PERRY'S CHEMICAL ENGINEERS' HANDBOOK

SEVENTH EDITION

Section 19

Solid-Solid Operations and Equipment

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SOLID-SOLID SYSTEMS

FLOTATION

INTRODUCTION

General References: *Proceedings of XIX International Mineral Processing Congress*, SME, Littleton, CO, 1995. Gaudin, *Principles of Mineral Dressing*, McGraw-Hill, New York, 1939. Kelly and Spottiswood, *Introduction to Mineral Processing*, Wiley, 1980. Roberts, Stavenger, Bowdersox, Walton, and Mehta, *Chem. Eng.*, **78**(4), 89 (Feb. 15, 1971). Taggart, *Handbook of Mineral Dressing*, 2d ed., Wiley, New York, 1964. Weiss, *SME Mineral Processing Handbook*, SME, Littleton, CO, 1985.

Most of the process industries deal with solid-solid systems which belong to the class of particulate systems. Particulate systems are composed of discrete solids known as particles dispersed in a gaseous or liquid phase. Solids dispersed in liquids are known as slurry systems. Thus, the processing of particulate solids might be carried out in either dry or wet state. Processing of particulate solids involves basically two kinds of operations: *mixing* leading to the generation of a homogeneous product, and *separation* in order to produce valuable solid components and to discard undesired less valuable solids.

The control of processes involving the treatment of solids generally requires means for careful sampling and analysis of solids and slurries at various points in an operation. Unlike liquids, particulate solids are not homogeneous. The composition of individual particles will vary with particle size and particle density. It follows that care must be exercised to take a sample that represents the entire solids mixture at the point of interest in the process. If the solids are not sampled in a representative manner, process and product control will not be reliable. The first subsection presents various aspects of sampling of solids and slurries including the underlying theory and details of different sampling equipment and their selection.

Mixing of solids is an important unit operation in the production of solids with consistent properties. A number of properties of the solid particles influence the mixing process, the design, and selection of mixing equipment. The second subsection elaborates on the theory of mixing, types of mixing equipment, and their operation.

Various techniques are available to separate the different types of particles that may be present in a solid mixture. The choice depends on the physicochemical nature of the solids and on site-specific considerations (for example, wet versus dry methods). A key consideration is the extent of the "liberation" of the individual particles to be separated. Particles attached to each other obviously cannot be separated by direct mechanical means except after the attachment has been broken. In ore processing, the mineral values are generally liberated by size reduction (see Sec. 20). Rarely is liberation complete at any one size, and a physical-separation flow sheet will incorporate a sequence of operations that often are designed first to reject as much

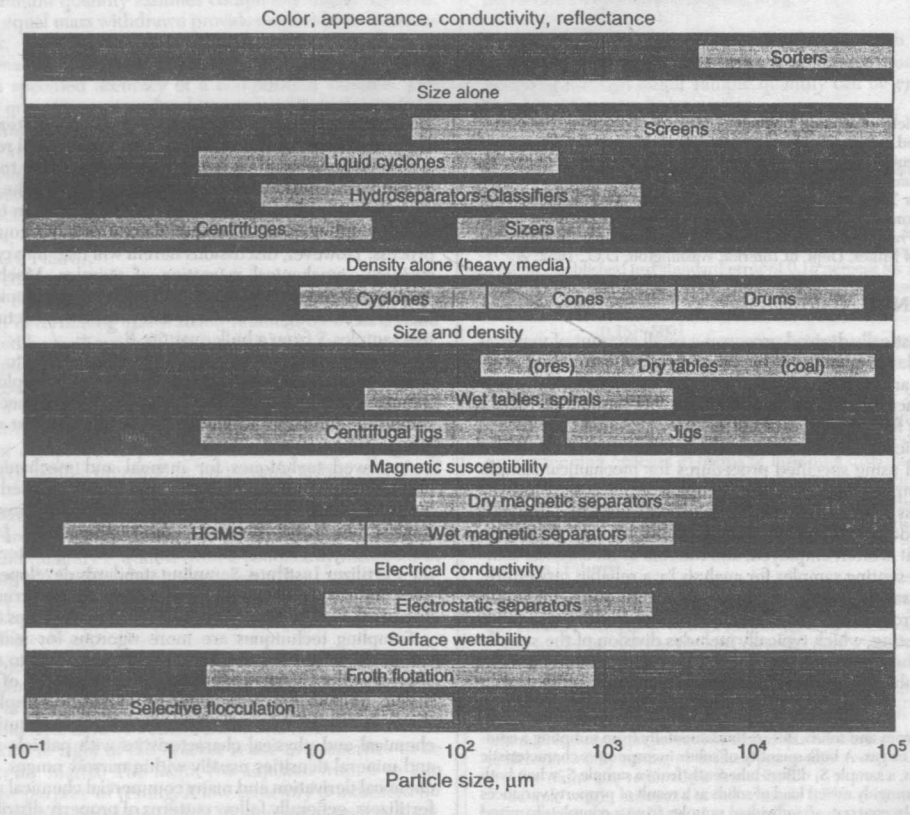

FIG. 19-1 Particle-size range as a guide to the range of applications of various solid-solid operations.

unwanted material as is possible at a coarse size and subsequently to recover the values after further size reduction.

Any difference in physical properties of the individual solids can be used as the basis for separation. Differences in density, size, shape, color, and electrical and magnetic properties are used in successful commercial separation processes. An important factor in determining the techniques that can be practically applied is the particle-size range of the mixture. A convenient guide to the application of different solid-solid separation techniques in relation to the particle-size range is presented in Fig. 19-1, which is a modification of an original illustration by Roberts et al.

The classification of solids by particle size is carried out for a number of reasons. Size classification can facilitate subsequent processing steps. An example is the scalping of tramp oversize material to avoid clogging a piece of processing apparatus. Similarly, better efficiency is achieved by removing fines before size reduction in crushers or ball or rod mills. Finished products generally are required to meet particle-size limits. Size separation is accomplished either in the dry condition or with the solids in suspension as a slurry. Wet classification allows higher process rates, particularly for materials of very fine sizes. Classification often is an integral part of a unit operation, as in closed-circuit grinding. Air classification methods for dry size classification in conjunction with size-reduction operations is covered in Sec. 20.

Gravity concentration is one of the oldest of the solids-separation techniques and the most important mineral-dressing method for obtaining ore concentrates. It is used mainly now for coal cleaning, yet Mills ["Process Design, Scale-Up and Plant Design for Gravity Concentration," in Mular and Bhappu (eds.), *Mineral Processing Plant Design*, 2d ed., Society of Mining Engineers, AIME, New York, 1980] notes that still more tonnage and greater values of material are concentrated by gravity methods than by a method such as froth flotation. The major unit operations which comprise gravity separation are jigging, tabling, spiral concentration, and dense-media separation. For high-capacity treatment of finer-sized low-grade ore materials, particularly the heavy mineral sands, the Reichert cone is becoming an industry standard [Ferree, "An Expanded Role in Minerals Processing Is Seen for the Reichert Cone," *Min. Eng.*, **25**(3), 29 (1973)].

Solids separation based on density loses its effectiveness as the particle size decreases. For particles below 100 microns, separation methods make use of differences in the magnetic susceptibility (magnetic separation), electrical conductivity (electrostatic separation), and in the surface wettability (flotation and selective flocculation). Treatment of ultrafine solids, say smaller than 10 microns can also be achieved by utilizing differences in dielectric and electrophoretic properties of the particles.

Physical separation methods are most widely used for the processing of coal and ore materials, and their basic development was designed for that purpose. Tremendous tonnages of solids are processed routinely at costs often as low at $1 per ton of material separated. The methods are applicable for other than ore processing, and solid-separation technology has become a more integral part of chemical-process operations. Recent requirements to recover values from various solid wastes have emphasized the need to adapt the relatively low-cost physical separation techniques of the ore processor, and as the needs to treat new types of materials and to improve recovery efficiency are constantly increasing, new designs are being developed.

The following subsections discuss the basic considerations involved in various unit operations of solid-solid separation and describe present industrial practice and equipment in general use.

SAMPLING OF DRY SOLIDS AND SLURRIES OF SOLIDS

REFERENCES: Society of Mining Engineers, *Minerals Processing Handbook*, Norman L. Weiss, ed., chap. 30, "Sampling and Testing", part 2. "Theory and Practice of Incremental Sampling", Littleton, Colorado, 1985. Gy, Pierre M., *Sampling of Particulate Materials—Theory and Practice*, Elsevier Scientific Publishing Co., New York, 1979. Pitard, Francis F., *Pierre Gy's Sampling Theory and Sampling Practice*, CRC Press, Inc., Boca Raton, Florida, 1995. Gayle, G. B., *Theoretical Precision of Screen Analysis*, Report of Investigations No. 4993, U.S. Bureau of Mines, Dept. of Interior, Washington, D.C., 1952.

INTRODUCTION*

Sampling is a statistically derived process—a small amount of material S is taken from a large quantity B for the purpose of estimating properties of B. If S is an accurate sample (or stated more correctly, is representative of B according to a defined statistical parameter), it is a suitable estimator for the properties of B.

Sampling is typically required for quality control, wherein statistical data are compiled using specified procedures for mechanical sample collection and sample testing. Another sampling application is providing data for process control. A key factor in process-control sampling is minimizing time delays in making data available for use. Automatic analysis equipment is often employed, and the role of mechanical sampling becomes presenting samples for analysis by a reliable procedure.

The process of sample taking encompasses several steps, beginning with (1) taking a gross sample S from bulk materials B; (2) preparation of sample S for testing, which typically includes division of the sample and possible further substeps according to whether sampling is for analysis, size distribution, moisture, ash, and so on; and (3) the testing (analysis) step itself to determine properties of interest. Each step of the process contributes statistical error to the final result.

Estimations based on statistics can be made for total accuracy, precision, and reproducibility of results related to the sampling procedure being applied. Statistical error is expressed in terms of variance. Total sampling error is the sum of error variance from each step of the process. However, discussions herein will take into consideration only step (1)—mechanical extraction of samples. Mechanical-extraction accuracy is dependent on design reflecting mechanical and statistical factors in carrying out efficient and practical collection of representative samples S from a bulk quantity B.

Although mechanical sampling methods are to be the focus of attention, manual sampling methods are also employed for practical sample collection in commerce. Techniques of mechanical sampling should be emulated as closely as possible for best results with sampling by manual procedures.

Approved techniques for manual and mechanical sampling are often documented for various commodities handled in commerce by industry groups. Examples are the International Standards Organization (ISO), British Standards Association (BSA), Japan Institute of Standards (JIS), American Society for Testing Materials (ASTM), and the Fertilizer Institute. Sampling standards developed for use in specified industry applications frequently include instructions for laboratory work in sample preparation and analysis—steps (2) and (3) above.

Sampling techniques are more rigorous for materials with large variations in particle size and density compared to sampling of fine-sized powders. Coarse solids are often comprised of substantially differing mineral and crystalline forms within complex solids matrix. Fine-sized solid materials typically are relatively uniform in terms of chemical and physical characteristics with particle-size distributions and mineral densities usually within narrow ranges. Solids of organic chemical derivation and many commercial chemical materials, such as fertilizers, generally follow patterns of property distributions typical of powdered-mineral solids.

* Sampling of slurries and solids, differs fundamentally from sampling a completely mixed liquid or gas. A bulk quantity of solids incorporates characteristic heterogenity—that is, a sample S_1 differs inherently from a sample S_2 when both are taken from a thoroughly mixed load of solids as a result of property variances embodied in solids. In contrast, all individual samples from a completely mixed liquid or gas container are statistically identical.

The following discussion centers on sampling applications for powder solids comprised of small particulate sizes and equivalents in dry form or slurries. Sampling applications involving coarser solids (⅜ inch or 10 mm nominal size) as encountered in mineral products, typical ores, coal, and quarry rock for cement manufacture, are given more complete discussion in the *Mineral Processing Handbook* published by the Society of Mining Engineers and in other references (Pitard, Gy). "Nominal" particle size implies 95 percent through-screen particle size.

THEORY OF SAMPLING

Two principal topics are considered under theory of sampling. First is theory accounting for physical properties of material to be sampled. Second is the process of mechanical sample extraction. The theory predicts accuracy of sample taking—how much sample to take and how to take it to meet an accuracy specification.

Theory related to material characteristics states that a minimum quantity of sample is predicated as that amount required to achieve a specified limit of error in the sample-taking process. Theory of sampling in its application acknowledges sample preparation and testing as additional contributions to total error, but these error sources are placed outside consideration of sampling accuracy in theory of sample extraction.

Variations in measurable properties existing in the bulk material being sampled are the underlying basis for sampling theory. For samples that correctly lead to valid analysis results (of chemical composition, ash, or moisture as examples), a fundamental theory of sampling is applied. The fundamental theory as developed by Gy (see references) employs descriptive terms reflecting material properties to calculate a minimum quantity to achieve specified sampling error. Estimates of minimum quantity assumes completely mixed material. Each quantity of equal mass withdrawn provides equivalent representation of the bulk.

The theory enables a reasonable estimate of sample quantity needed to attain specified accuracy of a composition variable. The result is an ideal quantity—not realized in practice. Actual quantities for practical estimation are larger by an appropriate multiple to account for the reality that material is incompletely mixed when stored in stockpiles or carried on conveyors. Sample quantity to accommodate incompletely mixed solids can be specified through evaluating variance by autocorrelation of data derived with a series of stockpile samples, or from multiple sample extractions taken from a moving stream (Gy, Pitard).

In addition to composition factors, a sampling theory is available in sampling for size distribution. Quantity of sample needed to reach a specified error in determining size fraction retained on a designated screen is estimated by application of the binomial theorem (Gayle).

The second topic in theory of sampling pertains to mechanical sample taking. Design of mechanical sampling must conform to established criteria for sample-taking error to be minimal. This ensures error variance introduced by mechanical sample extraction is statistically insignificant compared to physical factors of sampling arising from heterogeniety, sample preparation, and sample testing sources of error.

Estimating Minimum Sample Quantity for Analysis The fundamental theory of sampling error variance can be applied to estimating a minimum quantity required from a completely mixed lot of solids for attaining an objective level of accuracy (Gy):

$$V = \left[\frac{1}{W_S} - \frac{1}{W_B}\right]\left[\frac{1-F}{F}\{(1-F)A_m + FA_g\}\right] fgbd^3$$

where V is the objective sampling-error variance (weight fraction), W_S is weight of the sample, W_B is weight of the bulk-solids lot, F is weight fraction mineral or other measurable quantity in the solids, A_m is density of mineral, and A_g is density of the nonmineral matrix.

Remaining terms to right of the bracket relate to properties to be measured within the matrix. The factor f is adjusted from 0 to 1 in relationship to the purpose of testing. A low value of f is indicated for scarce elements such as precious metals in electronic-source scrap. Moisture content has a high f value. The factor g is adjusted from 0 to 1 according to the degree of particulate classification. A high degree of size classification, as in a case of fine powders from screening, indicates values of 0.5 or higher. Unclassified fine solids from crushing have a value assigned to g of 0.25 or less. The factor b relates to size of elemental or crystal particles in bulk-solids particulate and degree of liberation ranging from 0 to 1. The term d is nominally the largest particle size. Estimated values employed in calculations rely on sampling experience and from solids-property investigation according to development of the theory, as described in related publications (Gy).

Example 1: Sample Quantity for Composition Quality Control Testing An example is sampling for quality control of a 1,000 metric ton (W_B) trainload of ⅜ in (9.4 mm) nominal top-size bentonite. The specification requires silica to be determined with an accuracy of plus or minus three percent for two standard errors (s.e.). With one s.e. of 1.5 percent, V is 0.000225 (one s.e. weight fraction of 0.015 squared). The problem to be solved is thus calculating weight of sample to determine silica with the specified error variance.

Bentonite has expected silica content of 0.5 weight percent (F is 0.005). Silica density (A_m) is 2.4 gm per cu cm, and bentonite (A_g) is 2.6. The calculation requires knowledge of mineral properties described by the factor ($fgbd^3$). Value of the factor can be established from fundamental data (Gy) or be derived from previous experience. In this example, data from testing a shipment of bentonite of 10 mesh top-size screen analysis determined value of the mineral factor to be 0.28. This value is scaled by the cube of diameter to ⅜-in screen size of the example shipment. The mineral factor is scaled from 0.28 to 52 by multiplying 0.28 with the ratio of cubed 9.4 mm (⅜-in screen top-size of the shipment to be tested) and cubed 1.65 mm (equivalent to 10 mesh).

Minimum weight W_S of sample is 110 kg from

$$0.000225 = \left[\frac{1}{W_S} - \frac{1}{10^6}\right]\left[\frac{1-0.005}{0.005}\{(1-0.005)2.6 + (0.005)2.4\}\right] 52$$

noting dimension of d^3 (particle diameter) is cubic mm requiring division by 1000 to rationalize with cubic cm of density. Sample weight in grams (from density) is divided by 1000 in converting to kg.

Estimating Change of Sampling Error with Change in Sample Size Increased accuracy in estimating a quality parameter by sampling through larger sample quantity can be estimated using the simplified Gy sampling equation

$$W_1V_1 = W_2V_2$$

W and V are values for sample weights and variances of parameter measurements at states 1 and 2 respectively.

Example 2: Calculation of Error with Doubled Sample Weight Repeated measurements from a lot of anhydrous alumina for loss on ignition established test standard error of 0.15 percent for sample weight of 500 grams, noting V is the square of s.e. Calculation of variance V and s.e. for a 1000 gram sample is

$$V = \frac{(0.15)^2(500)}{(1000)} = 0.01125; \text{ standard error} = 0.11 \text{ percent}$$

Estimating Minimum Sample Quantity for Size Distribution Testing A simplistic approach to specifying minimum sample size for estimating particle distributions within allowed variance is based on a screening process in terms of binomial distribution. Each screening event is an outcome of two possibilities—particles either pass the screen or not. A relationship according to this principle presented by Gayle (loc. cit.) is employed in the example. Further development of sampling concepts for particle-size distribution is provided in the references (Pitard).

Example 3: Calculating Sample Weight for Screen-Size Measurement Weight W of bulk sample for screen analysis is calculated by the Gayle model for percent retained on a specified screen with relative standard error s.e. in percent

$$W = \frac{G(100-G)w}{V}; \quad \text{example } W = \frac{5.5(100-5.5)0.0120}{1.56} = 4.0$$

where G is the weight percent of the sample retained on the given screen either as determined by testing or defined per specification, and w is the weight of a particle of the size retained on that screen.

Sample weight estimated in this example is for two standard errors of 2.5 percent (resulting in V of 1.56) for testing iron ore (hematite) retained on a ½-in screen. Estimate of G is 5.5 for 94.5 percent of weight passing. Particle weight

w retained on a ½-in opening screen assuming spherical shape and 5.1 specific gravity is 0.0120 lb. The calculation yields 4.0 lb as a minimum sample size, W.

Estimating Minimum Sample Quantity for Moisture Measurement Estimates of material quantity for testing moisture content depend on mechanisms of moisture distribution in the material. Moisture is physically retained on particle surfaces, chemically adsorbed on surfaces and within pores of particulate solids, and contained as an internal constituent of solids. Significant internal moisture is most often encountered in organic and agricultural source materials.

Sample quantity to estimate moisture for specific material is influenced to various levels of significance by properties such as particle-size range as well as relative amounts of moisture distributed among denoted forms of retention. Practical sample size estimates require background knowledge of parameters derived from experience for specific materials. More detailed examination of moisture-sampling aspects is provided in reference texts (Pitard).

Example 4: Calculation of Sample Weight for Surface Moisture Content An example is given with reference to material with minimal internal or pore-retained moisture such as mineral concentrates wherein physically adhering moisture is the sole consideration. With this simplification, a moisture coefficient K is employed as multiplier of nominal top-size particle size d taken to the third power to account for surface area. Adapting fundamental sampling theory to moisture sampling, variance is of a minimum sample quantity is expressed as

$$V = \left[\frac{1}{W_S}\right]\left[\frac{1-F}{F}\right]Kd^3; \text{ example } 0.0000562 = \frac{0.95\ 5\ 0.00633}{W_S\ 0.05\ 1728}$$

where V is variance in weight fraction, W_S is minimum weight of sample, F is nominal weight fraction moisture, and K is a constant with dimension mass per unit volume. In absence of prior knowledge for material surface moisture characteristics, a value of K equal to 5 lb/ft^3 can be used for typical mineral concentrates and other nonabsorbing fine materials. This relationship is applied in an example of a crystalline product—hydrated sodium sulfate (Glaubers salt) with d of minus 4 mesh (0.185 in). Standard material moisture content is 5 percent by weight, with required sampling error of 1.5 percent relative to total weight for two s.e. Variance for this value in weight fraction is 0.0000562 in calculating 6.1 lb as sample weight (1728 converts in^3 to ft^3).

MECHANICAL DELIMITATIONS OF SAMPLING

Sample increment extraction requires a cutter to move through (traverse) a flowing stream being sampled while meeting accepted criteria of design and operation. Two methods of mechanical sampling for materials in flow regime are employed. A preferred first method is sample extraction from material in gravity free fall, such as from trajectory discharge at the head pulley of a conveyor or gravity flow down an enclosed chute. Cutter motion can be linear or rotational with constant speed while taking samples by traversing a gravity free-fall flow stream.

Sampling is required to meet the principle of mechanical sample extraction in maintaining statistical validity. This principle states that the cutter must take through-stream extractions during each traverse of the flow stream being sampled such that each particle in the flow stream at any place in the stream has equal probability of being extracted into sample. The diagram of Fig. 19-2 illustrates a typical arrangement meeting criteria (sampling delimitations) for a linear-traversing cutter installation extracting from a free-fall stream of material.

An alternative method is sampling directly from a moving or stationary conveyor with cutter traverse through the complete material bed carried on the conveyor. The alternative method cannot assure executing complete extractions, or through-stream sampling, because in many applications residual fines from the material stream remain on the conveyor surface.

The alternative method of sample extraction is termed the *cross-stream* sampling method, or *cross-belt* when used in conjunction with a belt conveyor. Sample extraction typically take place with a belt conveyor in motion. However, with a rotary table-feeder conveyor, extractions are made with the table stopped. A cutter can perform extractions by this means from a machined flat surface with negligible

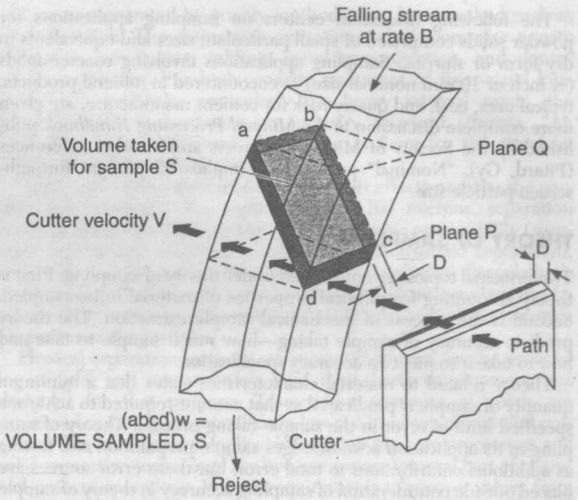

FIG. 19-2 Through-stream linear sampling. (*Courtesy of Harrison R. Cooper Systems, Inc. Salt Lake City, Utah.*)

residual fines left out of the sample. When sampling from a moving belt conveyor, residual fines become more significant resulting in loss of accuracy in extractions. This is due to clearances necessary between cutter edges and the conveyor belt, and also due to belt surface irregularities.

CRITERIA FOR SAMPLER DESIGN

Operation of a traversing sampler for *gravity flow* of material for through-stream sampling is required to meet the following design factors:

1. The cutter moves at constant speed (or constant rotation rate in the case of a rotary-motion sample cutter) such that the entire flow of material is traversed by the cutter, with the further requirement that the stopped position of the cutter at either limit of traverse (out of stream) is at sufficient distance from the stream so that no material from the stream enters the cutter while it is held stationary between traversing operations.
2. The sample cutter opening is set to specified width according to a multiple of the maximum (nominal) size of particulate being sampled and selected speed of the cutter. A minimum width of 10 mm or 0.375 in is recommended unless material is moist or has other properties to induce bridging of the cutter, suggesting need for a wider opening for practical operation. Experiments have determined that a cutter opening of a multiple of three times the nominal largest particle size and an 18-inches-per-second cutter speed (0.46 meters per second) is optimum to minimize sample extraction quantity with negligible delimitation error for fine-sized materials.
3. Cutter blade length extends beyond the material stream width on either side of the stream and volume of the cutter is sufficient to ensure all material taken into sample can be contained in the cutter body. Cutter blades are parallel, and are beveled to a sharp edge in the case of linear-motion traverse. For rotary-motion sample cutters, sharp edges of the cutter blades are radial to the center point of rotation.

Criteria for mechanical delimitations in sampling by the alternative cross-stream method to fulfill through-stream extraction requirements are revised from gravity-sampling criteria in the following respects:

1. The cutter opening is to exceed maximum (nominal) particle size by sufficient clearance to ensure that a large particle will not wedge into the opening. Sampling error due to free-fall deflection is avoided as a factor in setting cutter opening width. A 2 inch minimum cutter opening, required for practical operation, is recommended.

2. The cutter length should be approximately equal to the width of the material load carried on the conveyor.
3. When sampling from moving belt conveyors, the cutter operates in a radial mode with the belt surface contoured at the point of sampling by idlers, fixing radial curvature to the outer radius of the cutter. Clearance is minimized between outer edges of cutter blades and belt surface by cutter-shaft adjustment in the drive-clamping bracket.
4. Cutter speed at the outer radius is recommended at twice the conveyor belt speed for through-stream extractions from moving belts. The cutter is adjusted in a lateral angle to a 30-degree position, matching the cutter extraction path through the material bed on the belt at specified speed.

Cross-stream sampling from flat surfaces with material handled on a linear conveyor or rotary table is best carried out with the conveyor stopped. Sample extraction is then performed by linear traverse.

MECHANICAL SAMPLING EQUIPMENT

Repeating an axiom stated earlier, mechanical samplers are designed to extract increments of sample from a bulk quantity of material B in a manner that increments S are representative within statistical bounds of the bulk B. Further, the sampler is designed and constructed in conformance to criteria stated previously under "Mechanical Delimitations of Sampling" to assure that negligible errors arise from mechanical influence.

Many designs of equipment purported for sample extraction have been offered to industry or placed into service for sampling that fail to meet accepted mechanical standards. Extracted increments often have bias—inaccuracies found from tests on increments showing deviations usually with more or less fixed offset from true median values, or otherwise producing inconsistent and statistically poor test data compared to true values. Extraction increments using nonconforming designs may best be regarded as specimens of bulk B, but not samples in the statistical sense.

Mechanical sampling procedures further discussed are limited to sampling of flowing materials. Dry solid flows carried on a conveyor or in chute gravity fall are subject to through-stream sampling designed to extract correctly defined increments. Slurry gravity flows in launders and sloped pipes are sampled at the point of discharge, or slurries are sampled at open discharge from a vertical gravity pipe.

Static sampling methods with mechanical systems to operate thief-pipe sampling of solids taking increments from railroad hopper cars, trucks, or bins are seen in use. These are considered manual sampling methods operated mechanically. Applying criteria of through-stream sample extraction is infeasible, and it is inherently understood that bulk materials to be sampled in this manner are not perfectly mixed. An assured mode of sampling is providing through-stream sample extraction of bulk materials as they are loaded into bins, rail cars, trucks, and so on.

Various static thief or pipe samplers, often including pumps for stream transfers, are employed in slurry flows as well. These lack validity in terms of through-stream extraction capability. A pressure-thief sampler mounted on a pump discharge flange can be an approximation to through-stream sampling with assumption of complete mixing in flow from the pump if time lapse for flow to the thief from a pump is minimal, and pipe bends or other elements inducing classification are absent.

SELECTING A SAMPLER

Mechanical samplers meeting delimitation criteria are available in two basic designs for sampling material in gravity free fall. The basic designs are sampling with linear cutter motion and sampling with radial cutter motion (see Fig. 19-3 and Fig. 19-4 respectively). The net result is the same with either when equipment is properly designed and operated.

Selection of linear or radial (rotary cutter) sampling is made according to mechanical installation factors often on a basis of flow quantity. Smaller flows can be sampled in a cost-effective manner by rotary cutter samplers (frequently termed "vezin" design samplers, see Fig. 19-4).

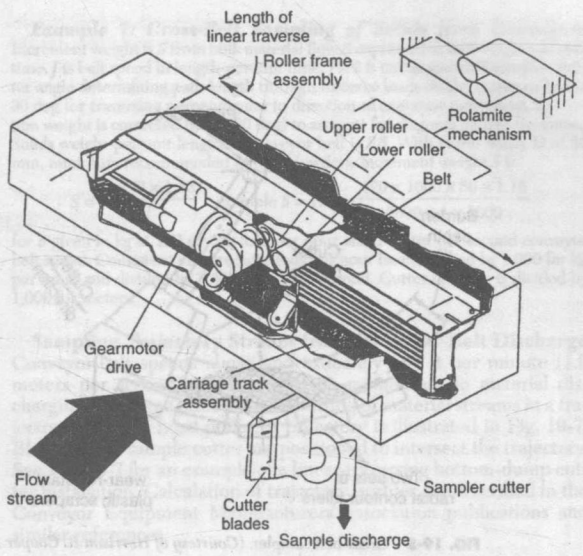

FIG. 19-3 Traversing sampler. (*Courtesy of Harrison R. Cooper Systems, Inc. Salt Lake City, Utah.*)

Sampling directly from material lying on the conveyor using a cross-stream cutter for extracting sample increments is diagrammed in Fig. 19-5 for moving conveyor belts and in Fig. 19-6 for a rotary table application. Cross-stream sampling can frequently be applied with acceptable delimitation error to materials of relatively low particle size and minimal variation, and also to materials with moisture content sufficient to avoid fines classification onto conveyor surfaces. A brush fixed to the cutter trailing edge aids in fines extraction to minimize residual sample remaining on the belt surface following cutter traverse.

In Fig. 19-5, the conveyor belt is radially profiled at the point of sample extraction with contouring idlers set to match the path of the cutter moving from its driveshaft rotation axis. Cutter edges are posi-

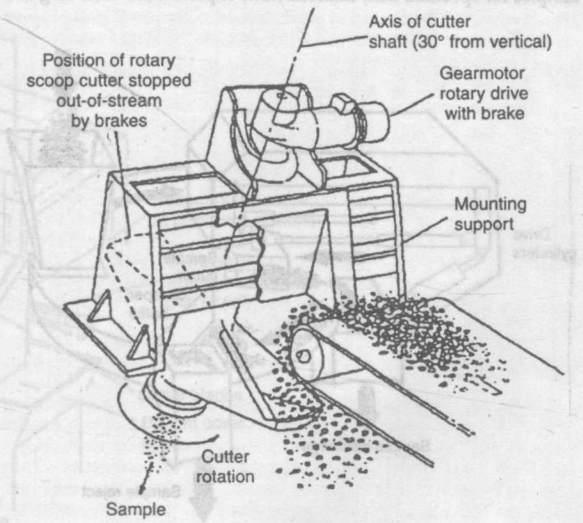

FIG. 19-4 Rotary sampler. (*Courtesy of Harrison R. Cooper Systems, Inc. Salt Lake City, Utah.*)

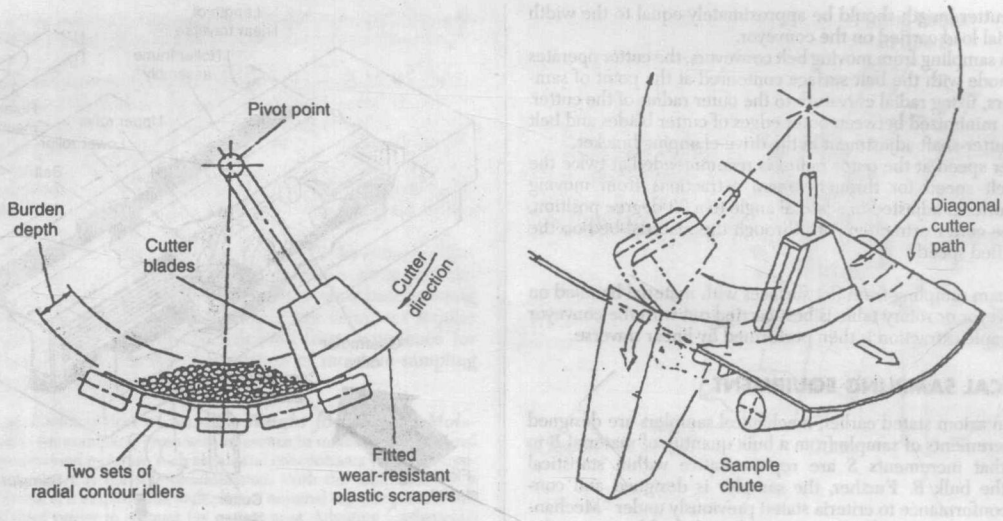

FIG. 19-5 Cross-belt sampler. (*Courtesy of Harrison R. Cooper Systems, Inc. Salt Lake City, Utah.*)

tioned with minimum clearance from the belt surface as is reasonably accomplished without contact of the cutter with the belt surface. Cutter blades are angled 30 degrees from the conveyor belt direction in positioning the cutter to its path through the conveyor belt load for cutter speed twice conveyor speed.

Extractions performed with the conveyor stopped allow more assured accuracy by the certainty of including fines in the sample increment. Sampler design to extract increments from a flat belt or rotary table sampler while the conveyor is stopped minimizes potential for residual fine particles remaining on the conveyor surface in carrying out extractions. See Fig. 19-6 for rotary table sampler extraction diagram.

Composite Samples Obtained by Multiple Sample Extractions Material flow streams are sampled in practice by combining extractions taken at successive time intervals into a composite sample. Multiple increment collection to obtain representative composite samples for specified bulk-material flows is performed according to a designated process in accommodating the presence of material property variations.

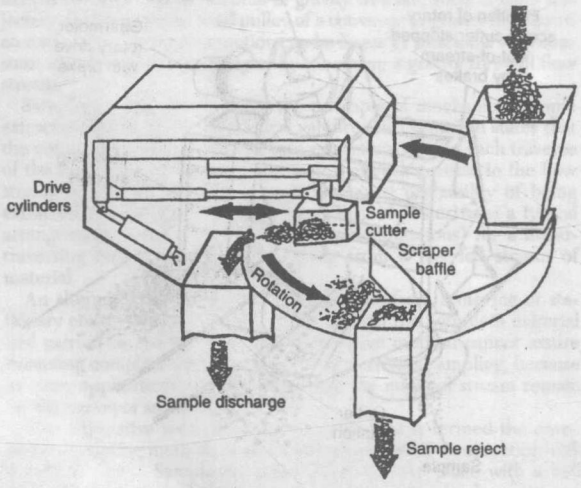

FIG. 19-6 Rotary-table sampler. (*Courtesy of Harrison R. Cooper Systems, Inc. Salt Lake City, Utah.*)

The requirement is to obtain proportional samples from the flowing material. This is accomplished in a technically accurate procedure by extractions taken on fixed time intervals. Variable time intervals with intervals determined from random selection are optionally employed to avoid bias error in sampling when characteristic periodic effects are known to be present in the stream of material. Possibilities for fixed sampling intervals to systematically coincide with periodicities are avoided by random time interval selection. Setting sampling intervals to material flow quantity, as in using belt weigh scale readings, opens potential for nonproportionalities and error in the composite sample.

Sampling of specified material flows to obtain representative composite quantities is a common practice for material accounting and quality control. A typical case is composite sampling of a shipload or trainload cargo transfer for either receiving or delivering materials. Another frequently used specification is eight-hour shift production quantities to be sampled to generate composite samples for testing.

Industry standards are frequently applicable in designing sampling procedures for many commodities in commerce transferred by ship cargoes or trainloads. Standards for iron ore, coal, metallurgical concentrates, and similar materials are often to be observed. Standards are likely to give details on sampling specifications necessary for acceptance-based material characteristics and lot size to mandate minimum number and weights of increments, gross (combined) sample weights, and other factors.

Selection of appropriate time intervals for increment extractions relates to property variation (inhomogeneity) within material flow streams. Ten minute extraction intervals are generally adequate to obtain suitably representative samples from material flows under practical circumstances. Precise determination of extraction intervals consistent with individual applications can be calculated through autocorrelation of historical sampling data, a statistical method described in references (Gy, Pitard).

Sample Quantity Reduction As sample increments are accumulated by multiple extractions from a bulk flow of material, according to the parameters of sampling to accommodate material stratification and nonhomogeneous composition, gross sample quantities (primary sample) often become quite extensive. Large primary sample volumes are subject to mechanical resampling to obtain final samples of practical, reduced quantities for testing. The same principles of sampling applied to primary sampling are used to design resampling to accomplish sample reduction without loss of sample statistical validity.

Sample reduction in successive stages—primary to secondary, secondary to tertiary, etc.—can be fulfilled using automatic sampling equipment while observing design principles of statistical sampling. Alternatively, sample quantity reduction may be carried out in a laboratory.

Sample reduction by mechanical procedures in automatic on-line mode encompasses (1) particle-size reduction preceding a following stage of resampling, and (2) multiple secondary increments taken for each primary increment when resampling without particle-size reduction. Particle-size reduction implies crushing or grinding the sample before resampling. A sampling-unit design incorporating primary and successive stages of sampling, with particle-size reduction and controlled flow of sample through intermediate stages, is developed in accord with application requirements while maintaining specified standards of sample accuracy.

Calculation of Sample Extraction Increments Sample quantities taken in an extraction increment are calculated in accord with the mechanical sampler employed. The following three examples illustrate calculations for three commonly used sampling methods.

Example 5: Solids Sampling by Linear Traversing Trajectory Cutter Increment weight S by a linear traversing cutter from bulk material flow of fine powder B expressed in unit weight per unit time is calculated by

$$S = \frac{B \times D}{V} \quad \text{example } S = 1.38 = \frac{120 \times 2000 \times 0.375}{3600 \times 18}$$

where V is cutter velocity and D is cutter opening. For S given in 120 short tons per hour converted to lbs, 0.375-in cutter opening, and 18-inches-per-second cutter speed, each increment is 1.38 lb. For consistent units, tons per hour is multiplied by 2,000 for lbs per hour, and divided by 3,600 for lbs per second.

Example 6: Slurry Sampling by Rotary Traverse of Gravity Flow Increment volume, quantity of slurry extracted by one cutter rotation, is S from bulk slurry flow B expressed in volume-per-unit time. R is cutter rotation per minute. D is cutter angle opening, with $D/360$ extraction ratio for continuous cutter rotation.

$$S = \frac{D \times B}{360 \times R} \quad \text{example } S = 0.055 = \frac{2.5 \times 200}{360 \times 25}$$

with S gallons per extraction for 200 gallons per minute, 2.5 degree cutter opening, and 25 RPM cutter rotation rate.

Example 7: Cross-Belt Sampling of Solids from Conveyors Increment weight is S from bulk material flow B expressed in unit weight per unit time. J is belt speed in length-per-unit time. $J \times 2$ is cutter speed. Therefore, cutter angle determining path length through material loads on the conveyor belt is 30 deg for traversing perpendicular to direction of conveyor movement. Extraction weight is corrected by csc(30 deg) to account for diagonal path of the cutter. Solids weight-per-unit length of conveyor belt is B/J. With cutter width D of 50 mm, minimum recommended for fine powders, increment weight S is

$$S = \frac{B \times D \times 1.16}{J} \quad \text{example } S = 1.93 = \frac{120 \times 1000 \times 50 \times 1.16}{3600 \times 1 \times 1000}$$

for S given in kg at 120 metric tons per hour and 1 meter per second conveyor belt speed. Consistent units require tons per hour be multiplied by 1,000 for kg per hour, and divided by 3,600 for kg per second. Cutter opening is divided by 1,000 for meters.

Sampling Trajectory Stream from Conveyor-Belt Discharge Conveyor-belt speeds above approximately 300 ft per minute (1.5 meters per second) impart sufficient momentum to material discharging at its head pulley to cause lifting of material streams in a trajectory from the head pulley. A trajectory is illustrated in Fig. 19-7. Blades of the sample cutter are positioned to intersect the trajectory. See Fig. 19-7 for an example of a linear-traversing bottom-dump cutter installation. Calculation of trajectory profiles are described in the Conveyor Equipment Manufacturers Association publications and similar references.

SAMPLING EQUIPMENT COST DATA

The cost of an electric-drive rotary-cutter sample of the smallest size manufactured—suitable for gravity sampling of fine particulate solids or slurry flow—including timer and control unit was approximately $5,000 in 1996.

An electric-drive linear-traversing sampler of minimum standard manufactured size with cutter and controls will range upwards of $8,000.

Pneumatic as well as electric-drive samplers are available. Generally, pneumatic-drive samplers are lower in cost.

Cross-belt samplers of minimum size for 24-in (600-mm) conveyors cost approximately $15,000 with controls using an electric drive, and about $12,500 with pneumatic drive.

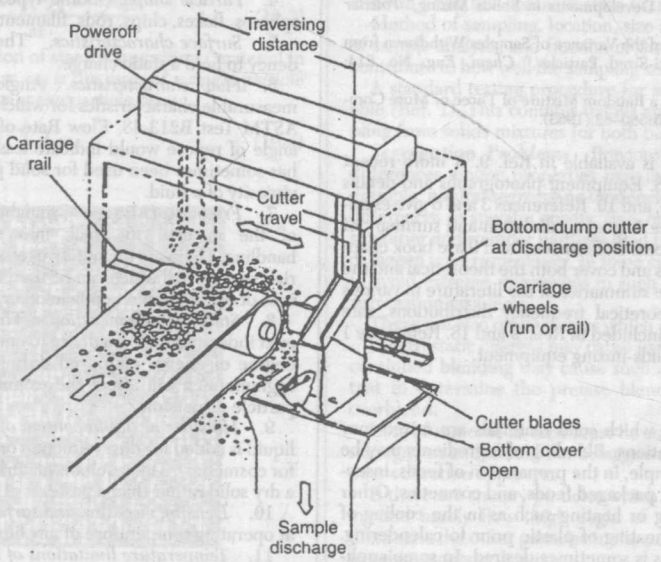

FIG. 19-7 Traversing linear bottom-dump sampler. (*Courtesy of Harrison R. Cooper Systems, Inc. Salt Lake City, Utah.*)

Hydraulic-drive samplers are also available, but cost factors tend to be substantially greater than electromechanical units. Recent use of hydraulic-drive systems has diminished with the availability of increased strength and durability electric-motor linear-drive units capable of reliable operation in high-capacity applications.

Sampling systems for multiple-stage sample reduction incorporating components such as crushing units, interstage feeders, reject handling, and others range up to several hundred thousand dollars in cost. A requirement would be rarely encountered in fine-powder applications.

SOLID-SOLID SYSTEMS

MIXING

General References

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A comprehensive bibliography is available in Ref. 9. A more recent update can be found in Ref. 18. Equipment photographs and details are available in Refs. 2, 4, 5, 7, 8, and 10. References 3 and 6 give excellent theoretical work. Reference 5 gives a tabulation and summary of many mixer types and applications. References 8 and 9 are book chapters dealing with mixing of solids and cover both the theoretical and the equipment aspects. Interpretive summaries of the literature in various areas (state of mixedness, theoretical frequency distributions, rate equations, and equipment) are included in Refs. 9 and 18. Reference 1 gives a procedure for testing solids-mixing equipment.

Fundamentals

Objectives Equipment in which solid materials are mixed may be used for a number of operations. Blending of ingredients may be the main objective, as, for example, in the preparation of feeds, insecticides, fertilizer, glass batches, packaged foods, and cosmetics. Other objectives may include cooling or heating such as in the cooling of limestone or sugar or the preheating of plastic prior to calendering. Drying or roasting of the solids is sometimes desired. In some applications, such as polymerization of plastics, catalyst manufacture, or the preparation of cereal products, the solids mixture may be reacted. Coating is desired in some cases, as in the manufacture of pigments, dyes, minerals, candy, and other food products and in the preparation of feeds. In certain of these cases, small amounts of liquid may be added, but the end product is a solids mixture. Sometimes agglomerates are desired, as in the preparation of food products, pharmaceuticals, detergents, and fertilizer. Often size reduction is desired while solids are being mixed. In all cases, the mixing of solids occurs. However, in some of these operations, the details of the equipment to accomplish operations other than pure blending may become a major problem. This portion of Sec. 19 will deal with equipment whose major function is to give a thorough mixture of solids. Specialized equipment to perform the other functions is discussed in other sections of the *Handbook* and will not be dealt with here. Thus, for example, Sec. 8 is devoted to size reduction and enlargement, although equipment mentioned there may also accomplish mixing.

Properties Affecting Solids Mixing Wide differences among properties such as particle-size distribution, density, shape, and surface characteristics (such as electrostatic charge) may make blending very difficult. In fact, the properties of the ingredients dominate the mixing operation. The most commonly observed characteristics of solids are as follows:

1. *Particle-size distribution.* This tells the percentages of the material in different size ranges.
2. *Bulk density.* This is the weight per unit of volume of a quantity of solid particles, usually expressed in kilograms per cubic meter (pounds per cubic foot). It is not a constant and can be decreased by aeration and increased by vibration or mechanical packing.
3. *True density.* The true density of the solid material is usually expressed in kilograms per cubic meter (pounds per cubic foot). This, divided by the density of water, equals specific gravity.
4. *Particle shape.* Some types are pellets, egg shapes, blocks, spheres, flakes, chips, rods, filaments, crystals, or irregular shapes.
5. *Surface characteristics.* These include surface area and tendency to hold a static charge.
6. *Flow characteristics.* Angle of repose and flowability are measurable characteristics for which standard tests are available (e.g., ASTM Test B213-48, Flow Rate of Metal Powders, etc.). A steeper angle of repose would indicate less flowability. The term "lubricity" has sometimes been used for solid particles to correspond roughly to viscosity of a fluid.
7. *Friability.* (Also see "Grindability," Sec. 8.) This is the tendency of the material to break into smaller sizes in the course of handling. There are quantitative tests specially devised for certain materials such as coal which can be used to estimate this property. Abrasiveness of one ingredient upon another should also be considered.
8. *State of agglomeration.* This refers to whether the particles exist independently or adhere to one another in clusters. The kind and degree of energy employed during mixing and the friability of the agglomerates will affect the extent of agglomerate breakdown and particle dispersion.
9. *Moisture or liquid content of solids.* Often a small amount of liquid is added for dust reduction or special requirements (such as oils for cosmetics). The resultant material may still have the appearance of a dry solid rather than a paste.
10. *Density, viscosity, and surface tension.* These are properties at operating temperature of any liquid added.
11. *Temperature limitations of ingredients.* Any unusual effects due to temperature changes which might occur (such as heat of reaction) should be noted.

A look at these properties for the ingredients to be mixed is a first step toward selecting mixing equipment.

Measuring Uniformity Except for cases in which a coating of one ingredient with another takes place, the theoretical end result of mixing will not be an arrangement in which one type of particle is directly next to a different type. Rather, the theoretical end result when random tumbling takes place will be a random mixture along the lines shown in Fig. 19-8.

The variation among spot samples of known size can be predicted theoretically for a random mixture and used as a guide to determine how closely random blending of the ingredients has been approached. Various types of analyses can be made on spot samples to determine batch uniformity. These could include x-ray fluorescence, flame spectrometry, polarography, emission spectroscopy, and so on, depending on the powder being examined. Radio-tracing techniques may also be appropriate. As many spot samples as possible should be analyzed. These should be taken at random from different locations in the batch. Sample size is an important consideration and is discussed below.

Evaluation Statistical tests can be used to evaluate relative homogeneity based on observed variations in spot sample composition. For a simple binary mixture such as that shown in Fig. 19-8, it can be shown (see Ref. 9) that the expected variance among samples containing n particles each is given by

$$\sigma^2 = \frac{p(1-p)}{n} \tag{19-1}$$

where p is the overall fraction of black (or white) particles in the mixture. The observed sample variance can be computed using

$$S^2 = \frac{1}{m-1}\left[\sum_{i=1}^{m} p_i^2 - \frac{1}{m}\left(\sum_{i=1}^{m} p_i\right)^2\right] \tag{19-2}$$

where p_i is the fraction of black (or white) in the i^{th} sample and m is the total number of samples taken. The expected and observed variances can be compared using the statistical F-test (see Sec. 2 or any standard reference on statistics) which determines the likelihood that the F-ratio (S^2/σ^2) could be obtained from a random mixture, purely by chance.

The procedure can be readily extended to multicomponent systems by applying the test to each component in turn. In real systems, it is generally convenient to take samples of fixed volume or mass rather than fixed number of particles. In such cases, the expected variance can be computed using (see Refs. 19 and 20)

$$\sigma^2 = \frac{f_{ij}(1-f_{ij})w_{ij} + f_{ij}^2(\overline{w} - w_{ij})}{M} \tag{19-3}$$

where f_{ij} is the overall mass fraction of size i composition j material in the mixture, M is the sample mass, w_{ij} is the mass of a single particle of size i composition j and $\overline{w}$ is the mean particle mass:

$$\overline{w} = \sum_i \sum_j f_{ij} w_{ij} \tag{19-4}$$

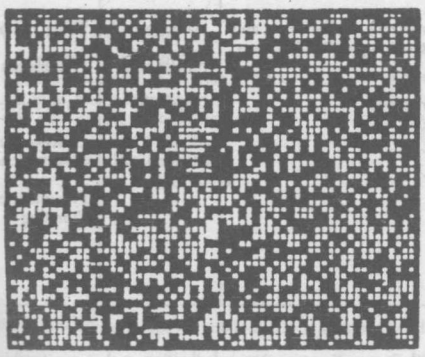


FIG. 19-8 Random arrangement of black and white particles. [*Lacey*, Trans. Inst. Chem. Eng. (London), **21**, 52 (*1943*).]

The test for homogeneity is based on the probability of including different kinds of particles in a sample. For large samples, containing many particles, the expected variance given by Eq. (19-3) becomes extremely small and will often be exceeded by the variance due to experimental (analytical) error. The approach described above is, therefore, appropriate only for evaluating homogeneity at a scale approaching the size of the individual particles. If information at that scale is needed, it is necessary to use extremely small samples, containing no more than some hundreds of particles each. For very fine powders, this may seriously limit the choice of analytical techniques.

The use of very small samples to evaluate fine-scale homogeneity will often tend to mask long-range but small variations in composition. The use of somewhat larger samples is appropriate for detecting and quantifying such variations. In such cases, the sample variance can be compared, using the F-test, with an experimental variance S_E^2 obtained from replicate testing of the analytical procedure used to determine sample composition.

In general, a two-level procedure is recommended in which very small samples are used to evaluate microhomogeneity at the individual particle scale and larger samples are employed to investigate longer range variability. The actual sample sizes should be chosen such that microhomogeneity is evaluated from samples for which σ^2, as calculated using Eq. (19-3), is substantially less than the experimental (analytical) variance S_E^2 while macrohomogeneity is tested using samples with $\sigma^2 >> S_E^2$.

Whether the desired end product is satisfactory can also be used as a practical criterion of the adequacy of the solids mixture. A further consideration is the effect of the solids mixture on the overall economics of the manufacturing process. Studies of the type mentioned in the preceding subsection *may* be part of such an evaluation. When the solids mixture is made directly into a product, as in the case of feed pellets or pharmaceutical tablets, uniformity tests on these items will speak for themselves. If the solids mixture must be further processed, as in the manufacture of glass or plastics, the efficiency and costs of the subsequent operations can often be related to the starting solids mixture. In such cases, knowledge of the homogeneity of the solids mixture is needed to determine its effect on the manufacturing process.

Regardless of the method of evaluating the solids mixture, the sampling procedure is vital. Often a sampling thief, or other special device, is used to remove samples from the mixture without excessive disturbance of the batch. If an easier method of sampling is obvious and will bring less contamination to the batch, it should be used.

Method of sampling, location, size and number of samples, method of sample analysis, and fraction of the batch removed for sampling all contribute to how well the sampling study reflects the actual conditions.

A standard testing procedure for solids-mixing equipment is available (Ref. 1). This contains details and references pertaining to sampling from solids mixtures for both batch and continuous mixing.

Segregation Problems Previously it was pointed out that wide differences among properties may make blending very difficult. For example, natural segregating tendencies will be observed with extreme differences in specific gravity, size, or shape. The heavier, smaller, or smoother and rounder particles tend to sink through the lighter, larger, or jagged ones respectively. In some cases, preparation of the materials to avoid extreme differences in such ingredient properties can avoid segregation problems.

There are also other factors which can cause segregation.

Electrostatic charges may cause particles to repel each other. When continued blending may cause such charges to build up, it is important to determine the precise blending time required and not to overblend.

Loss of material as dust must be considered as a possible means of segregation and should not be aggravated by too strong suction in the dust-collection apparatus.

If there are smeary particles which have an almost pastelike behavior and barely flow (high angle of repose), frictional anchorage of these onto the other particles in the mixture may be necessary in order to achieve good mixing.

If a batch ingredient is in agglomerate form, some device to break up the agglomerates should be used to prevent them from segregating

from the rest of the mixture and to ensure the intimate dispersion of this ingredient throughout the mixture.

The use of a liquid such as water (possibly with a surface-active agent) can have remarkable effects in overcoming segregation which may appear inevitable otherwise.

Although these statements apply to the actual solids-mixing operation, thought must also be given to the subsequent processing steps. Thus, the solids-mixing operation must be checked from the point of view of delivering a well-mixed batch to a certain point. The system must be scrutinized for possible segregating points such as transfer points, long drops, flow through silos, and vibratory equipment. Where a liquid is used, the amount that can be added without getting into caking problems which may upset the later processing of the solids mixture should be determined.

Equipment

Mixing Mechanisms There are several basic mechanisms by which solid particles are mixed. These include small-scale random motion (diffusion), large-scale random motion (convection), and shear.

Motions which increase the mobility of the individual particles will promote diffusive mixing. If there are no opposing segregating effects, this diffusive mixing will in time lead to a high degree of homogeneity. Diffusive mixing occurs when particles are distributed over a freshly developed surface and when individual particles are given increased internal mobility. A plain tumbler gives the former, while an impact mill gives the latter.

For most rapid mixing, in addition to diffusive (fine-scale) mixing, there should be a means by which large groups of particles are intermixed. This can be accomplished by either the convective or the shear mechanism. A ribbon mixer illustrates the former, whereas a plain tumbler gives the latter.

The diffusion mechanism occurs readily for free-flowing powders in which individual particles are highly mobile, but is inhibited by cohesion among particles. It follows that cohesive powders, containing fine material or liquid phases, are relatively difficult to mix. At the same time, reduced particle mobility inhibits demixing so that once mixed, cohesive powders tend to remain so. Free-flowing powders, on the other hand are prone to demixing during any transport/handling operation. The beneficial effects, noted above, of liquid addition presumably result from increased cohesion.

Types of Solids-Mixing Machines There are several types of solids-mixing machines. In some machines the container moves. In others a device rotates within a stationary container. In some cases, a combination of rotating container and rotating internal device is used. Sometimes baffles or blades are present in the mixer. Most types can be quite effective for free-flowing powders, bearing in mind that segregation may also be favored. Highly cohesive powders generally require high shear (velocity gradient) to achieve a high degree of microhomogeneity. Table 19-1 classifies solids-mixing machines via the characteristics given in the column headings. Illustrations of several of the machines listed there are shown in Fig. 19-9. The various types listed in Table 19-1 will be briefly discussed, with paragraph numbers referring to the columns.

1. *Tumbler.* Suitable for gentle blending; capable of handling large volumes; easily cleaned; suitable for dense powders and abrasive materials. Not for breaking up agglomerates.

Figure 19-9*a* and *b* (without broken-line portions) shows some unbaffled tumblers.

Figure 19-9*c* and *d* shows some baffled tumblers.

2. *Tumbler with agglomerate breaker.* See Sec. 20: "Tumbling Mills," for ball mill, rod mill, and vibratory pebble mill which will accomplish mixing along with size reduction.

Several tumblers are available with separately driven internal rotating devices for breaking up agglomerates. The tumbler itself can be used for gentle blending if agglomerate breakdown is not required.

The broken-line portions of Fig. 19-9*a* and *b* show some types of agglomerate-breaking devices for tumblers.

Table 19-2 includes impact velocities for some internal rotating devices in tumblers as well as other mixers. Contamination and wear problems of internal rotating devices are discussed under "Performance Characteristics."

3. *Stationary shell or trough.* There are a number of different types of mixers in which the container is stationary and material displacement is accomplished by single or multiple rotating inner mixing devices.

a. Ribbon mixer (Fig. 19-9*e*). Within this subgroup there are several types. Ribbon cross section and pitch, clearances between outer ribbon and shell, and number of spirals on the ribbon are some features which can be varied to accommodate materials ranging from low-density finely divided materials that aerate rapidly to fibrous or sticky materials that require positive discharge aid. Other construction variations are center or end discharge and the mounting of paddles or cutting blades on the center shaft. A broad ribbon can be used for lifting as well as for conveying, while a narrow one will cut through the material while conveying. The ribbon is adaptable to batch or continuous mixing.

b. Vertical screw mixer. This subgroup also has several variations. One type is shown in Fig. 19-9*f*. In this type, the screw rotates

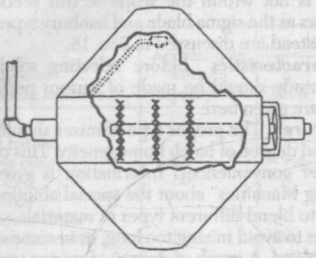
TABLE 19-1 Types of Solids-Mixing Machines*

Tumbler (1)	Tumbler with internal agglomerate breaker (2)	Stationary shell or trough (3)	Both shell and internal device rotate (4)	Impact mixing (5)	Process steps which can affect solids mixing‡ (6)
Without baffles:					
Drum, either horizontal or inclined	Ball mill Pebble mill	Ribbon	Countercurrent, muller turret and pan rotate in opposite directions	Hammer mill	Filling of hoppers
Double cone	Rod mill	Stationary pan, rotating muller turret†		Impact mill	Fluidization
Twin shell	Vibratory pebble mill	Vertical screw	Planetary types	Cage mill	Screw feeders
Cube					
Mushroom type	Double cone	Single rotor		Jet mill	Conveyor-belt loading
	Twin shell	Twin rotor		Attrition mill	Elevator loading
	Cube				
		Turbine			Pneumatic conveying
		Paddle mixer			Vibrating
With baffles:					
Horizontal drum		Sifter (turbosifter)			
Double cone revolving around long axis					

* Diagrammatic sketches of many of these machines are shown in Fig. 19-9.

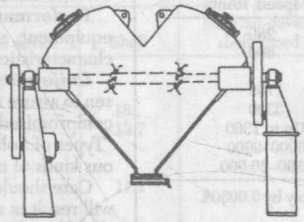
† There is also a muller in which the turret is stationary but the pan rotates.

‡ Although these steps, when carefully selected, can aid mixing, caution must be exercised with pneumatic conveying and vibrating, as they may tend to separate materials.



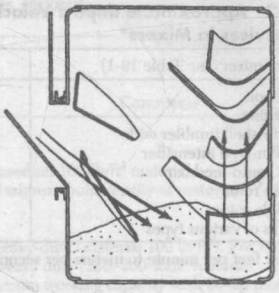
(a) Double cone

Agglomerate breaking device shown in broken line. Spray nozzle shown in dotted line. Tumblers of this type available plain or with either or both of the above features.

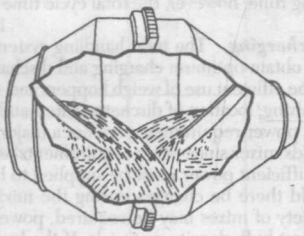


(b) Twin shell (Vee)

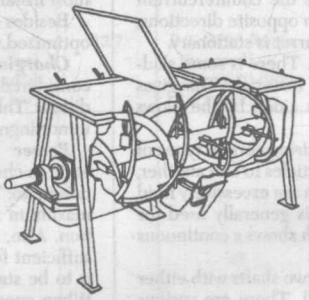
Agglomerate breaking and liquid feeding device shown in broken line. Where no liquid feeding is necessary, a pin-type agglomerate breaking device is used. Tumblers of this type are available plain or with any of the above features.



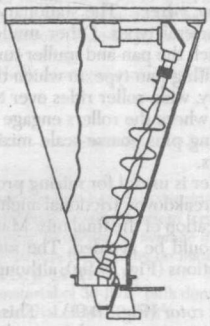
(c) Horizontal drum (with baffles)



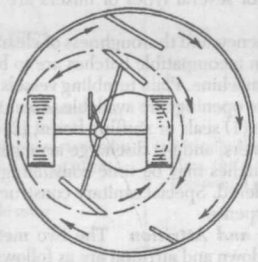
(d) Double-cone revolving around long axis (with baffles)



(e) Ribbon

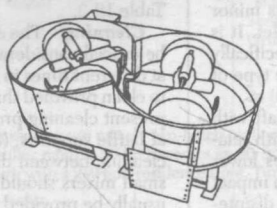


(f) Vertical screw (orbiting type)

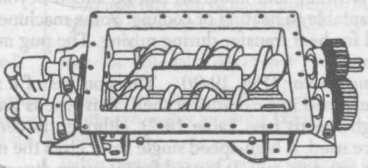


(g) Batch muller

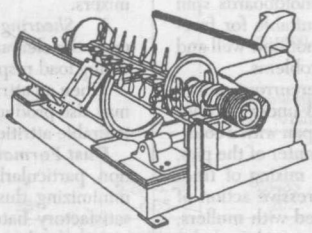
Three types are available:
(1) pan is stationary and muller turret rotates;
(2) muller turret is stationary and pan rotates;
(3) pan rotates clockwise, muller turret rotates counterclockwise.
Type 3 is illustrated above



(h) Continuous muller (stationary shell)



(i) Twin rotor (adapted to heat transfer-jacketed body and hollow screws)



(j) Single rotor

(k) Turbine

FIG. 19-9 Several types of solids-mixing machines. (See Table 19-1).

TABLE 19-2 Approximate Impact Velocities of Some Rotating Internal Devices in Mixers*

Type of mixer (see Table 19-1)	Tip speed, ft/min
Ribbon	280
Turbine	600
Twin-shell tumbler with	
Pin-type intensifier	1700
Liquid-feed bar	3300
Twin rotor	Up to 1300
Single rotor	6000–9000
Mills of various types	2500–20,000

*To convert feet per minute to meters per second, multiply by 0.00508.

about its own axis while also orbiting around the center axis of the conical tank. In another variation, the screw does not orbit but remains in the center of the conical tank and is tapered so that the swept area steadily increases with increasing height. In another type, the central screw is contained in an inner cylindrical casing. This type of mixer is primarily suitable for free-flowing dry solids.

c. Muller mixer. The stationary-pan muller with rotating turret is one of several types. Other muller types are the countercurrent type, in which the pan and muller turret rotate in opposite directions, and the rotating-pan type, in which the muller turret is stationary.

The heavy, wide roller rides over the material. There is some skidding action where the rollers engage the mass of materials. This gives local shearing plus coarse-scale mixing which is aided by the plows and scrapers.

The muller is useful for mixing problems requiring certain types of aggregate breakdown, frictional anchorage of particles to one another, and densification of the final mix. Materials which are excessively fluid or sticky should be avoided. The muller mixer is generally used for batch operations (Fig. 19-9*g*), although Fig. 19-9*h* shows a continuous muller.

d. Twin rotor (Fig. 19-9*i*). This consists of two shafts with either paddles or screws encased in a cylindrical shell. There are various types available with shaft speeds ranging from moderately low to relatively high (see Table 19-2). The twin rotor is useful for continuously mixing non-free-flowing solids; liquids can be added, there is minor product attrition, and materials can be added beyond the inlet. It is easily adaptable to heating or cooling. Some machines are specifically designed for heat transfer during mixing. The pug mill is one type of twin rotor.

e. Single rotor (Fig. 19-9*j*). This consists of a single shaft with paddles encased in a cylindrical shell. This type is available with relatively high speeds (see Table 19-2), although in certain cases lower speeds are used. A high-speed single rotor gives the maximum impact short of a grinding mill. It is used for intensive dispersion and disintegration. The type is available with split casing and is suitable for heating or cooling and for small amounts of liquid addition.

f. Turbine mixer (Fig. 19-9*k*). This is a circular trough with a housing in the center around which revolves a spider or a series of legs with plowshares or moldboards on each leg. The moldboards spin around through the circular trough. This mixer is suitable for free-flowing dry materials or semiwet materials which do not flow well and is also adaptable to liquid-solid mixing and coating problems.

4. *Shell and internal device rotate.* The countercurrent muller (Fig. 19-9*g*), which is in this category, is mentioned under "Muller mixer." This machine has a clockwise rotating mixing pan with a counterclockwise rotating mixing tool head mounted off center of the pan, thus providing a planetary mixing pattern. For the mixing of free-flowing solids not requiring the shearing and compressive action of mullers, plows are sometimes used alone. When used with mullers, plows deflect material into their path. Special mixing tools are also available.

5. *Impact mixing.* This process, which includes size reduction, is covered in Sec. 20.

The process steps listed in Table 19-1 can sometimes be used to promote mixing. However, they are primarily for functions other than solids mixing. (Note precautions for pneumatic conveying and vibrating in Table 19-1.)

Since paste mixing is not within the scope of this section, such widely used paste mixers as the sigma blade and banbury types will not be covered here but instead are discussed in Sec. 18.

Performance Characteristics Before selecting solids-mixing equipment, a careful study should be made of various performance characteristics. These are given here.

Uniformity of Mixture The proper type of mixer should be chosen to assure the desired degree of batch homogeneity. This cannot be compromised for other conveniences. Information is given under "Types of Solids-Mixing Machines" about the special abilities of various kinds of machines to blend different types of materials.

Care should be taken to avoid mixing too long, as in some cases this will result in a poorer blend. A graph of degree of mixing versus time should be made to select the proper mixing time quantitatively.

Mixing Time The actual time during which the batch is being mixed is usually less than 15 min if the proper type of machine and working capacity have been chosen. In some cases much more lengthy mixing times are tolerated so as to avoid the cost of purchasing more efficient equipment. However, there is usually a machine that can properly homogenize almost any type of mixture in less than 15 min provided one is willing to pay the price. In fact, proper mixer design in most instances will produce the desired blend in a few minutes.

Besides actual mixing time, however, the total cycle time should be optimized.

Charging and Discharging The total handling system must be considered in order to obtain optimum charging and discharging conditions. This includes the efficient use of weigh hoppers and surge bins, minor-ingredient premixing, location of discharge gates, and so on.

Power In general, power requirements are not a major consideration in choosing a solids mixer since other requirements usually predominate. However, sufficient power must be supplied to handle the maximum needs should there be changes during the mixing operation. Also, when a variety of mixes may be required, power must be sufficient for the heaviest bulk-density materials. If the loaded mixer is to be started from rest, there should be sufficient power for this. When speed variation may be desirable, this should be taken into account in planning power requirements.

Horsepower requirements of several types of mixers are listed in Table 19-3.

Cleaning The ease, frequency, and thoroughness of cleaning may be crucial considerations when incompatible batches are to be mixed at different times in the same machine. Plain tumbling vessels are easy to clean provided that adequate openings are available. Areas that may present cleaning problems are (1) seals or stuffing boxes, (2) crevices at baffle supports, (3) any corners, and (4) discharge arrangement. If cleaning between different batches may be time-consuming, several small mixers should be considered. Special sanitary construction can usually be provided at extra expense.

Agglomerate Breakdown and Attrition The two methods of producing agglomerate breakdown and attrition are as follows:

1. *Impact.* The major factor is the peripheral speed of the rotating internal device. Table 19-2 gives impact-velocity data for various mixers.

2. *Shearing and compressive action.* In mullers this depends upon the clearance between muller and pan and the muller weight or spring load respectively.

When an attrition device is necessary to break down aggregates but may also produce too much size reduction on other batch ingredients, tolerable attrition should be determined by tests.

Dust Formation Loss of dust can seriously affect batch composition, particularly when vital minor ingredients are lost. Methods of minimizing dust formation are: (1) Use of less dusty but equally satisfactory batch ingredients. Sometimes a pelletized form of an extremely dusty material is available. (2) Proper venting so as to enable filtering of displaced air rather than unregulated loss of dust-laden air. (3) Dust-tight arrangements for loading and unloading the mixer. (4) Addition of liquids if tolerable. Not only is water effective in minimizing dust upon discharging from the mixer, but if properly added it will also render the batch less dusty in subsequent handling steps. The addition of a small quantity of surface-active agent will improve the penetration of the water throughout the batch and enable

TABLE 19-3 Horsepower Requirements and Speeds of Rotation for Some Commercial Solids Mixers
[Approximately 1.5 m^3 (50 ft^3) Working Capacity]

Type of solids-mixing machine	Approximate working capacity, ft^3	Horsepower, hp		Rotational speed, r/min		Comments
		Shell	Internal device	Shell	Internal-device shaft speed	
1. Tumbler						
Without baffles						
Double cone	54	7½		18		Based on 100-lb/ft^3 material.
Twin shell	50	5		13.7		Maximum bulk density of material = 55 lb/ft^3.
With baffles						
Horizontal drum						
Manufacturer E	50	20		11.1		Heavy-duty (material 100 lb/ft^3). For extremely heavy duty (150–200-lb/ft^3 material), the maximum working capacity with 20-hp motor is 35 ft^3.
Manufacturer F	50	10		14		For material of 40-lb/ft^3 maximum bulk density.
Double cone revolving about horizontal axis	56	25		11.5		Mixer can be tilted. Rear end charger. Capacity based on mixed concrete.
2. Tumbler with agglomerate breaker						
Double cone	54	7½	See Comments.	18	See Comments.	Horsepower requirement for internal device depends on character of material, type, and speed of agitator. These are to be determined by adequate testing.
Twin shell	50	5	5 (pin-type intensifier bar) 7½ (liquid-solids intensifier bar)	13.7	945 (1730-ft/min tip speed) 1055 (3320-ft/min tip speed)	Maximum bulk density of material = 55 lb/ft^3.
3. Stationary shell or trough						
Ribbon						
Manufacturer C	50		12		28	Horsepower required based on material of 50–60-lb/ft^3 bulk density, medium free-flowing, using 10 hp/ton for average mix cycle of 3–10 min (depending on material, range can be 3–18 hp/ton).
Manufacturer A	46		10		37	Based on material of 30-lb/ft^3 bulk density.
Manufacturer D	50		15		45	Based on material of 40–50-lb/ft^3 bulk density.
Three-shaft ribbon	50		Blender shaft 20 Feeder shaft 7½ (total)		Variable-speed drives on all shafts	This blender is rated at 300 ft^3/h on batch-mixing basis; 900 ft^3/h on continuous-mixing basis. Materials rated at 70-lb/ft^3 bulk density.
Vertical screw	52.9		5		Screw, 64.4 Orbit, 2.2	Horsepower based on 37-lb/ft^3 bulk density. This may vary with different materials. Maximum hp = 10, maximum weight = 4410 lb.
Muller:						
Batch; stationary pan, rotating turret	40		60		24 (turret speed)	Based on material of 60–75-lb/ft^3 bulk density.
Continuous; stationary pan, rotating turret	Basically, the continuous mullers are merely two-batch mullers joined together at the cribs, making a figure-8 design. Thus, the 40-ft^3 batch muller rated at 60 hp becomes an 80-ft^3 working-capacity continuous muller requiring 125 hp. This would give 125 tons/h with a 2½-min residence time. Turret speeds are 24 r/min.					
Single rotor		See Comments.				In this *continuous* unit, output can range from 25–600 lb/min with hp from 5 to 100 and r/min of 500 to 4000, depending on the materials mixed.
Double rotor		See Comments.				In this *continuous* unit the output can range from 200–500 lb/min with hp from 5 to 40 and r/min from 200 to 300, depending on the materials mixed.
Twin-rotor heat-exchanger mixer	49.2		5–15		20–100	Amount of conveying and mixing action affected by amount of pitch and type of ribbons mounted on exterior of hollow screws.
Turbine	50		50		Peripheral speed of 600 ft/min	
4. Both shell and internal device rotate						
Countercurrent muller	45	*	*	6.75–8.75	28–35	
	60–90†	20	25	6.65	20	

*One 25-hp motor drives both the shell (mixing pan) and the internal device (mixing star).
†Batch-capacity range depends on nature of materials to be mixed.
NOTE: To convert cubic feet to cubic meters, multiply by 0.02832; to convert horsepower to kilowatts, multiply by 0.7457; to convert pounds per cubic foot to kilograms per cubic meter, multiply by 16.02; to convert tons per hour to kilograms per second, multiply by 0.252; to convert revolutions per minute to radians per second, multiply by 0.1047; to convert pounds per minute to kilograms per minute, multiply by 0.4535; and to convert horsepower per ton to kilowatts per metric ton, multiply by 0.8352.

it to wet even such materials as coal dust. The method of adding water is important (see "Method of Adding Liquids").

Care should be taken to avoid powerful suction or air flow on the mixer or the weigh hopper from which the ingredients feed into the mixer. If the dust-collection suction on the mixer is too strong, vital ingredients may be sucked out. If the dust-collection suction on the weighing system is too strong, errors in weighing may result.

Electrostatic Charge Certain batch materials such as plastics tend to accumulate a charge easily. Work input will affect the charge on the batch. Coating of the inside of the mixer shell or rotating elements may occasionally result because of electrostatic charge. This can present a cleaning problem. Possible aids in overcoming this are (1) addition of special solid materials with very high surface area to weight ratios, (2) addition of liquids (see "Dust Formation" and "Method of Adding Liquids"), (3) proper choice of material of construction of the mixer, (4) controlling humidity, (5) preparation of the batch ingredients so as to minimize accumulated charge.

Equipment Wear Simple tumbling mixers give the least wear. Attrition devices in tumblers may present serious abrasion problems with certain materials such as sand and abrasive grinding-wheel grains. Abrasion-resistant coating such as rubber coating, special alloys, or platings should be considered for these cases. An internal agitator device may wear even though its speed is low. Particularly when highly abrasive materials are to be mixed, the benefits of an agglomerate-breaking device must be weighed against potential contamination and replacement and maintenance costs.

Contamination of Product This has been partially covered under "Cleaning" and "Equipment Wear." Other sources of contamination are lubricants and repair materials. Types which are not compatible with the batches to be mixed should be avoided.

Heating or Cooling Nearly all commercial mixers can be heated or cooled. Some can be provided with heated or cooled agitators. If temperature rise during mixing is detrimental, cooling facilities should be provided. The various manufacturers can provide details on the means of heating their machines. Most common heating means are (1) water or steam in the jacket and in hollow-screw or paddle-type internal agitator, (2) hot oil, (3) Dowtherm liquid or vapor, (4) electric heaters, contact or radiant, (5) hot air in direct contact with product (suitable only for revolving-drum-type mixers), (6) exterior heating of drum by direct or indirect firing. For cooling, the most common means are (1) water or refrigerated fluid in the jacket and in hollow-screw or paddle-type internal agitator, (2) an evaporant such as liquid ammonia, (3) direct air contact (for rotating-shell mixers), and (4) oil or Dowtherm (or its equivalent) for cooling high-temperature materials.

Flexibility When batches of widely different size must be mixed, flexibility of operating capacity may enable use of fewer mixers. Certain features may necessitate a nonflexible capacity requirement. For example, ordinarily an internal agitating device in a tumbling mixer does not function effectively unless the batch is loaded to a certain level. The need for such features must be weighed against the limitations imposed by a narrow operating-capacity range when choosing equipment for an operation in which batch size will vary considerably.

In general, the effect of percentage of mixer volume occupied by the batch on the adequacy of mixing should be borne in mind, particularly when any change from the recommended volume percent is considered.

Vacuum or Pressure Most tumbling mixers can have provision for vacuum or pressure. Mixers which cannot be adapted to these conditions are mullers with rotating pans. Continuous mixers introduce problems of sealing the charge and discharge ends.

Method of Adding Liquids When the addition of liquids may be desirable (see "Dust Formation" and "Electrostatic Charge"), this should be considered when designing the mixing system rather than hastily improvised. The purpose of the liquid should be considered, whether for (1) dust suppression, (2) product, or (3) heating and cooling. If a viscous liquid must be well distributed, this requirement should be considered when choosing the mixer.

Liquid should be directed into the batch materials and not onto bare mixer surface since this could cause buildup. Nozzle spray pressure should be sufficient to penetrate the batch but not so high as to cause heavy splashing. The liquid should be added to the well-mixed batch. In particular, when premature addition of liquid could impair the adequacy of blending, both the time during which it is added in the mixing cycle and the time taken to add the liquid are important.

Automated equipment for the addition of liquids can be worked into the overall mixing plant when necessary. For dust-reduction purposes, a volumetric method of metering is satisfactory. However, should a critical batch ingredient be added in liquid form, a more precise method of metering may be necessary.

Other considerations are (1) proper ventilation and discharge enclosures, (2) provision for relief of internal explosion, (3) vibration isolation (shock mounts), (4) remote operation of charge and discharge, (5) noise during operation.

Equipment Selection Types of mixers and performance characteristics have been given. Segregating tendencies among solid materials have also been described. A sound approach to solids-mixer selection starts with a careful examination of these areas. However, mixer selection should also involve consideration of the mixer's place in the overall process. Possible consolidation of many solids-processing steps or the opposite (splitting one operation into several) deserves scrutiny at this time. If no one standard machine has all the necessary requirements, thought should be given to which machine can best be modified to achieve the most desirable combination of features. One should look at the overall process objectives as well as at equipment details when selecting a solids mixer.

Pilot Tests In some cases, it is possible to perform pilot tests on a small-scale version of the equipment to be used in production. Much useful information can be found here but the following must be borne in mind:

1. In general, the larger the pilot unit, the more reliable the prediction of large-scale performance. The pilot unit should be a prototype with all dimensions properly scaled down.
2. Published solids-mixing scale-up data are rare. Equipment suppliers can provide scale-up information for their particular types of equipment on the basis of experience. With geometrically similar tumblers, if the speeds are adjusted to give comparable motion and the mixer volume fraction occupied by the charge is the same, scale-up of results will be straightforward. The presence of a rotating internal device presents problems in the scaling up of clearances, blade area to mixture volume, and sizes and speeds of the rotating devices. For agglomerate breakers, the key factor in scaling up is impact velocity. Scale-up in cylinders is discussed on pages 290–292 of Ref. 9. Solids-processing scale-up is discussed in a paper by Sterret (*Chem. Eng.*, Sept. 21, 1959).
3. The actual process materials should be used if possible. If substitute materials must be used, they should have the same mixing characteristics. Tests with differently colored but otherwise identical beads can be misleading, and so can tracers. The reason is that the flow properties of the specific materials to be mixed in the plant may not be the same as these demonstration materials. Regardless of how the mixer contents appear to be moved around, the properties of the actual batch ingredients may cause segregation or other problems.
4. Differences in materials of construction between the pilot unit and the production unit should be considered. These may have a bearing on caking, abrasion, and electrostatic effects.

Continuous Mixing Although batch mixing has been the predominant method of mixing solids, consideration is being given to the use of continuous mixing in many industries. There are two types of continuous-mixing operations. The first type has a low holdup volume and will provide fine-scale blending of the particles via impact and shear elements such as are used in grinding machines. Some machines of this type are hammer, impact, cage, and jet mills. It is essential that the feed to these machines be properly proportioned and premixed to achieve a uniform product.

The second type of continuous mixer involves high holdup machines which contain agitating and conveying mechanisms. These rearrange the individual particles and also displace large volumes of material and move the batch through the machine. Mixers of this type can produce both fine-scale and coarse-scale blending. The ribbon-type mixer is frequently used for continuous mixing, although this is also used for batch mixing. A continuous muller mixer has been developed as shown in Fig. 19-9*h*.