation. This is particularly true if the weighing chamber is at a different temperature or humidity compared to the sample's storage location. In weighing highly volatile liquids, evaporation during the weighing process may cause a steady decline in the weight reading. In either case, the sample should be weighed in the smallest practical covered container.

Materials subject to variable moisture content are frequently treated on a dry weight basis, or on some other standard moisture content basis. In such cases, the moisture content of the material being weighed must be determined, and the actual weight converted to the desired basis. Moisture analyzers are available that incorporate a balance and heating element in one unit. They monitor a sample's weight while the temperature is elevated to expel moisture. Typically, such units operate automatically and display the moisture content directly as a percentage of the original weight.

4.3. Temperature Effects

The output of a strain-gauge load cell changes with temperature because of, for example, changes in gauge resistance and because the gauge and spring element have different coefficients of thermal expansion. Also, with EMFC balances the strength of the permanent magnet changes with temperature, changing the amount of current necessary to balance the load. Good design and careful manufacturing can compensate for most of these effects, but they will not eliminate them completely.

When power is applied to an electronic scale, it warms up and is somewhat unstable until thermal equilibrium is reestablished. The manufacturer's recommendations with regard to warm-up period should be followed.

Strain-gauge load cells are sensitive to temperature gradients induced by, for example, radiant heat from the sun or resulting from high temperature wash down. Load cells should be shielded from such effects or given time to stabilize before use.

Scales will always perform better in a temperature-controlled environment; this is particularly important for high precision balances. Those designed to automatically recalibrate as conditions change will perform better in less-than-ideal conditions.

Where there is a temperature difference between the object to be weighed and the surrounding air, air currents will be induced close to the object's surface (12). These can be significant if extreme accuracy is required. Objects should be allowed to reach thermal equilibrium in the laboratory before weighing. Just as important, the balance should be designed to minimize the temperature rise inside the weighing chamber. In extreme cases, the object should be placed inside the chamber until it reaches thermal equilibrium before weighing. Needless to say, drafts must be avoided.

4.4. Buoyant Effect of Air

Weighing operations performed *in vacuo* are not affected by buoyancy forces. An object in air, however, is subject to a buoyancy force that is equal and opposite to the gravitational force on the mass of air the object displaces (10). If the equal arm balance of Figure 1 is in balance with a test weight of mass, m', in one pan, and material of mass, m, in the other, $m = m'$ if they have the same density. If the densities are different, then the buoyancy forces acting on each pan affect the result. Taking moments about the center pivot point gives

$$g\,(m - \rho_{\mathrm{air}} V_m) = \left(m' - \rho_{\mathrm{air}} V_w\right) g \qquad (4)$$

where ρ_{air} is the density of air (1.2 kg/m^3 on average), V_{m} and V_{w} are the volumes of the material and test weight, respectively, in m^3. By expressing V_{m} and V_{w} in terms of mass and density, this equation can be expressed as

$$m = m'\,(1 - \rho_{\mathrm{air}}/\rho_w)\,/\,(1 - \rho_{\mathrm{air}}/\rho_m) \qquad (5)$$

where ρ_m and ρ_w are the densities of the material and test weight, respectively, in kg/m^3. This expression can be used to calculate the actual mass, m, from the apparent mass, m', indicated by a scale (true for all scales except nuclear). From equation 5, it can be seen that if $\rho_m = \rho_w$, then $m = m'$, as would be expected.

If a 1-kg stainless weight ($m' = 1,000\mathrm{g}$, $\rho_w = 8,000$ kg/m^3) is added to one pan of the balance in Figure 1, and material with a density of 1,000 kg/m^3 is added to the other until equilibrium is reached, the amount of the material needed is 1001.05 g, using equation 5. Thus, it takes 1001.05 g of this material to counterbalance 1,000 g of stainless steel, because of the buoyancy effects on the dissimilar volumes.

Buoyancy has no effect in weighing material of the same density as the test weight (used for direct comparison, or used to calibrate the balance), or in proportioning materials of approximately the same density. In general, the recipes used in proportioning are derived empirically, and account for the effects of buoyancy. Buoyancy effects can be significant when the absolute mass must be known accurately, eg, in a laboratory environment, and corrections can be made using equation 5. In industrial and commercial weighing, the effect of buoyancy is generally not considered. Note that variations in air density, eg, due to variations in temperature, can also have a slight effect on weighing repeatability.

4.5. Electrostatic and Magnetic Effects

These two effects are generally small but may be significant in laboratory weighing.

If an electrostatically charged object is weighed close to a charged or conducting surface not being weighed, then weighing accuracy is likely to be affected by the forces which result. Similar problems arise as a result of magnetic effects. Some materials can be permanently magnetized, and others temporarily exhibit magnetic behavior when placed in a magnetic field. When weighed, these materials can seem heavier or lighter if they are in close proximity to a magnetically permeable material, or if they are surrounded by a magnetic field, eg, the earth's magnetic field, or one produced by external equipment.

To avoid electrostatic problems, the air in the laboratory should be maintained at 40% relative humidity or higher, or the air should be ionized. Shielding the sample is also effective against electrostatic and magnetic influences. If the item is electrostatically charged or in a magnetized state, it should be weighed in a metal container. The container can be any conductive metal for electrostatic problems, but it should be magnetically permeable (such as soft iron) for magnetized items. Also, an item that is strongly magnetic should be placed on a nonpermeable spacer such as plastic to lift it away from the scale.

A slightly different arrangement is called for if the balance becomes electrostatically charged, which may happen to the glass panels of the draft shield in low humidity environments, for example, or if it is subjected to an external magnetic field. In this case a shield of the materials described above should be inserted between the item on the balance and the external influence. The shield, eg, a bell-shaped container, must not be supported by the pan of the balance. To facilitate shielding, some balances have an opening which allows a weighing pan to be suspended at any distance below it.

5. Types of Scales

Scales are available in a variety of designs and configurations to facilitate different weighing operations (7). The two principal categories are industrial and retail scales, and precision scales and balances.

5.1. Industrial and Retail Scales

Scales using strain-gauge load cells predominate in this market segment, although mechanical and hydraulic scales are also used to some extent. Many are used in commercial applications, and are typically of accuracy class III or III L with up to 10,000 divisions. The following are descriptions of some industrial and retail scales.

Bench scales are small and light enough to be placed on a bench or table. They generally have a platform on which small quantities can be placed by hand. Alternatively, some have a roller conveyor platform on which the item is moved across the scale. Capacities range from 5 kg to 250 kg.

Retail scales in various configurations are used in stores and supermarkets to determine price. They range from simple weigh-only scales to ones having touch screens and enough memory to store and print data on thousands of products, including the data necessary to print nutritional labels. They range in capacities up to 25 kg.

Portable scales generally have a platform near the floor with the indicator mounted on a column for ease of operation. These scales may be on wheels, and many are battery-powered. Capacities are generally less than 600 kg. Bench scales can be placed on a wheeled table for similar use.

Counting scales are a form of bench scale that can display not only weight, but also the number of parts on the weighing platform. In operation, a small number of parts is put on the scale, which then automatically establishes the average piece weight; if a large quantity is placed on the scale, the scale divides the total weight by the average piece weight and displays the number of parts.

Floor scales are platform scales which are permanently installed in a pit, flush with the floor, or which sit on the floor. These scales typically range in capacity from 500 kg to 30 t, and in size up to that required to accommodate a fork-lift truck.

Truck scales weigh highway vehicles; they may be installed in a pit or above-ground with inclined approach ramps. A capacity of 100-t is typical. For monitoring axle weights, the scale deck can be broken into three scales, which are monitored independently; the individual axle weights or total vehicle weight can be displayed by the indicator.

Railroad-track scales are installed in a pit and support the appropriate length of rail to weigh railroad cars. For static weighing of cars, the rails are generally long enough to support the entire car; capacities range up to 350-t. Some railroad weighing is done with the cars coupled and in motion (CIM). In this case the rails of the scale may be long enough to weigh the entire car or just each truck. Some scales have a flat deck so that highway vehicles can be weighed in addition to railroad cars.

Monorail scales are constructed by removing a section of monorail track and replacing it with a similar section that is mounted on a scale. Loads transported by crane or on roller hangers can be weighed quickly and easily. Capacities range up to 5 t.

Crane scales are designed to be inserted between the hook of a crane and the load being lifted. The upper end of the scale has an eye which attaches to the crane's hook, whereas the lower end has a hook that picks up the load. A tension-type load cell connects the eye and hook. The display may be either integral with the load cell or remotely mounted. Capacities range up to 50 t.

Tank and *hopper scales* weigh liquids or bulk materials. The materials may be stored in the scale, or may be weighed while being transported for sale or for use in a process. The scale is usually part of a much larger material handling system. Capacities are mostly under 20 t, but can be as large as 200 t or more.

Drum-filling scales position a container on the weighing platform and, using a suitable lance, fill the container to the required weight. The handling and filling of the containers can be either manual or fully automated. *Bag-filling scales* are of a similar type; the material may be weighed either in the bag or in a hopper scale before discharge into the bag.

Belt- conveyor scales determine the amount of material being conveyed on a belt. A section of belt is weighed by placing the belt support rollers on a scale; the belt speed is also measured. Weight and speed data are supplied to a controller which integrates them to arrive at a material flow rate, often stated in tons per hour. The controller may display a flow rate, shut the conveyor down when a predetermined amount of material has passed, or it may be used to maintain a specified flow rate. Accuracy is limited because of the number of detrimental influences involved, eg, variable belt tension.

In-motion checkweighers weigh discrete items as they move along a production line on a belt or chain. The checkweigher may automatically eject items of unacceptable weight, or may divert them into several streams corresponding to predetermined weight categories. The weight information may be analyzed statistically and used to adjust the filling equipment automatically. In certain applications, the checkweigher may regulate the spacing of packages before weighing. Systems are available to handle various package sizes at speeds of up to 900 packages per minute.

5.2. Precision Scales and Balances

These products today rely predominantly on electromagnetic force compensation (EMFC) technology. Most are not used in commercial transactions; however, many approved models are available. Some of the precision scales fall into accuracy class III, but Class I and Class II are more typical for the balances. *Handbook 44* is of limited value in describing the accuracy characteristics of these products because, for example, 1 mg is the smallest division size allowed. For this reason, only the number of displayed divisions is discussed herein.

Types of precision scales and balances include the following:

Precision bench scales are designed for use in industrial settings; they typically have capacities below 50 kg and 30,000 or more displayed divisions. Typical applications are counting very small parts or weighing hand-add materials for proportioning operations.

Precision floor scales have platform sizes of 1.5 m square or larger, and typically use a lever system to transmit the load to a single EMFC load cell. Capacities range up to 6 t with a minimum of 30,000 displayed divisions.

Precision balances are similar to precision bench scales but are typically used in laboratory settings with up to 500,000 displayed divisions.

Analytical balances are higher accuracy laboratory balances with capacities up to 400 g, and up to 20 million displayed divisions.

Microbalances typically have capacities from 2 g to 5 g, with 20 to 50 million displayed divisions.

Mass comparators are balances of particularly high accuracy and are designed, as the name implies, for comparison of masses within a very narrow weighing range. A typical application is the calibration of test weights by comparison to known standards. Repeatability of weighments is the critical factor; a typical comparator might have a capacity of 1,000 g, a displayed division size of 1 μg and a repeatability of 2 μg (one part in 500 million). Capacities range from 5 g to 1.5 t.

6. Weighing Methodologies

Scales can be portable so that they can be moved about and temporarily located where the weighing operation is to take place; they may be light enough to be carried by hand, or they may be on wheels or be transported using a lift truck. Even some truck scales are considered portable because, for example, they are designed to be transported from one highway construction project to another. Some scales are attached or built into portable material-handling devices such as cranes and lift trucks, so that the weighing operation can take place while material is being transported.

Some scales are fixed in position and the material to be weighed is brought to the scale. Higher capacity floor scales, truck scales, and railroad-track scales are typically fixed in position; these scales should be located where they are convenient for the weighing operation, but are not subjected to unnecessary abuse from through traffic. Scales are often built into fixed material handling or processing equipment so that material can be weighed as it is being moved, eg, as in the cases of conveyor, tank, and hopper scales. Scales can be built into tanks or silos used for storage, either for inventory control or for controlling the discharge of these materials.

The object of a weighing operation may be to determine the gross weight (the weight of the material plus the tare weight of its container) or, more commonly, the net weight (the weight of material exclusive of its container). Gross weight is used to determine shipping charges, for example, while net weight is used to determine selling price.

There are various reasons for weighing materials and various methods employed; the most common ones are discussed below. It is assumed for the sake of discussion that net weight is the requirement, since it is the more common.

6.1. Weighing Predefined Quantities

In this form of weighing, the amount of material has been defined prior to weighing, eg, by filling a truck to a certain level, and the weighing operation is carried out simply to determine what the weight is. An object may be placed on a scale and its net weight will be displayed directly (assuming the object is not packaged). Bulk materials may be handled in anything from small containers to railroad cars; the weighing operation consists of measuring the gross weight and subtracting the container's tare weight to arrive at the material's net weight. A truck in–out operation provides a good illustration of this form of weighing; when a truck arrives at a terminal, it pulls onto the scale and its weight (gross or tare, depending on whether it is delivering or picking up a load) is stored in memory by the scale. The truck is then filled or emptied and returns to the scale before exiting the terminal; the scale now has the truck's gross and tare weights and can automatically display the net. Typically the scale prints a ticket listing gross, tare, and net weights, along with the time and date. The information may also be transmitted to a computer for accounting or inventory control.

Tank and hopper scales can weigh in one draft or in multiple drafts. A hopper scale used for multiple-draft weighing of material in transit is commonly called a bulk weigher (Fig. 13). An accumulating or surge hopper with a feed gate is installed above the scale hopper; a surge hopper is also installed below the scale hopper. In operation, material flows into the scale until the feed gate is closed by the controller; the actual load on the scale is recorded and the scale hopper's discharge gate is opened temporarily to empty the scale. Any material left in the scale is weighed and subtracted from the stored weight to arrive at the net weight for that draft. This operation is repeated until the quantity to be weighed has passed through the scale. This system can be used to weigh a definite amount, such as that contained in a railroad car or a ship, with an error of $<0.1\%$ of net weight. If the input is from a car or ship and the output is to storage, it functions as a receiving scale; if the input is from storage and the output to a car or ship, it functions as a shipping scale. As a receiving scale, it weighs a predefined quantity; as a shipping scale, it may be used to weigh out a particular quantity to fill a car or ship optimally.

Some of the various methods of weighing the material in a railroad car, arranged approximately in increasing order of accuracy, are:

- Weighing the loaded car on a coupled-in-motion track scale. An entire train, typically, is hauled at slow speed over the scale. The net weight is determined by subtracting the tare weight stenciled on the car
- Weighing the material on a belt-conveyor scale as it is put into, or removed from, the car
- Weighing the gross weight of the car on a static railroad track scale and subtracting the actual tare weight of the car, determined by weighing the empty car before loading or after emptying, as appropriate
- Using a bulk weigher as described above to measure the material either being placed in, or removed from, the car
- Weighing the complete load delivered to, or received from, the car as a single draft in a hopper scale.

6.2. Controlling Weight

Filling containers to predetermined weights is the most common example of controlling weight. One method is the net-weighing process, in which material is fed into a hopper or tank scale until the desired weight is reached; it is then discharged into the container. This method is often used in bag filling. In the gross-weighing method, the container is placed directly on the scale and filled to the required weight. Drum fillers are an example of the use of this method. Either filling operation may be controlled manually by an operator observing the scale display; more typically, the filling is completely automated for better consistency and greater speed.

6.3. Continuous Weighing and Controlling

Scales can be used to determine the weight per unit length of material in sheet or strip form as it is being manufactured or transported. This weight information can be used to control moisture content, addition of sizing or other materials, or to control an extrusion process. The material can pass over a roll that is weighed, or over a belt-conveyor scale. Direct mass measurement with a nuclear scale can also be used for this application.

Process industries frequently need to weigh and control the flow rate of bulk material for optimum performance of such devices as grinders or pulverizers, or for controlling additives, eg, to water supplies. A

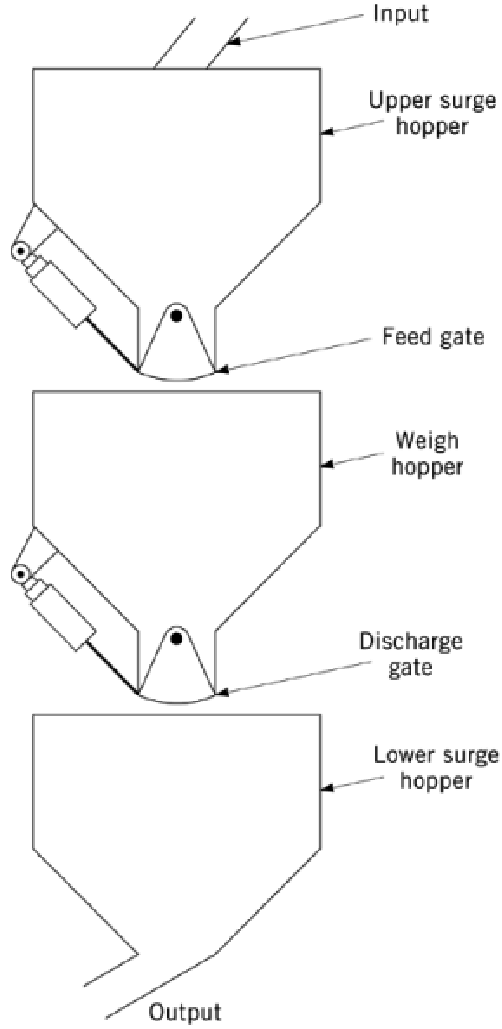

Fig. 13. Bulk weigher.

scale can be installed in a belt conveyor, or a short belt feeder can be mounted on a platform scale. Either can be equipped with controls to maintain the feed rate within limits by controlling the operation of the device feeding the material to the conveyor. Direct mass measurement with a nuclear scale can also be used to measure and control such a continuous stream of material.

Two weigh hoppers can be arranged in parallel to provide accurate quantities of material without interruption (Fig. 14). In operation, weigh hopper A discharges while weigh hopper B is being filled to the appropriate weight. When hopper A empties completely, hopper B begins discharging; hopper A begins filling again, ready to discharge when hopper B is empty. Through correct sequencing, a continuous stream of material can be supplied.

The most accurate flow rate control can be achieved by using the loss-in-weight method. The total amount of material required for a downstream process is first added to a tank or hopper scale. As the material is

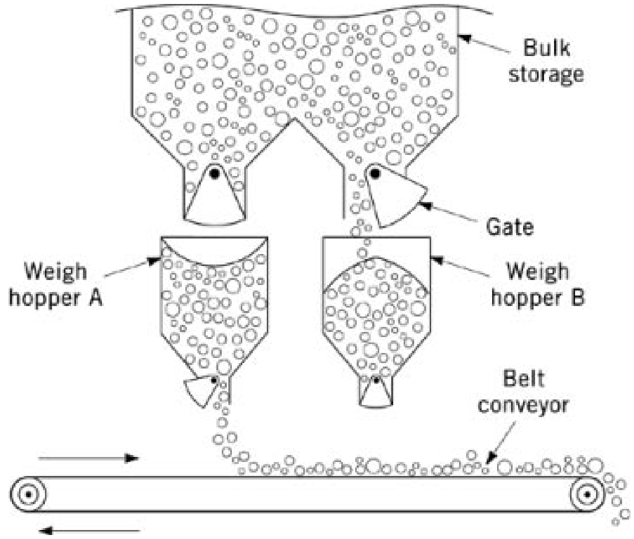

Fig. 14. Parallel weigh hoppers.

discharged, the loss-in-weight is monitored and used to modulate the discharge valve or gate to achieve the desired flow rate.

6.4. Material Proportioning

In proportioning operations, two or more materials are weighed and mixed according to a recipe for use in a chemical process or to make a mixed product, such as animal feed. Proportioning can be performed manually on a bench scale or automatically in tank and hopper scales employed with elaborate material handling systems and controls. Proportioning can be done on a continuous basis or, more typically, in batches, which yield greater accuracy.

Where the manufacturing process is continuous, the equipment described herein on continuous weighing can be used. For low accuracy systems, two or more belt-conveyor scales can be run in parallel, supplying different materials at appropriate feed rates. For higher accuracy, two or more parallel weigh hopper systems (see Fig. 14) can be sized appropriately for each material and run in parallel to provide continuous proportioning. Multiple loss-in-weight systems may also be used. In some processes, the flow of the primary ingredient is measured but not controlled, and the addition of minor ingredients is modulated accordingly for correct proportioning, using a belt-conveyor scale or loss-in-weight feeder.

The three principal methods of batch proportioning are accumulative, sequential, and simultaneous; the best method for a given application depends on the processing equipment available and the accuracy required.

In the case of accumulative proportioning, a single-weigh hopper having adequate capacity for the entire batch is used (Fig. 15). Each ingredient is weighed in turn and accumulated in the hopper scale until completion of the batch. This system has the advantage of lower cost and space requirements; the disadvantage is that the accuracy of minor ingredients suffers if a small amount of these materials is weighed relative to the scale's capacity. Also, in multiple-recipe systems there is the danger of cross contamination if some materials are not used in all recipes.

In sequential proportioning, the physical configuration is the same as that shown in Figure 15, but each material is weighed and discharged before weighing of the next ingredient begins. If all ingredients weigh

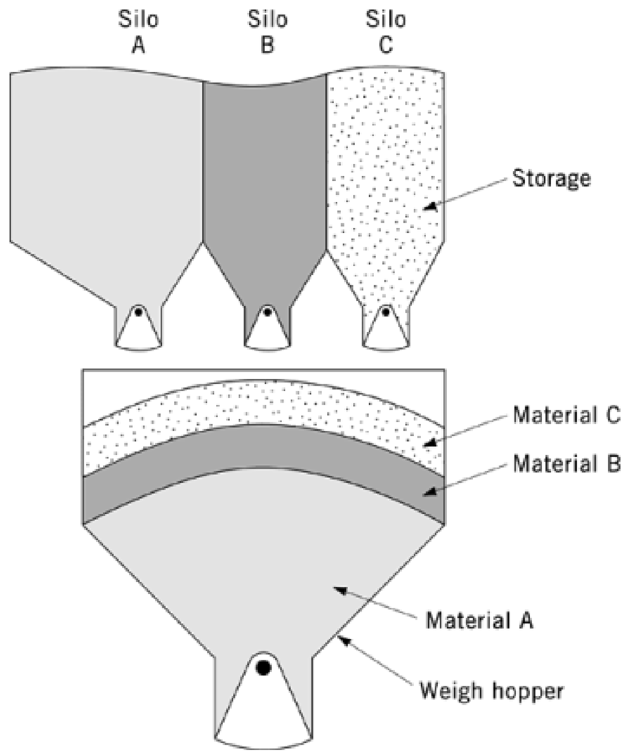

Fig. 15. Accumulative proportioning system.

about the same, higher accuracy can be achieved with this system by matching the weigh hopper capacity with the weight of material to be weighed. This system is relatively slow because of the multiple-discharge cycles.

In the case of simultaneous proportioning, a weigh hopper is provided for each material, as shown in Figure 16. This system has several advantages. It is fast because all materials are weighed and discharged simultaneously. Before discharging, the weight of each ingredient can be compared to the recipe and adjusted if necessary. There is less danger of contamination if some materials are not used in all recipes. The capacity of the weigh hoppers can be matched closely to the weight of each ingredient. By simultaneous discharge onto the belt, a certain amount of premixing can be achieved. The disadvantages are the relatively high cost and the amount of space required. Simultaneous systems can be designed to handle up to 150 tons per hour or more, and are often used to feed several mixers or processes. Combination systems are becoming more common: in this arrangement, an accumulative hopper is included in a simultaneous proportioning system. Individual weigh hoppers are provided for the high volume and critical materials, whereas several of the lower volume or less critical materials are proportioned in the accumulative weigh hopper. Assuming proper sizing of such a system, cost is reduced without compromising speed. Regardless of the system used, critical ingredients such as food additives or dyes are often weighed on an appropriate balance and added manually.

7. Scale Functionality

Mechanical scales indicate the weight applied to the scale through the manipulation of a poise weight on a beam, or automatically using a pointer and dial. Simple control functions can be accomplished by adding

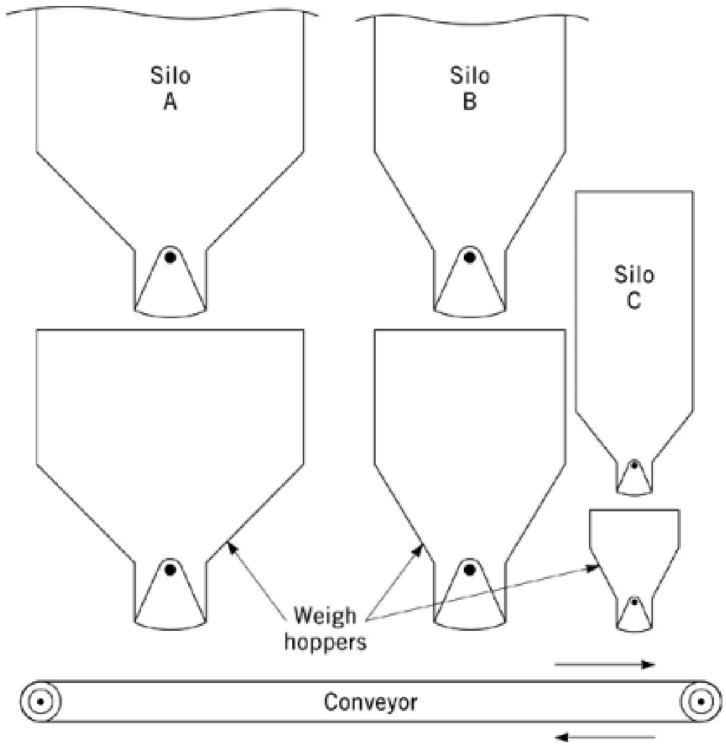

Fig. 16. Simultaneous proportioning system.

position sensors to the indicator or lever system. However, many mechanical scales have been converted to electromechanical by inserting a load cell in the steelyard rod; this allows the scale to take advantage of the wide range of functionality available from electronic indicators. In new installations, electronic scales are typically installed if any form of data collection or control is required.

Electronic scales are microprocessor-based devices that provide a range of features for various applications. At its most basic, an electronic scale provides a digital display of the applied weight; a zero button is usually provided so that slight deviations from the zero indication can be corrected periodically. Many simpler scales also provide tare and gross/net buttons. The tare button is used to store an empty container weight in memory for subtraction from subsequent weighments; the gross/net button allows the display to toggle between the gross and net weights. Where it is equipped with numeric or alphanumeric keypads and various function keys, an electronic scale can perform a number of functions directly or indirectly related to weighing. The following examples illustrate some possible uses.

Some indicators are designed for truck in–out operations. The indicator can store tare weights for several hundred vehicles, linking them to the trucks' registration numbers. Regardless of the sequence in which the trucks arrive and depart, the scale can provide a printout of gross, tare, net, and time and date for each transaction with just a single weighing of each vehicle. Net weights can also be accumulated in user-specified categories to provide totals and subtotals for billing or inventory control.

Counting scales display the number of parts on the scale as well as the total weight. They establish the average piece weight (APW) of the parts to be counted, which can be stored in memory along with the part number and an associated tare weight. In the case of cycle counting operations, for example, a bin of parts is placed on the scale and the APW and container weight is recalled by keying in the part number; the scale then calculates the net weight of the parts and divides by the APW to arrive at the parts count. This information can be displayed and stored in memory for automatic uploading to the main computer for correction of inventory records. Counting scales can also be used with bar code scanners to eliminate the need for keying part numbers. It is common practice to store all APW and tare weights on a main computer from which it is downloaded to the scale daily, as an indication of what needs to be cycle counted that day.

Over/under scales are often used for manually filling containers to a desired weight; they are often found in the meat and poultry industry. In addition to the normal weight display, these scales typically have lights or a bar graph to indicate to the operator when the weight is under, within, or over the desired weight range. Employing a part or product look-up (PLU) number, various information can be stored for several items, eg, the target weight, the allowable tolerance values around this target, and an associated tare weight. This information can be programmed at the scale or downloaded from a central computer. Groups of these scales are often networked together with a central computer which can be used to download setup parameters to the scales for fast production line changeovers. The central computer can also collect weight information from each scale for production monitoring and statistical process control.

Scales can be connected with printers, remote displays, bar code scanners, keyboards, relays, computers, and various controllers such as programmable logic controllers (PLCs). Scales typically have one or more simplex or duplex serial ports that can be current loop, RS-232, RS-422, or RS-485. Frequently ports are programmable for on-demand or continuous data output, eg, for periodically transmitting weight data to a printer or continuously to a remote display. RS-422 and RS-485 are typically used in multidrop systems where a single computer may be used to communicate with several scales. Scales can be part of a local area network such as ARCnet, together with other devices such as printers, controllers, and computers. Scales often have an analogue output such as 4-20mA or 0-10 VDC for communication with controllers such as PLCs. Some weight indicators have digital inputs and outputs (I/O); the inputs, for example, could be used for remote operation of scale buttons such as print or tare, whereas the outputs could be used to activate alarms when a particular weight is achieved. Weight indicators designed specifically for batching applications are also discussed herein.

8. Tank and Hopper Scale Design Considerations

Industrialapplications often require that bulk materials or liquids be weighed in hoppers, silos, tanks, or reactor vessels, referred to collectively as vessels. Because they come in such a wide variety of sizes, shapes, and capacities, scales using these vessels as load receivers are not typically available as standard products. Vessels are usually custom-fabricated to suit a particular application, then mounted on a scale. Some can be mounted on a standard scale such as a bench, portable, or floor scale. More typically, a number of weigh modules are used to support the vessel. This offers the scale designer great flexibility but certain precautions are necessary in order to construct an accurate scale. Some of the more important factors associated with the design of vessel scales are discussed herein.

8.1. Weigh Modules

Load cells have a single axis along which load should be applied; forces applied in other directions or torques can have a very detrimental effect on weighing accuracy (13). Weighing technology is often applied to existing vessels which were not designed with weighing in mind. Complicating factors can include less-than-ideal sites, excessive deflections of the vessel and support structure, and thermal expansion and contraction of the vessel, particularly where heated materials are weighed. All of these factors can contribute to poor scale performance by applying extraneous forces to the load cells. To accommodate these problems, load cells are incorporated into weigh modules, which are mechanical assemblies designed to introduce the load correctly to the cell while allowing the vessel to expand and contract, and deflect under load. Weigh modules typically have top and bottom plates that allow them to be inserted conveniently between the vessel and support structure. Several weigh modules are usually used per scale to provide the required stability. Weigh modules are available in capacities of from 25 kg to 100 t or more; they use both hydraulic and strain-gauge load cells, the latter being the more common. The outputs from the various load cells are summed and a signal provided to an indicator for display and control.

8.2. Tension and Compression Arrangements

Vessel weighing configurations can be divided into tension and compression systems.

Tension systems are often used where a suitable overhead structure already exists, or where the area under the vessel must be kept clear of obstruction. Figure 17 illustrates the use of tension weigh modules on a weigh hopper. Each module typically consists of an S-type load cell, two rod end ball joints, and two clevises. This arrangement allows the load to be applied correctly in the axial direction, while minimizing any bending or twisting forces. Tension systems easily accommodate thermal expansion or contraction of the vessel because of the long suspension rods and hardware used. The hardware is simple and the floor space under the vessel remains free of obstruction. Disadvantages include the need for a rigid overhead structure, and a relatively limited capacity, usually 20 t or less. Lateral checking may be required to prevent swaying or twisting.

Figure 18 illustrates a vessel mounted on compression weigh modules. Compression systems can accommodate a wide variety of vessel configurations and support structures, including concrete slab and structural steelwork. Weigh modules with capacities from 25 kg to 100 t and more are available. Most designs are self-checking and some include protection against tipping; both make the installation easier. On the other hand, care must be taken to level and align the modules carefully, and the floor-level modules can be subject to flooding, severe washdown, and debris accumulation, which can adversely affect accuracy and cause corrosion.

8.3. Weigh Module Capacity

The number of weigh modules to be used is often dictated by the geometry of the vessel. Low capacity tanks can be hung from a single load cell, but most vessels are supported by three or four modules. In the case of horizontal tanks or upright vessels of square or rectangular cross section, it is often most convenient to use four weigh modules. In the case of vertical vessels of circular cross section, it is common to use three modules symmetrically arranged. Three-module arrangements are preferred; when more than three are used, it is usually necessary to shim some of the modules to achieve correct load distribution. Systems using more than 8 modules are rare for this reason.

Weigh module capacity can be calculated from the following:

$$\text{weigh module capacity} = \frac{K\,(\text{live load} + \text{dead load})}{N}$$

where K is a safety factor usually between 1.25 and 2, and N is the number of supports, usually the same as the number of weigh modules. The live load is the total weight of material to be weighed on the scale; it should be conservative and take into account variations in material density and moisture content. The dead load is the total weight of the empty vessel including all equipment mounted on the vessel, heating and cooling fluids in a jacketed vessel, the weight of piping supported by the vessel, etc. The factor K is to some extent dictated by the capacities of available weigh modules. If the scale capacity and dead load are known with certainty, and the scale will be loaded without shock, it may be acceptable to use $K = 1.25$. Where the capacity and dead load are based on estimates, where the vessel is subjected to vibration or material surges, or where the weigh modules are not loaded equally, then K values closer to 2 should be used. If the material is in large chunks and

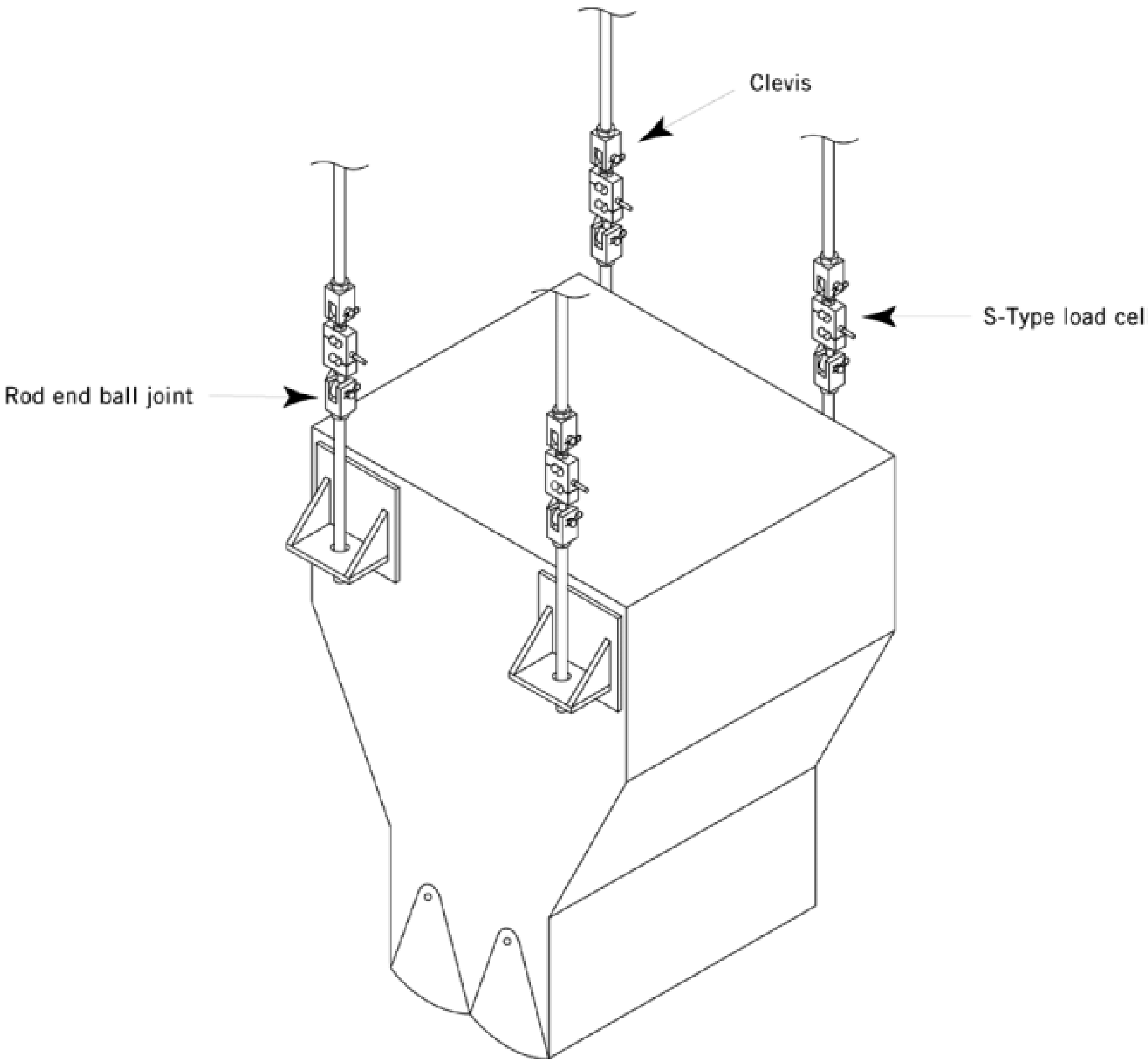

Fig. 17. Tension configuration.

falls from a height onto the scale, there is the danger of shock damage to the load cells, and a K factor larger than 2 may be necessary. It must be noted that all weigh modules on a particular vessel must be of the same capacity.

8.4. Mechanical Considerations

The support structure for a weigh vessel needs to be rigid so as to minimize undesirable forces on the weigh modules (14). This rigidity also has the beneficial effect of increasing the natural frequency of the scale, which is important where accuracy and speed are required. Support points need to be equally rigid to prevent the transfer of load between weigh modules; also, vessels with long legs need bracing to prevent lateral deflection of the legs as the load is applied. Where modules are used, as shown in Figure 17, gussets should be used to

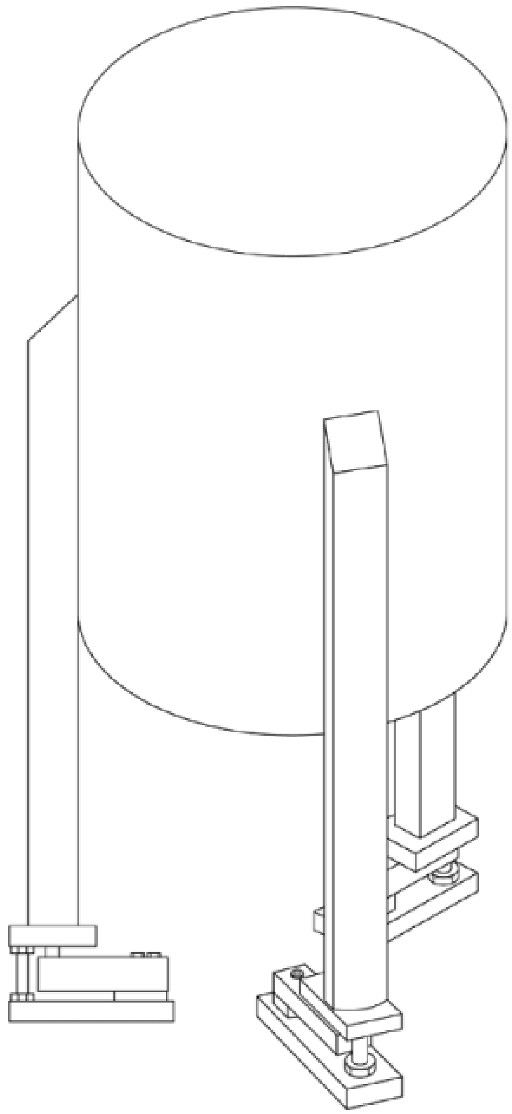

Fig. 18. Compression configuration.

support the horizontal bracket; the vessel wall may need reinforcement also. For highest weighing accuracy, the vessel should be located where it is free of vibrations from rotating equipment or vehicular traffic. Where more than one vessel is supported on a common structure, care must be taken to avoid deflection of one vessel as another is being filled or emptied.

As a vessel is loaded, it moves downward because of deflection of the load cells and support structure. Pipes rigidly attached to a vessel restrict its free movement and assume some portion of the load that cannot be measured by the load cells. This is very detrimental to scale accuracy. Deflection of the load cell is unavoidable; deflection of the vessel support structure should be minimized. Anything which increases vessel deflection, eg, rubber pads used for shock protection, must be avoided. The total number of pipes should be minimized and

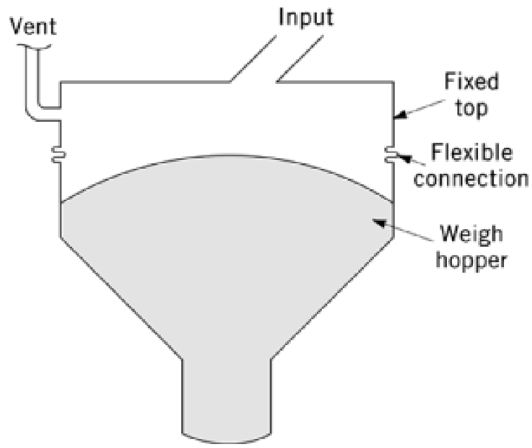

Fig. 19. Hopper top fixed to structure.

be of the smallest diameter, thinnest wall possible. Pipe runs to weigh vessels must be horizontal and the first pipe support should be as far as possible from the vessel. Alternatively, a section of rubber hose or flexible bellows should be used to make the final connection to the vessel. The scale should be calibrated using weights, not by means of an electrical simulation method, which cannot account for the effects of the piping or test the correct functioning of the scale.

If a weigh vessel is located outdoors, the effect of wind forces on the vessel's stability should be considered, particularly if it is a tall slender vessel in an exposed location. An empty vessel may be in danger of tipping; wind forces transfer weight from one module to another and, when full, may cause load-cell damage. In many areas the effects of earthquakes must be considered in the design of the scale and its supporting structure. Building codes exist for the design of structures subjected to wind or seismic loading (15, 16). In many instances a weigh module can be selected which can withstand these effects; however, in some cases it may be necessary to add additional horizontal or vertical checking. Vessel stability can be greatly improved if compression mounts are applied in a horizontal plane close to the vessel's center of gravity; this arrangement is convenient if the vessel passes through a floor, for example. All vessels should have safety supports that can hold the vessel if failure of the primary support could lead to loss or injury. This safety backup could be provided by loosely fitting chains or check rods.

It may be necessary to contain dust by enclosing a weigh hopper and using dust seals or flexible connections to seal openings. Figure 19 shows an arrangement where the top of the hopper is fixed to the structure, and the hopper must have an effective vent which minimizes even transient pressure surges; otherwise, unwanted vertical forces will be applied to the scale.

Figure 20 shows an arrangement which is unaffected by air pressure fluctuations, because any force applied to the material is canceled by an equal and opposite force applied to the inside top surface of the hopper. It may be desirable or necessary to vent the hopper for efficient material handling.

8.5. Calibration

The greatest accuracy will be achieved by calibrating with test weights equivalent to scale capacity. Provision should be made for test weights when designing a weigh vessel by providing, for example, a shelf on which the weights can be placed, or eyes from which the weights can be hung. Scales used in commercial applications must be calibrated using test weights or material substitution methods using a specified minimum amount of test weights (5). The substitution method can be used where the amount of test weights available is small

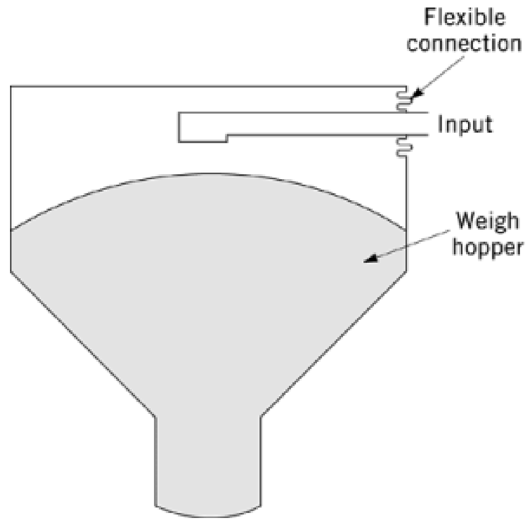

Fig. 20. Top attached to hopper.

compared to scale capacity. The weights (15% of scale capacity, for example) are used to calibrate the scale roughly initially and the scale reading is noted; the weights are removed and any available material is then added until the scale reads the noted value. The test weights are added to the scale along with the material added previously and the new reading is noted; the weights are then removed and more material added until the scale reads the second value noted. This process is repeated until a load close to scale capacity has been added and the final calibration can be performed with what is now a known quantity of material and test weights.

Calibration can also be accomplished using material weighed on another scale. The accuracy of this method depends on the accuracy of the other scale, and care must be taken not to lose any of the weighed material. Scales can also be calibrated electrically using a load cell simulator if the load cells' rated outputs are known accurately. This method does not test the mechanical functioning of the scale and is not very accurate, particularly if it has attached piping that restricts its vertical movement.

8.6. Feeding Equipment

For consistency in filling or proportioning operations, the design of the feeding equipment is critical. A front-end loader can be used to fill a hopper scale; however, it will be very difficult to achieve a specific weight repeatedly. If a belt-conveyor is used for filling, the results can vary because of lumps and variations in the quantity of material on the belt. The problem will be compounded if the conveyor coasts after power is removed. The scale and material-handling equipment must be designed as a system to achieve the required accuracy.

The choice of feeder is often dictated by the material properties. For free-flowing materials that do not tend to bridge, rathole, or flood, electric vibrating feeders, belt feeders, screw feeders, and power-operated gates are used. For material that is predominantly in large lumps, recommended types include electric vibrating feeders, belt or slat feeders, and screw feeders of proper design if lumps are not too large. For finely pulverized materials that tend to flood, screw feeders are recommended, preferably double-flight or half-pitch (an auxiliary gate may be required), and rotary vane or star feeders. For some applications it may be desirable to use a rotary vane feeder in conjunction with a vibrating feeder; this combination prevents flooding, and the desired smooth control of flow is achieved because of the vibrating feeder.

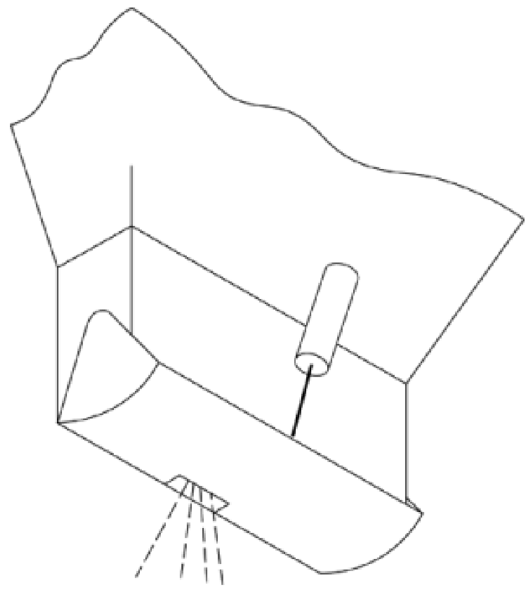

Fig. 21. Hopper with bulk and dribble fill.

The highest throughput can be achieved by filling a hopper directly from a silo or upper surge hopper (Fig. 13) equipped with a feed gate. An upper surge hopper is also useful for eliminating the erratic flow associated with devices such as belt-conveyors; it also allows the incoming material to be conveyed continuously despite the batch nature of the weighing process.

Where the scale activates an output, indicating that the desired weight has been achieved, the feeding equipment must stop operating immediately. Some feed devices may need a brake to eliminate coasting. Even if a feeder stops instantly, there will be a certain amount of *in-flight* material added to the scale after the desired weight has been achieved. The average amount of in-flight material can be determined and the scale can be programmed to *pre-act*, ie, it activates the stop output signal when the weight on the scale has reached the desired weight minus the in-flight material. For this to be effective, the rate of material flow must be consistent. Best results are achieved by minimizing the amount of in-flight material; hence the height of the feeder over the scale should be minimized and the rate of fill should be very slow. Where the latter is not practical, a *two-speed fill* can be used. Figure 21 shows a storage hopper with a three-position simplex gate. At one extreme it is fully open, allowing fast (*bulk*) fill; at the other extreme it is fully closed, and in the intermediate position (illustrated) it feeds slowly (*dribble*) through a small notch in the gate. Figure 22 illustrates a similar arrangement for filling liquids; in this case, bulk fill is achieved by opening both solenoid valves, and dribble fill is achieved by closing the larger one. Motor-driven feeders can perform bulk and dribble fill conveniently by varying the motor speed. The ratio of bulk to dribble volume can be as much as 1,000 to 1; dribble is often used for the last 5–10% of the material filled. A further refinement is an *autojog* feature. A pre-act is set to ensure that the filled weight is always light; after filling and settling, the weight is compared to the required value. If it is low, the scale jogs the feeder until the batch is within tolerance.

8.7. Discharging the Scale

Where a gate is used to discharge a hopper scale, very little control can be exercised over the rate of discharge. In some cases, particularly where the various scales of a simultaneous batching system discharge onto a

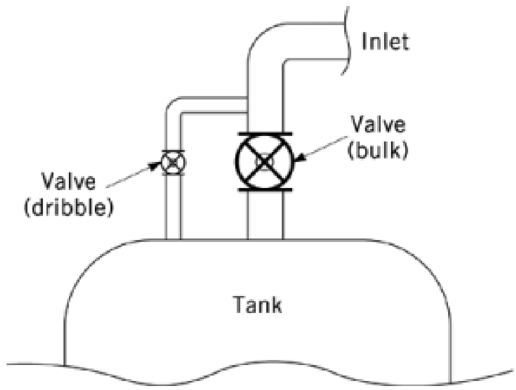

Fig. 22. Tank with bulk and dribble fill.

single conveyor belt, it is desirable to control the discharge rate so as to premix the materials. This can be accomplished by using a suitable feeding device in place of the gate. Also, using a controllable feeder as the discharge device, it is not necessary to empty the hopper or tank completely since material can be accurately weighed out of the hopper, as well as into it. In the case of materials that cling to the sides of a hopper, use of this device provides a definite advantage. In the case of liquids, more rapid discharge of a definite amount can be accomplished because the last material does not have to be discharged fully with diminishing pressure head; this method is also very useful in the case of very viscous liquids. Of course, it cannot be used when different materials are accumulated in a scale hopper because the composition of the material remaining in the hopper would vary.

8.8. Indicators and Controllers

A batching scale can be controlled manually by an operator observing the weight display and operating the feed and discharge devices at the appropriate time. Some scale indicators are designed specifically for automatic control of batching systems, and the recipe and batching routine can be programmed at the indicator. These indicators can perform functions such as two-speed fill, pre-act, and autojog. They also have digital I/O capability; the inputs can, for example, be used to start and stop the batching process, whereas the outputs are used to control the filling and discharge equipment. This system works well in automating a standalone batching system, because fast reaction times and repeatability can be achieved. The disadvantages are that it is difficult to integrate into a larger system and that the programming can be slow and error-prone.

Another approach to the control of batching systems is to use a relatively simple scale indicator which does nothing but supply weight data to a controller such as a PLC, which in turn controls the fill and discharge system. The communications between the scale and controller can be serial such as RS-232, or it can be an analogue signal such as 4-20 mA. While this system minimizes operator interaction with the scale, it sacrifices speed and accuracy because of the relatively slow communications.

Yet another approach is a hybrid of the last two, and is particularly applicable to complex processes. The overall process, including the batching scale, is controlled by a controller, such as a PLC. The PLC downloads the recipe to the scale and tells it when to commence; the batching is then controlled completely by the scale through its own digital I/O. The advantage is that the scale is fully integrated into the larger process without compromising speed and accuracy of the batching operation.

Regardless of which form of control is used, the update rate of the indicator is critical. The update rate is the number of times per second the scale samples the weight on the load cells and compares the result with the programmed target weight. Between updates, the indicator is blind to the material being added to the scale. For conventional weighing scales the update rate might be no more than 5 or 10 updates per second, because time is not critical. In high speed filling, a lot of material can be filled in 1/10 of a second, and weight indicators with 20 to 100 updates per second are typically used.

Another important feature of the scale is the filtering. The weight signal from the load cells can be contaminated by noise generated by vibrations from adjacent machinery, rotating equipment mounted on the scale, or vehicular traffic. Noise can also be electrical, eg, electromagnetic interference (EMI) or radio frequency interference (RFI) from adjacent electrical equipment. To determine the actual weight from this signal, sophisticated batching indicators use a combination of analogue and any of several types of digital filtering that can be optimized for a given scale. The disadvantage of too much filtering, or filtering of the wrong type, is that it increases the reaction time of the indicator.

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