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Methods to survey and sample grinding circuits for determining energy efficiency

SUBMITTED BY
The Sampling and Surveying Sub-Committee
of the Industrial Comminution Efficiency Working Group

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1. FOREWORD

The Global Mining Guidelines Group (GMG) is a global, multi-stakeholder community to advance the availability and use of standards and guidelines for the international mining industry. This GMG document was prepared by a GMG working group. Draft documents are checked and approved by working group members, prior to approval by the GMG Governing Council.

Formed as part of the Canadian Institute of Mining, Metallurgy and Petroleum (CIM), GMG is supported by CIM and three other Partner Organizations: the Australasian Institute of Mining and Metallurgy (AusIMM), the Southern African Institute of Mining and Metals (SAIMM), and the Surface Mining Association for Research and Technology (SMART), as well as its Member Companies and participants.

Please note: if some of the elements of this document are subject to patent rights, the GMG and CIM are not responsible for identifying such patent rights.

2. DEFINITIONS OF TERMS, SYMBOLS, AND ABBREVIATIONS

AG	Autogenous Grinding
F80	80% passing size of the circuit feed (μm)
HPGR	High Pressure Grinding Roll
P80	80% passing size of the circuit product (μm)
PSD	Particle Size Distribution
ROM	Run-of-Mine
SAG	Semi-Autogenous Grinding
SMC Test®	SAG Mill Comminution Test

3. KEYWORDS

Autogenous Grinding (AG) mill, Ball mill, Comminution, Conveyor sample, Grinding circuit, Particle Size Distribution (PSD), Rod mill, Sampling, Semi-Autogenous Grinding (SAG) mill, Slurry sample, Surveying

4. INTRODUCTION AND BACKGROUND

This guideline has been developed to support the Industrial Comminution Efficiency (ICE) initiative, which aims to provide tools for practitioners to measure the energy efficiency of comminution circuits using standardized metrics. The focus of the ICE working groups is to define the recommended methods for quantifying grinding circuit efficiency using grinding power analysis, following the approaches developed by Bond (1961) and Morrell (2009). Consequently, this guideline details methods to survey and sample grinding circuits to generate sufficient information of suitable quality to support reliable efficiency analysis by these and comparable methods. This guideline deals specifically with surveying and sampling Autogenous Grinding (AG), Semi-Autogenous Grinding (SAG), rod, and ball mill circuits operating within the normal range of application. This guideline does not directly address analysis of crushing plants and fine grinding circuits, but it is a useful reference for such endeavors.

Applying power-based analysis techniques requires sufficient input information to allow actual specific energy consumption to be compared with a calculated estimate of the required energy usage to perform the equivalent size reduction, namely the:

- primary mill feed 80% passing size (F80),
- final grinding circuit product 80% passing size (P80),
- ore hardness measurements,
- grinding circuit feed rate at the time of survey, and
- size reduction equipment power consumption at the time of survey.

5. SCOPE

The intended application of this analysis is to treat a complete grinding circuit as a singular process block, irrespective of the number of grinding stages or internal classification steps. This approach allows a quick, relatively low-cost assessment of overall grinding circuit efficiency and can identify if more detailed analysis or circuit optimization work is required. Following circuit changes, the same methods can be used to compare the impact on circuit efficiency of varying operating conditions.

This approach removes the need to survey internal circuit streams and mass balance around classification stages, greatly reducing labor requirements, survey turnaround time, and costs associated with sampling, sample analysis, and circuit modelling. While the intent of this guideline is not to define a full grinding circuit survey procedure—as would be required to support population balance modelling of the circuit—the techniques described observe industry best practice and can provide a firm starting point to analyze mineral comminution circuits at any required level of detail.

6. OTHER USEFUL DOCUMENTS

Several excellent references discuss the sampling and surveying of comminution circuits in more detail than the scope of this guideline allows. These references provide the basis for this guideline; the reader is referred to these publicly available documents listed in Section 11 of this document.

Two Microsoft Excel-based tools are available for download at http://www.gmggroup.org/library_categories/tools/

- Moly-Cop Tools Media Charge Level Spreadsheet for Calculating Mill Load Levels.xlsx

- Example Worksheet for Calculating Particle Size Distributions for Coarse Ore Samples.xlsx

7. PLANNING AND PREPARATION

7.1 Safety

Comminution circuit surveys must always first consider the management of risks to persons or property, in order to avoid damage or injury to personnel involved with, or influenced by, the survey process. At all times, follow site-specific policies for equipment isolation, manual handling, working from heights, and mobile equipment operation. Where necessary, apply industry best practices over and above site policies to ensure risks are mitigated. It is crucial to perform a thorough risk assessment prior to commencing sampling—involving all survey team members—to develop risk mitigation plans. Complete all risk mitigation actions identified prior to commencing the survey. The surveying process extends to sample handling and testing in the laboratory; therefore, the risk analysis should encompass these activities, through to completion of all sample analyses. Specified tasks such as equipment isolation and mobile equipment operation should only be performed by trained and competent personnel.

7.2 Target Streams

In order to support the high-level analysis of grinding circuit energy efficiency, it is typically necessary to collect only two samples: grinding circuit feed and grinding circuit product. More rigorous analysis of individual mill efficiency or classifier performance, particularly within a multistage grinding circuit, requires sampling several intermediate streams and hence is a significantly more onerous task. The sampling requirements to support overall circuit efficiency analysis are therefore greatly simplified.

Sampling of the grinding circuit feed is required to allow accurate determination of the grinding circuit feed size, specifically the F80 value, and to provide samples for ore characterization. A full fresh mill feed Particle Size Distribution (PSD) is also valuable information to support future circuit modelling and optimization studies. If the grinding circuit feed PSD is too fine to provide sufficient coarse particles for the required hardness tests, an additional sample from the crushing circuit may be required to provide sufficiently coarse sample for analysis.

When sampling coarse streams, it is essential to collect sufficient sample mass to minimize errors in the measured PSD. Guidance is given in the following sections to ensure that the samples collected and the analyses performed are fit for purpose, particularly that the sample mass collected and any subsequent sample mass reduction stages give due consideration to the impacts on measurement accuracy.

Sampling of the grinding circuit product is required to generate an accurate P80 value. Use full cross-stream sampling techniques to sample slurry streams, and take care to ensure adequate sample mass is collected to allow accurate analysis of the PSD. This is particularly important where the grinding circuit feed is a wet screen undersize stream.

7.3 Sample Size

When sampling comminution circuit streams, it is important to recognize that sample mass significantly influences the accuracy of subsequent measurement of stream PSD. Both Pitard (1993) and Napier-Munn, Morrell, Morrison, and Kojovic (1996) provide methods to estimate the required sample mass in a manner allowing management of the fundamental error in size analysis, which is driven by the coarseness of the stream PSD.

The sample size requirements of crushed ore vary as a function of PSD: finer crushed PSDs require less sample mass than coarse PSDs (e.g., produced by crushing a very competent ore). In the case of cyclone overflow streams, the sample mass produced by taking multiple cuts during a grinding circuit survey generally exceeds the sample mass required for size analysis of the stream. However, it is preferable to take several cuts and generate a larger volume of sample that subsequently requires splitting ahead of size analysis, rather than downsize the initial sample mass and risk compromising sample quality.

When applying calculation methods as described by Pitard (1993) and Napier-Munn et al. (1996), we observe that for streams coarser than a P80 of 25 mm, the required sample mass calculated quickly reaches several tonnes of sample as the feed size coarsens. As a result, experienced practitioners typically apply more empirical guidelines for the required sample quantities for coarser streams. Table 1 provides some indicative sample masses as a function of particle size for typical grinding circuit feed and product samples. Detailed guidance and examples for calculating sample size requirements provided by Napier-Munn et al. (1996) are provided in Annex A of this guideline, with the kind permission of the Julius Kruttschnitt Mineral Research Centre.

Table 1. Indicative sample size requirements

Stream type	Nominal size (mm)	Sample mass (kg)
Primary crushed ore	< 250	500–1,500
Secondary crushed ore	< 50	100–500
Ball mill feed	< 12	20–30
Cyclone overflow	< 1.5	0.5–1.0

7.4 Equipment

Prior to commencing the survey, all required safety, sampling, and laboratory equipment must be available and inspected to ensure good operating condition. Table 2 provides a list of equipment that is typically required to execute a grinding circuit survey and complete the sample analysis. The $\sqrt{2}$ sieve series is a common requirement for analyzing samples from a comminution circuit. This typically starts with a top screen size of 300 or 250 mm aperture and works down to 38 µm. A regular logarithmic spacing ($\sqrt{2}$ or similar) is necessary to provide the required resolution and minimize the potential for overloading sieve screens during particle size analysis. The same sieve series must be used for all samples collected during a circuit survey to simplify mass balancing efforts, although the very coarse screens are obviously not required for sizing product samples. An indicative $\sqrt{2}$ sieve series distribution is as follows, with screen apertures in mm: 250, 200, 175, 150, 125, 100, 75, 50, 37.5, 25.4, 19, 12.7, 9.5, 6.7, 4.75, 3.35, 2.36, 1.70, 1.18, 0.85, 0.6, 0.425, 0.3, 0.212, 0.150, 0.106, 0.075, 0.053, and 0.038.

Lifting aids may consist of pallets on which to store buckets and drums for sample transport, or certified slings or drum lifting clamps for lifting drums using overhead or mobile cranes. Consideration should be given to minimizing manual handling by using mobile equipment and approved, fit-for-purpose lifting aids.

For ball mill fresh feed samples, where a relatively small belt cut length (1–5 m) may be required, a purpose-built belt cut frame, usually 1–2 m long, can be applied to effectively delineate the sample lot from the bulk of the material on the conveyor.

When accessibility to a conveyor sampling location is restricted, heavy-duty sample bags can be a practical means to transport material from the sampling point. The bags must be sealed to avoid moisture loss, and the bag weight kept to a manageable level to avoid manual handling injuries.

Sample cutters for cross-stream sampling of flowing streams require careful design and operation. Very detailed guidance on design considerations for sample cutters is provided by Pitard (1993). Briefly, cutters typically need to be purpose fabricated for a specific sampling task, and their design needs to consider many important aspects, including:

- cutter edges should be sharp, horizontal, and parallel;
- cutter opening width should be at least 3 times the diameter of the largest particle in the stream to be sampled, and no less than 8 mm;
- the internal volume of the cutter should be sufficient to prevent sample splashing; and
- the sampler mass should be manageable and an appropriate weight to safely use.

A detailed example of sample cutter design provided by JKTech (Indooroopilly, Australia) is shown in Figure 1 and in detail in Annex B. This guidance recommends that a cutter slot width of at least six times the largest particle size is provided. The final design is at the discretion of the practitioner, but should observe Pitard's (1993) recommendation on slot width as a minimum standard.

Figure 2 shows further examples of cutters and handle alignments to suit sample points.

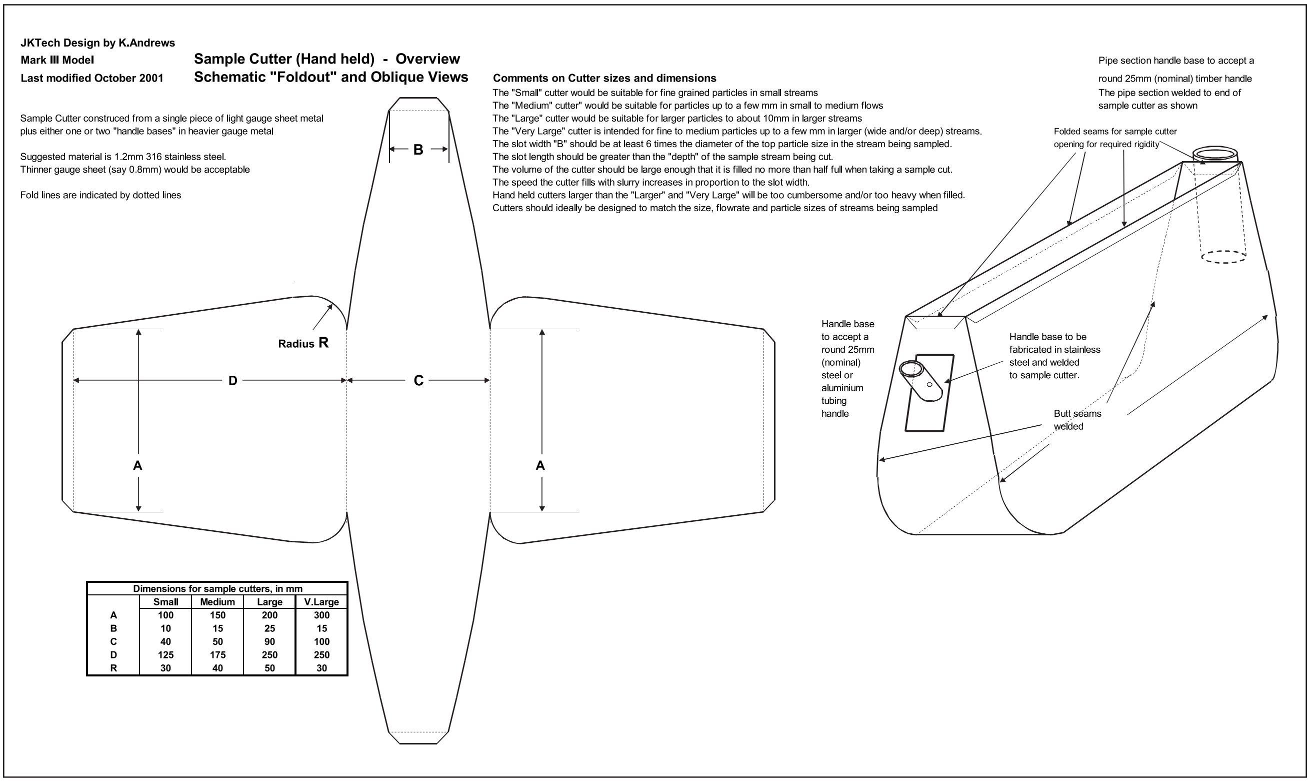
7.5 Instrument Calibration

Calibrate all instrumentation on a regular basis, including power meters, conveyor belt weightometers, density gauges, mass flow meters, pressure sensors, and other instruments and sensors that are critical to comminution circuit operation. The accuracy of these measurements must also be confirmed prior to any attempt to define comminution circuit efficiency. Instrument calibrations can be performed by in-house qualified personnel, but have key instrumentation for metal and mass balancing periodically calibrated by certified, third-party personnel.

The methodology for measuring power on all comminution equipment must be confirmed, especially in older plants that may not have reliable power meters on individual equipment. If power costs are allocated, or if power is calculated from amperage measurements rather than from power

Table 2. Survey equipment

Safety equipment	Conveyor samples	Slurry samples	Laboratory equipment
Personal protective equipment: gloves, safety boots, hard hat, safety glasses or goggles, respiratory protection, hearing protection	200 L drums, lids	20 L buckets, lids	0–500 kg platform balance
Fall restraint equipment	20 L buckets, lids	Sample cutter	0–20 kg balance
Lifting aids	10 m tape measures		$\sqrt{2}$ screen series, 200 or 300 mm screens
Hand-held radios	Brooms, flat nosed shovels, dustpans		Rotap or Gilson screen shakers
Isolation tags, isolation locks	One hole, 75 mm screen		Rotary sample splitter
	Spray paint, stopwatch		75, 100, 125, 150, 175, 200, and 250 mm one-hole screens
	Belt cut frame		Filter press
			Drying oven and trays



Dimensions for sample cutters, in mm				
	Small	Medium	Large	V.Large
A	100	150	200	300
B	10	15	25	15
C	40	50	90	100
D	125	175	250	250
R	30	40	50	30

Figure 1. Example Sample Cutter Design (reprinted with permission from JKTech)

(Photo courtesy of Dr. Adrian Dance)

Figure 2. Examples of Cutter Design and Handle Arrangements

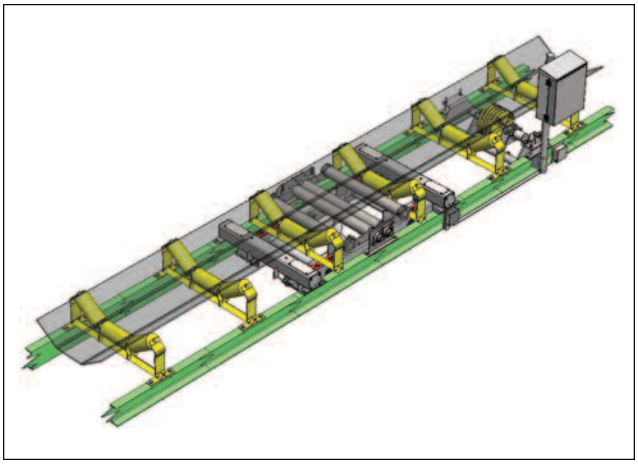


Figure 3. Two Idler Weighframe

meters, it may be necessary to install power meters on key equipment (e.g., mills and crushers) in order to accurately define the energy efficiency in the process. If the intent is to compare the performance of different comminution circuits (e.g., SAG ball mill, high pressure grinding roll (HPGR)/ball mill), power requirements for ancillary equipment (e.g., conveyors, pumps, screens) should also be measured so that total process power consumption can be assessed.

Conveyor belt weightometers consist of a weigh frame with a load cell and belt speed sensing device mounted to a conveyor frame. Output from the load cell and speed sensing device is digitally translated into a tonnage rate. The weigh frames can range from single idler up to six idler, depending upon the degree of accuracy required. An example of a two idler weightometer with a speed sensor is shown in Figure 3.

As part of the audit process, inspect conveyor belt weightometers to ensure that they are correctly installed in suitable locations and that housekeeping is properly maintained, with no build-up of material on the weightometer frames or idlers. Manufacturers provide detailed installation requirements for their weightometers, so use the manufacturer manual to verify proper installation. Examples of proper installation criteria include:

a) The weightometer is installed in a location with minimal variation in belt tension.

b) The weightometer is installed near the tail section of the conveyor, with a minimum of five idlers spaces between the weightometer and loading point/skirt boards.
c) The weightometer is not installed near curves in the conveyor (minimum of five idler spacing before and after weightometer frame).
d) For outdoor installations, enclosures to minimize wind loading and other environmental sources of error extend a minimum of five idler spacing before and after the weightometer.
e) Conveyor frame and weightometer frame are aligned, as are weightometer-mounted idlers and +/– five conveyor idlers.

Inspect static weights and chains to ensure they are in good condition and clean. Review inspection, maintenance, and calibration records for conveyor belt weightometers and validate calibration methodologies to confirm the accuracy of the weightometer readings. The belt conveyor calibration can be confirmed during the survey with belt cuts and verification of belt speed. Belt speed can be checked by either marking the belt with spray paint or using visible damage or other features of the belt as a marker. The time taken, measured by stopwatch, for the belt to complete three full revolutions typically provides an accurate measurement of belt speed. Ideally, this is coupled with confirmation of belt length, usually measured on an unloaded belt by a surveyor's wheel, to calculate a measured mill feed rate for comparison to the distributed control system value recorded during the survey. This permits direct estimation of mass flow when combined with the wet and dry weights of the belt cut sample.

Inspect density gauge and mass flowmeter installations to ensure they are properly installed. Confirm that calibration methodologies are consistent with manufacturer instructions. Often, initial calibrations are conducted during plant commissioning, when normal operating conditions have not been achieved. Therefore, when it is practical, verify density calibrations with statistically correct hand-cut samples over typical operating ranges and verify flowmeter calibrations by measuring drawdown or filling times of tanks with known dimensions. Further, to determine if magnetic flowmeter readings are compromised by magnetic material accumulation, turn off the power supply for a time and observe if the measured flow rate has decreased when power is turned back on.

8. SURVEYING

8.1 Survey Feed Controls

It is essential that the feed to the grinding circuit is as consistent as possible during the initial stabilization period and for the survey duration. This ensures that circuit stability is acceptable, recirculating loads have sufficient time to find their balance point, the survey conditions are well defined, and the associated samples are as representative as possible. This firstly requires liaison with the mine engineering department to source an adequate supply of primary crusher feed from a well-defined material type or blend. The volume should be sufficient to allow an extended period of operation on the specified feed in the lead-in to the survey and allow some contingency for stabilization time extension or a survey repeat. Ideally, identify at least two days of broken ore stocks.

In a direct feed situation—where ore is fed into the primary crusher and then immediately to a mill—the feed must be kept as consistent as possible. If Run-of-Mine (ROM) blending fingers (small stockpiles) are carefully prepared on the ROM pad, then the plan should avoid a change in ROM fingers during the stabilization and survey period. If the feed is a blend of fingers having different properties, then the blend ratios must be maintained throughout the stabilization and survey period. If the mill is direct feed and the ore is sourced from the mine by truck, stability is more difficult to achieve: there are unavoidable wide variations in PSD from truck to truck because blasted muck piles are naturally heterogeneous.

If crushed ore is stored between the primary crusher and milling, but it has minimal live capacity (<2 h), then the mill can also be assumed to be direct fed. If substantial storage exists between the primary crusher and the mill, management of the storage level is essential to achieve milling stability. The level of the plant feed bin or stockpile should not be allowed to drop below the level at which it becomes susceptible to coarse particle rilling or otherwise causes a significant change in the PSD of the mill feed. A change from stockpile drawdown to rilling behaviour is sufficient reason to abandon a survey or postpone a stabilization period. The safest approach is to maintain the stockpile or bin level at 50–80% for the period of interest.

8.2 When to Survey

The grinding circuit should be operating at steady-state for at least one hour prior to commencing the survey. To ensure that steady-state is reached during this stabilization period and this stability is maintained during the sampling period, monitor circuit variables such as mill feed rate, circulating load, feed size, water addition, cyclone feed pump speed, crusher closed-side setting, mill speed, mill power draw, mill weight (by load cell measurement or inferred from bearing pressure), cyclone pressure, and number of cyclones operating. If any significant changes to operating conditions occur during the survey, the survey must be abandoned and the samples discarded, unless the survey is near completion, in which case, immediately conclude the survey.

A dedicated person should be in the control room monitoring key process variables, with the necessary experience to assess process stability and make prompt decisions in the event that the survey needs to be abandoned or concluded prior to the scheduled completion time.

8.3 Survey Duration

Grinding circuit surveys typically require a one hour sampling duration to collect the required number of sample cuts, while minimizing the survey duration and potential for the circuit performance to change dramatically. Both shorter and longer sampling periods can be successfully executed, given appropriate consideration of sampling frequency and circuit stability requirements to ensure reliable data collection. The processes detailed in this guideline relate to a sampling duration of approximately one hour.

8.4 Sampling Procedures

In this guideline, mill feed conveyor samples are the only samples not collected during the defined survey period. These samples must be collected as soon as practically possible after the survey period, in order to avoid material changes in the PSD or changes to physical properties of the mill feed.

8.4.1 SAG Mill Feed Samples In order to ensure sufficient coarse particles (+75 mm) are collected to accurately represent a coarse PSD and to keep the sample mass at a manageable level, collect two distinct samples from the SAG mill feed conveyor belt: a full belt cut of all material present and a coarse rock sample.

- Shovel the belt cut sample comprising all material (including fines) from 2–7 m length of the belt. Collect enough material to fill two 200 L drums, and then accurately measure and record the length of belt cut to achieve this target volume.
- Along the next 3–15 m of the conveyor belt length, hand select and collect all lumps or rock particles coarser than approximately 75 mm. Take care to collect all coarse particles, including the lumps beneath the surface of the material. Use a "one hole screen" (with a single 75 × 75 mm opening) to manually identify and collect the coarse rocks, ideally in a separate 200 L drum. Sample sufficient length of the belt to provide one full drum of rocks and subsequently measure and record the sampled belt length. A minimum of 50 rocks must be collected, nominally +75 mm or another size determined to appropriately reflect the coarser end of the PSD, which may require more than 15 m of conveyor to be sampled. After sampling is complete, accurately measure and record the conveyor length used for this sample.
- A third sample may be collected at this time to provide sample for hardness testing. Collect sufficient sample to provide enough coarse particles for testing, based on the guidance provided in Table 3. This is often ensured by preferentially selecting rocks approximately 8 cm in size. Alternatively, split the hardness samples from the bulk sample collected for size analysis, or reconstitute them following the particle size analysis process.

Exercise care when preparing the comminution test samples, such that the subsamples tested most closely represent the circuit feed comminution characteristics. Common pitfalls in subsample preparation include over crushing the sample and improperly splitting the subsamples. In all cases, follow the specific sample preparation guidelines for each comminution test procedure.

8.4.2 Rod and Ball Mill Feed Samples Rod and ball mill fresh feed sizes typically range from 80% passing 50 mm to 80% passing 6 mm when operating in primary grinding duty. Consequently, the primary mill feed conveyor can be sampled by a single belt cut. The sample mass depends on the expected coarseness of the feed PSD, and can be estimated using the techniques described in Section 7.3. As a guide, expect that a ball mill fresh feed sample is at least 20 kg, and a rod mill fresh feed sample may need to be as large as 100 kg.

Again, perform a full belt cut—requiring all material including fines to be removed from the belt—to generate this sample. Accurately measure the length of the belt cut to allow a kg/m belt loading to be calculated and the mill

Table 3. Comminution test sample requirements

Test	Benchmarking method	Particle size (mm)	Sample size
Bond low energy impact test	Bond, 1961	−75 to +50	20 pieces
Bond rod mill grindability test	Bond, 1961	−12.7	15 kg
Bond ball mill grindability test	Bond, 1961; Morrell, 2009	−3.35	10–15 kg
SMC Test®	Morrell, 2009	−31.5 to +13.2	20 kg

feed tonnage to be estimated from the measured belt speed, as described in Section 7.5.

In some instances, the primary mill is fed by a slurry stream, as is the case when HPGR product is wet screened and the screen undersize is discharged to the cyclone feed hopper/sump. This presents a more significant sampling challenge because of the higher volumetric flow rates. A purpose-built sample cutter is required, observing the design considerations described in the Section 7.4. Consider installing a mechanical sampling device of similar design to minimize the risk of injury when sampling a high slurry flow rate and to further ensure a consistent cross-stream sampling technique. If a manual sample is to be collected, it may be necessary to divide the stream into segments to prevent sample cutter overflow, and to ensure the risks associated with collecting the sample manually are appropriately addressed in the survey risk assessment.

8.4.3 Grinding Circuit Product Samples Grinding circuit product is commonly represented by hydrocyclone overflow, but the final product separation may be performed by screens or mechanical classifiers. In any event, the sampling options are to either take:

- a full cross stream cut of a full product flowing stream, segmented cuts of a full product flowing stream; or
- full cross-stream cuts of individual cyclone overflow discharges.

In all instances, it is essential not to overfill the cutter, because this gives a biased sample. Perform sample cuts at constant speed and alternate the direction of the cut each time to minimize the potential for bias. Wash the sample cutter in the slurry stream and tap to ensure it is empty before sample cuts are taken. This avoids the need to wash the cutter with water between cuts, which would influence sample pulp density.

A manually collected, full cross-stream cut of a flowing stream is possible when the stream flow rate is suitably low, nominally less than 250 t/h, to allow the cut to be safely and reliably performed. At high slurry flows, there is tendency for the cutter to overflow, resulting in a biased sample that must be discarded. For suitably high slurry flows, a larger, mechanically operated sample cutter is required to obtain a representative sample in a single cut.

The full cross-section of the stream should ideally be cut in a single pass. If this is not possible, perform and combine individual cuts of sections of the stream. The volume of each cut should be approximately proportional to the volumetric flow of that stream section.

When sampling individual cyclone overflow pipes, alternate the sample point around the cyclone cluster each time to ensure that the performance of the full cluster is approximated by the composite sample. Ideally, sample each operating cyclone overflow an equal number of times during the survey. If this is not feasible, sample one in two cyclones—or one in three cyclones in the case of large clusters—an equal number of times during the survey.

The practitioner may prefer to either keep the individual sample cuts separate for individual analysis when the survey is completed, or combine into smaller combinations of cuts that represent the survey period in sections. In that way the analysis may be used to define the impact of changes in plant performance during the survey. This approach is less practical when individual cyclones are sampled, because any measured differences in PSD between individual cuts could be the result of differences in cyclone liner condition. However, this approach is suitable when good quality, full product stream, cross-stream cut samples are collected. One technique that can be used as a check of steady-state operation involves dividing the survey into two halves. Separate analysis and comparison of the two sample sets allows a quantitative assessment of stability.

8.5 Circuit Data Collection

Minimal operating data are required to support the prescribed objective of determining the grinding circuit energy efficiency, as described above. Aside from the data generated by the analysis of samples (feed moisture content, hardness, PSDs), the only additional data specifically required for efficiency analysis are circuit feed rate and total power consumption measurements during the survey period. Accurate power measurement is critical to the success of the survey, so it is important to fully understand the power measurement methodology (e.g., motor input or output power, amperage, variable frequency drive input or output power). The Bond and Morrell reference specific energy values are based on power measured at the mill shell (or pinion), and the survey power draw measurements must be mathematically corrected to that same basis. The conversion process and drive specific correction factors are presented in a technical article by Doll (2012).

Each grinding circuit survey is an opportunity to collect additional optional information that describes the circuit operating condition, providing valuable context for future circuit optimization efforts. Consequently, the practitioner should consider collecting the same data as would be required for a full grinding circuit survey. A significant volume of these data can often be collected from a data historian or the process control system, while other information must be generated from manual checks and measurements on equipment—in many cases requiring a temporary circuit shutdown. Perform such measurements while the circuit is off-line to collect the mill feed sample, and base all information on measurements rather than anecdotal or supplier-provided values. This supplementary information—not expressly required for the efficiency analysis step—is noted as optional in the following sections.

8.5.1 SAG Mill Data

Required data

- fresh feed tonnage rate
- total feed tonnage rate (fresh feed + pebble recycle) Optional data
- feed conveyor imaging software 100, 90, 80... 10% passing sizes
- feed water flow rate
- load weight (or bearing pressure indication)
- power draw (or motor current)
- sound (if available)
- field measurement of mill rotational speed in rpm
- grate/pebble port apertures (measurement of opening dimensions during mill inspection)
- ball charge level (measured after mill grind out)
- ball size
- total mill filling level (measured after mill crash stop)

8.5.2 Crushers (primary, secondary, tertiary, quaternary, pebble)

Required data

- power draw or motor current
- tonnage rate

Optional data

- closed side setting

8.5.3 Rod/Ball Mill Data

Required data

- power draw (or motor current)

Optional data

- feed water addition rate
- field measurement of mill rotational speed in rpm
- discharge density (field measurement of pulp density by Marcy scale or laboratory analysis)
- rod/ball charge level
- rod/ball size

8.5.4 Screens

Optional data

- panel aperture
- current draw
- water flow rate

8.5.5 Cyclones

Optional data

- feed sump level
- feed sump dilution water flow rate
- feed pump speed
- feed pump amps
- feed density
- feed flow rate
- feed mass flow
- pressure
- number of operating cyclones
- liner dimensions (inlet opening, vortex finder, spigot, cylinder length) and cone angle

8.5.6 Measurement of Mill Charge Levels (optional data)

Measuring charge levels at the time of the survey provides information that is useful to diagnose the observed circuit performance, but these optional data are not required in the analysis of total circuit energy efficiency using the Bond or Morrell methods.

In order to measure the ball charge level of any tumbling mill or the total volumetric filling level of an AG or SAG mill, the mill needs to be stopped under controlled conditions and made available for inspection. As a result, collect this information only when deemed necessary or convenient.

Follow site isolation and confined space entry procedures prior to and during a mill inspection to ensure the safety of personnel and equipment. Measuring total volumetric filling requires a crash stop of the mill, which entails the immediate stoppage of water flows, recirculating loads, and fresh feed flows into the mill at the same time the mill is stopped. Ball charge measurements require grind outs to ensure the ball load is exposed and free of unbroken ore particles. Grind-out times are site and mill specific, but typically range from 20 to 60 minutes.

Once the necessary preparations have been made to allow safe access to the mill, the charge level can be measured in several ways. The most accurate methods involve chord measurements across the exposed surface area of the charge and measurement or estimation of the free height between the charge and the mill shell at its highest point. Additionally, it is possible to estimate the charge level by counting the number of exposed shell lifters. All of these methods are contained in the "Moly-Cop Tools Media Charge Level Spreadsheet for Calculating Mill Load Levels" spreadsheet (provided with the kind permission of Moly-Cop and available for download at http://www.gmggroup.org /library_categories/tools/), along with the necessary calculations to convert the measurements into an estimate of volumetric filling levels.

If the mill is shut down for inspection or charge measurement, take photographs of the liners, charge, and grates. These photographs can provide useful information and a record of the operating conditions inside the mill.

Having measured the ball charge level and the mill filling level in the case of AG or SAG mills, it may be desirable to calibrate a power draw prediction model for the mill. This requires an estimate of the average mill shell liner thickness to allow the effective mill diameter inside liners to be calculated. This estimate can be generated using the mill liner supplier's techniques for measuring the in-situ liner profile, or from an estimate of worn liner thickness based on typical shell liner service life.

9. SAMPLE PROCESSING

9.1 Conveyor Samples

For mill feed conveyor samples, wet weigh the entire sample, then air dry or dry in a low-temperature (< 50°C) oven and then reweigh to determine the moisture content. The size of the sample requires a large walk-in drying oven or large indoor open space.

1. Following drying and weighing, dry screen the entire sample at 12.7 mm.
2. Wet screen the resulting +12.7 mm size fraction at 12.7 mm to remove attached or agglomerated fines. Then filter, dry, and dis-agglomerate the wet screen undersize and combine with the –12.7 mm dry screen fraction.
3. Dry the +12.7 mm wet screen fraction at low temperature, then screen on 250, 200, 175, 150, 125, 100, 75, 50, 37.5, 25.4, and 19 mm screens and weigh. Screen the entire +12.7 mm size fraction. Particles larger than 75 mm can also be screened manually using "one hole" square opening screens if large screens are not available. These are typically made of plywood or a bucket lid. Particles smaller than 75 mm are typically screened using a multiscreen sieve shaker. Ensure that the screen panels are not overloaded so that suitable screening efficiency is maintained.
4. Weigh the entire –12.7 mm fraction, then blend and subsample to 20–25 kg using a 12 or 24 cup rotary splitter. Run the rotary splitter such that at least 50 cuts are taken from the feeder.
5. Weigh and dry screen the 20–25 kg subsample at 1.7 mm. Reweigh the dry –1.7 mm material and set aside for further processing.
6. Wet screen the +1.7 mm size fraction at 1.7 mm to remove any attached or agglomerated fines. Treat the wet –1.7 mm material with flocculant, decant, filter, dry, weigh, and de-lump, and then recombine with the dry –1.7 mm material. Air or low-temperature (50°C) oven dry and weigh the wet +1.7 mm material.
7. Dry screen the resulting –12.7 +1.7 mm size fraction on 9.5, 6.7, 4.75, 3.35, 2.36, and 1.7 mm screens and then weigh. Check the total losses up to this point to ensure good procedures and maintain sample accounting.
8. Blend the entire –1.7 mm fraction using a V-blender or similar, then pass at least five times through a Jones splitter or pass through a rotary splitter. Subsample the total –1.7 mm fraction to approximately 500 g using a 12–24 cup rotary splitter.
9. Weigh the 500 g subsample. If possible, prescreen at 0.15–0.30 mm to reduce the subsample mass and then wet screen at 0.038 mm. If prescreening is not possible, then do the 0.038 mm wet screening in 0.5 kg (maximum) portions to avoid overloading the test screen and causing premature wear and failure of the 0.038 mm wire mesh. Do not flocculate the wet –0.038 mm material; instead, filter, dry at 100°C, and weigh.
10. Dry screen the resulting –1.7 + 0.038 mm size fraction on 1.18, 0.850, 0.600, 0.425, 0.300, 0.212, 0.150, 0.106, 0.075, 0.053, and 0.038 mm screens and weigh.
11. Add the deslime fraction to the –0.038 mm screened size fraction to allow calculation of the belt cut sample PSD.

9.1.1 SAG Mill Feed Sample – Coarse Rock Sample Size the coarse rock samples from approximately 7–15 m of the conveyor belt on coarse screens (250, 200, 175, 150, 125, 100, and 75 mm). Discard the –75 mm fraction, then calculate the full individual stream PSD, taking weighted averages of the belt cut and coarse rock samples.

9.2 Slurry Samples

9.2.1 Coarse Slurry Stream Samples Analyze coarse slurry stream samples such as new mill feed from wet screen undersize using the following procedure:

1. Wet weigh each slurry sample and then pressure filter and dry. Weigh the dry sample and calculate the percent solids.
2. Screen each entire sample at 2.36 mm. Dry screen the entire +2.36 mm fraction on 25.4, 19.0, 12.7, 9.5, 6.7, 4.75, 3.35, and 2.36 mm screens and weigh. Weigh the –2.36 mm fraction and subsample (rotary split) to 3 kg. Weigh this subsample, dry, reweigh, and wet screen at 0.038 mm. Dry both samples and screen the +0.038 mm fraction over the following sizes: 1.70, 1.18, 0.850, 0.600, 0.425, 0.300, 0.212, 0.150, 0.106, 0.075, 0.053, and 0.038 mm. Sieving time should be approximately 30 minutes.
3. Record final dry weights retained on each screen.

4. Combine the –0.038 mm material from both wet and dry screening to obtain the total amount of material within this fraction.

9.2.2 Fine Slurry Stream Samples Analyze fine slurry streams such as cyclone overflow using the following procedure:

1. Wet weigh samples and then pressure filter and dry. Weigh dried samples and calculate the percent solids. Riffle out and weigh a subsample of approximately 1 kg.
2. Wet screen the sample at 0.038 mm. Filter, dry, and weigh both oversize and undersize; record dry weights. Dry screen the +0.038 mm fraction over the following sizes: 1.70, 1.18, 0.850, 0.600, 0.425, 0.300, 0.212, 0.150, 0.106, 0.075, 0.053, and 0.038 mm. Sieving time should be approximately 30 minutes.

10. DATA ANALYSIS

Prior to evaluating and summarizing specific energy values for the comminution circuit, conduct a final review and validate all data, including operating data collected during the sampling period, PSDs of the survey samples, and power data.

Review operating data for the one-hour period prior to the survey and for the survey period (see Section 8.2 for the list of key operating variables) for circuit instability that may have gone unnoticed during the survey. Upward or downward trends or variability greater than normal operating ranges indicate that the process was unstable, and survey results may be unreliable.

Plot the PSD of the feed and product samples and confirm that the PSD plots have no step changes or abnormal distributions in the coarse or fine fractions that could indicate improper sampling methods or locations, equipment inefficiencies, or maintenance issues.

Prior to calculating circuit specific energy, review the source and measurement method of all power data (e.g., motor input or output, shell power, pinion power, variable frequency drive supply, conversion of current to power), so that total circuit power can be correctly summed.

11. RESOURCES, REFERENCES, AND RECOMMENDED READING

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ANNEX A: DETERMINING THE SAMPLE MASS REQUIRED FOR SIZE ANALYSIS AND THE MEASUREMENT PRECISION (reprinted from Napier-Munn et al. (1996) with permission from the Director, Julius Kruttschnitt Mineral Research Centre)

The problem is really a statistical one, since it depends on the nature and magnitude of the errors which accumulate when collecting and processing a sample. Some of the errors and disturbances which can contribute to overall error in determining some quantity such as a solids concentration or particle size distribution are:

1. Plant dynamics. Processes are rarely in steady state, and sampling policy must be determined accordingly. A 'snapshot' sample may be appropriate for a single device with essentially no dynamics, such as a crusher or hydrocyclone, but a circuit is usually sampled by accumulating a number of incremental samples taken over 1-2 hours to 'smooth out' disturbances in the process.

2. Sample cutter design - see Section 5.2.4.

3. Sub-sampling a primary sample.

4. Analytical errors, e.g. weighing, screens with worn or incorrect apertures, inadequate screening time, incorrect calibration or selection of constants, etc. Such errors are more common than generally admitted (see also Appendix 3).

5. The propagation of error when calculating quantities - see Section 5.2.3.

6. The fundamental statistical uncertainty (error) involved in choosing a small, finite sample to represent the properties of a large (effectively infinitely large) population - see Section 5.2.2.

The surveyor has some control over the first five of these, but essentially no control over the fundamental error (FE) which is a statistical property of the particulate system being studied. The object of any sampling and analysis exercise should therefore be to minimise the effects of items 1 - 5 so that their contribution to overall error is small relative to FE. The size of sample is then chosen to achieve the required confidence in the light of the prevailing FE.

Sampling statistics is a complex topic. Gy (e.g. 1976) has developed a widely-used theory of particulate sampling, which has been adapted and described by Pitard (1993), who also discusses many other aspects of sampling such as cutter design.

5.2.2 Size of Sample for Size Analysis

How large a sample of solids from a process stream should be presented for size analysis? One answer is: as large as possible, since this will maximise the reliability of the final result. In practice, however, the selection of sample size is a pragmatic compromise between economics (the cost of collecting and processing the sample) and the confidence needed in the answer.

Chapter 18 of Pitard's book deals specifically with sampling for size analysis. However, to give a simple estimate of the order of sample size required to accommodate the FE, Barbery (1972) derived an expression based on Gy's theory, which is easy to use:

$$M = \frac{f \rho d_m^3}{\theta^2 P} \tag{5.1}$$

where
- M = mass of sample required (g)
- f = shape factor for material ($0 < f < 1$)
- ρ = density of material (g/cm^3)
- d_m = mean size in size range of interest (cm)
- P = expected proportion of material in size range of interest (to be measured)
- θ = standard deviation of the number of particles in that size range.

(The variance θ^2 is essentially the FE referred to earlier).

These terms require some explanation. The shape factor of a single particle is $f = m/\rho d^3$. $f = 0.1$ for flat, plate-like particles and approaches 1 for spheroidal particles. For most natural ores and coal, $0.3 < f < 0.7$, and 0.6 is not a bad guess in many cases.

d_m^3 can be calculated as (Barbery 1972):

$$d_m^3 = \frac{d_1^3 + d_2^3}{2} \tag{5.2}$$

where d_1 and d_2 are the limiting sizes of the size range of interest. The size range of interest is that which is likely to have the least number of particles in it, which is nearly always the coarsest size interval. This ensures that the error on the proportions estimated for the other size intervals will always be less than this, thus ensuring a conservative choice. However, it is pointless to choose an interval with practically no material in it. A good rule of thumb is that the coarsest size interval should be chosen to give $P \approx 5\%$.

θ is determined from the precision of estimation and confidence required:

$$\theta = \frac{\phi}{z} \tag{5.3}$$

where
- ϕ = chosen precision (relative proportion)
- z = normal ordinate at the chosen confidence level.

Table 5.1 gives values of z for different confidence levels.

Table 5.1: Normal ordinates (from the normal distribution)

Confidence Level (%)	z
50	0.6745
80	1.2816
90	1.6449
95	1.9600
99	2.5758
99.9	3.2905

A confidence level of 90% (z = 1.64) is usually adequate. The definition of θ is interpreted as follows: if the proportion of material expected to lie in the coarsest size range is 5% (P = 0.05), and we want to estimate this to a precision of 10% relative with 90% confidence, then

$$\theta = \frac{(10/100)}{1.64} = 0.061, \text{ and } P = 5\% \pm 0.5\%, \text{ with } 90\% \text{ confidence.}$$

<u>Example 5.1</u>: A SAG mill trommel oversize stream in a base metal concentrator is to be sampled in a plant survey to determine its size distribution. It is expected that all the material will be less than 50mm, and about 10% will lie in the (top) screen size range - 50 + 25mm. How much sample should be screened to ensure 90% confidence of determining this proportion to a relative precision of 20%? (ie. P ≅ 10 ± 2%).

$$d_m^3 = \frac{5^3 + 2.5^3}{2} = 70.3 \text{ cm}^3$$

$$\theta = 0.2/1.64 = 0.122.$$

Trommel oversize from SAG mills is often quite rounded, so assume f = 0.7. Also ρ = 3.0 and P = 0.10. Substituting these values in equation 5.1 gives M = 99kg. This is a large sample and demonstrates the uncertainties in sizing coarse material. If the size interval had been -5 + 2.5mm, M = 99g, because of the much larger numbers of particles per unit mass at this finer size. The calculated mass is also conservative, because the coarsest fraction and smallest mass proportion (10%) is very much the worst case; the other size intervals would have much better precision.

Clearly equation 5.1 can be re-arranged to calculate the precision or confidence limits on an actual result:

$$\theta = \sqrt{\frac{f \rho d_m^3}{MP}} \qquad (5.4)$$

Example 5.2 : In the preceding example, only 10kg was screened, and the amount in the -50 + 25 mm fraction was found to be 14.5%. What are the 90% confidence limits on this result?

M = 10^4 g, and P = 0.145. From equation 5.4, θ = 0.319 and thus the 90% confidence limits are ± 0.319 x 1.64 x 14.5 = ± 7.6%, ie. the 90% confidence interval is (14.5 - 7.6)% to (14.5 + 7.6)%. The relative precision is therefore 7.6 x 100/14.5 = 52% - very poor!

Clearly the FE for size analysis is really only an issue in the coarsest sizes, ie. in crushing, AG/SAG milling and coarse rod and ball milling. For flotation or fine gravity concentration streams and in fine grinding, the FE can be accommodated with only a few grams of material, or less, and the size of sample is then determined more by the other sources of error than by the FE. For very coarse materials, the required sample size will be larger than it is practicable to process in a reasonable time-frame (typically 5 tonnes for a 200mm top size), and some compromise is generally sought. Means by which an acceptable estimate of run-of-mine (ROM) sizing can be obtained are discussed in Section 5.4.2.

5.2.3 Propagation of Error in Calculated Quantities

Some quantities in a survey will be calculated rather than measured. A good example is solids concentration in a slurry. Although it is advisable to 'measure' it directly by dewatering and drying a sample of slurry, it is sometimes inferred from a slurry density measured with a Marcy scale. The solids concentration by weight, C_w , is then given by

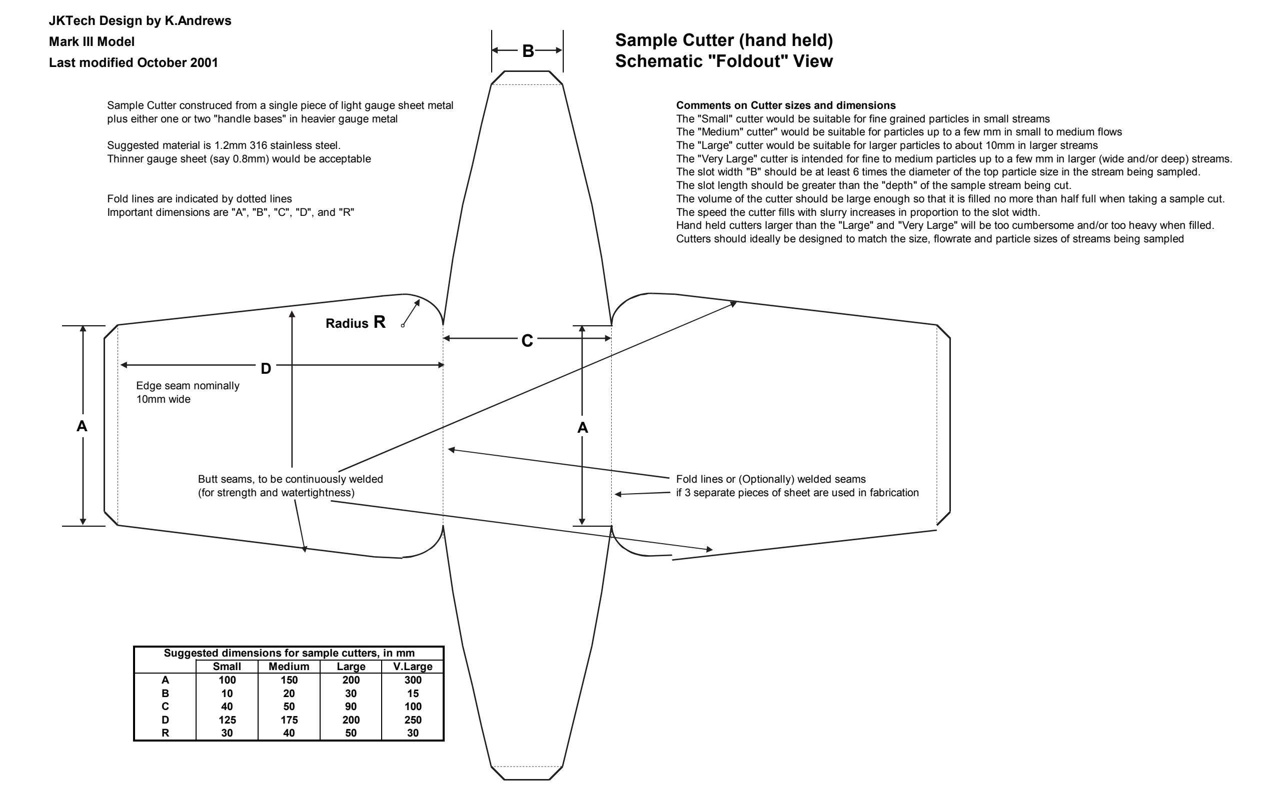
$$C_w = \frac{\rho_s(\rho_p - 1)}{\rho_p(\rho_s - 1)} \qquad (5.5)$$

where ρ_s and ρ_p are the solids and slurry densities respectively, with water as the fluid.

Assuming the errors in measuring or 'knowing' ρ_s and ρ_p are small, the law of partial differentiation states that

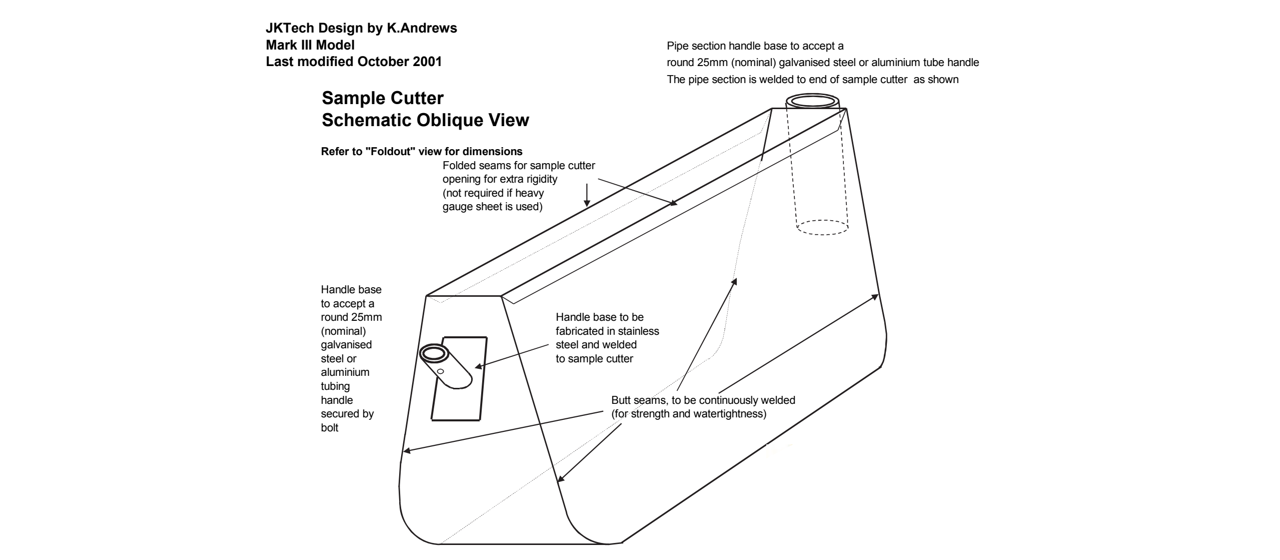
$$\delta C_w = \frac{\partial C_w}{\partial \rho_s} \cdot \delta\rho_s + \frac{\partial C_w}{\partial \rho_p} \cdot \delta\rho_p \qquad (5.6)$$

ANNEX B: EXAMPLE SAMPLE CUTTER DESIGN DIMENSIONS AND SCHEMATICS (reprinted with permission from JKTech)



Suggested dimensions for sample cutters, in mm

	Small	Medium	Large	V.Large
A	100	150	200	300
B	10	20	30	15
C	40	50	90	100
D	125	175	200	250
R	30	40	50	30



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