Critical aspects of sampling in mills and plants: a guide to understanding sampling audits

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Synopsis

When it comes to sampling theory, a bad sampler is a bad sampler, no matter what, and a sampler is either bad or good. It also is of critical economic importance to tell and understand the difference, especially in a metallurgical plant. In this paper, the grand principles of Sampling Theory are first recalled, then the most popular types of sample cutters for plants are critically reviewed. It is concluded that the industry has a lot of progresses to make in that direction, although improvements usually pay for themselves very quickly.

Introduction

In sampling theory, a cat is a cat, and a door is either open or closed. Implying that, a bad sampler is a bad sampler, no matter what, and a sampler is either bad or good. Until now, however, plant designers and most sampling equipment manufacturers alike, have traditionally displayed a complete ignorance of sampling theory basic concepts, although these concepts can very easily help distinguish between a 'bad' sampler (which can and usually does generate biased samples), and a 'correct' one (for which this risk is virtually eliminated).

Largely due to the lack of proper teaching of the concepts of sampling theory in most geology, mining, chemical and engineering schools, this rampant ignorance costs many a mining company many millions a year in bad reconciliations, as it translates into poor optimization of both mine and mill operations, biased metallurgical balances, under-estimated concentrates, etc. This is without counting with the very high, after the fact, unplanned, and not uncommon cost of reinstalling new, correct samplers in due course, to replace the incorrect, original ones when time has finally come to seriously tackle reconciliation problems.

It can be, and has been in many cases, demonstrated, that a small general improvement to sampling reproducibility in a mine-plant complex can reach millions of dollars in additional yearly profits, and that conversely, unattended sampling biases can cause net losses of the same order of magnitude.

After reviewing the grand principles of sampling theory, this paper then apply them in a critical way to the most common types of samplers encountered in metallurgical plants around the world. It is hoped that this will help plant managers better understand the point of view and the critical comments often received from sampling equipment auditors.

The grand principles of sampling theory

Ideal case: Fundamental error and Gy's formula

When a sample of mass M_S is collected at random, fragment per fragment with the same probability, from a lot of fragmented material of mass M_L, a sampling error arises between the true unknown grade of the sample and that of the lot. This error is the smallest in absolute average for a sample collected under these ideal conditions and because of that is called *fundamental sampling error (FSE)*. It is due to the natural, constitutive heterogeneity of the lot, which for this reason is called *constitutive heterogeneity.*

This error usually has a negligible algebraic mean, and is characterized by its variance, classically calculated as relative to the true grade of the lot using the well known formula called (except by its author) 'Gy's formula'

$$\text{Rel.Var.} = cfgl\, d^3 \,(1/M_S - 1/M_L) \qquad [1]$$

which happens to be the *stricto sensu* relative variance, in the statistical meaning of the term,

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of the possible outcome of the sample grade. In formula [1], *d* is the nominal size of the fragments, and *c,f,g* and *l* are factors which can be either calculated or experimentally assessed.

In this ideal case, never realized in practice, each fragment is assumed to have the same probability of selection as any other, and, most importantly, is selected independently from the others.

Sample correctness and representativeness

In order to rationally introduce the central concept of representativeness of a sample, one must first be concerned with its unbiasedness. Unfortunately, however easy it may be to demonstrate the existence of a bias (i.e. a systematic error) when it exists (suffices evidencing its existence in only one case), *it is theoretically impossible to demonstrate its absence*[(i)].

It is therefore important to define a condition which could guarantee in advance a *structural* absence of bias: this condition is *sample correctness*:

A sample is said to be 'correct' when any fragment in the lot to be sampled has the same probability of being selected in the sample as any other one.

This condition guarantees unbiasedness, since any bias would preclude it.

It is then possible to simply formalize the concept of *representativeness* of a sample:

A sample is said to be 'representative' if the two following conditions are met:

- ➤ it is unbiased, and
- ➤ it has a sufficiently small variance.

Under these conditions, if a sample is *correct and sufficiently reproducible,* it automatically qualifies as representative.

Representativeness therefore contains a precise, technical, objective, qualitative condition (correctness) and a (quantitative) element of subjectivity ('sufficiently' reproducible).

Real life: Segregation problems

In real life, regrettably, things are not that simple. Firstly, it is impossible to strictly execute this fragment per fragment selection. One then will have to think of a slightly different, more practical sampling mode: instead of selecting individual fragments, successive increments of a certain size (i.e. small sub-samples) will be collected.

But then, the sample reproducibility suddenly becomes very sensitive to another type of heterogeneity which did not affect in any way a fragment per fragment sample: the *distributional heterogeneity.* Better known as *segregation,* this type of heterogeneity can strongly diminish the sample reproducibility and multiply its variance by a large factor, which is unpredictable, but can nevertheless reach several orders of magnitude.

A mathematical development fortunately shows that the additional variance component which ensues inversely proportional to the number of increments used to constitute the sample. One will therefore take as many (and therefore as small) increments as practically possible. This is known as the, method of *incremental sampling.* It is a very valuable method, but it will however generally be impossible to predict how many increments are needed. Experimentation therefore will be crucial.

Another solution consists of not taking the sample or the increments at random, but instead structuring the segregation into a known geometry, for instance in layers, and sampling perpendicularly to that geometry. This is the very powerful method which underlies Gy's modern theories of pre-homogenization and *bed-blending*.

Resulting philosophy

General practical rules

From all those considerations result the following practical golden rules of the quest for sample representativeness:

- ➤ With the risk of bias never being acceptable, one shall only accept correct samplers and sampling procedures. Any sampler or procedure deemed or only suspected to be incorrect shall be eliminated as its unbiasedness will never be guaranteed.
- ➤ To seek protection against the negative effects of segregation, one shall:
  - either take advantage of the incremental sampling method while avoiding at the same time to accentuate segregation by carelessness, or, whenever possible
  - use the general principles behind the theory of bed-blending.
- ➤ Finally, one shall control the mass of the collected sample in order to bring its variance below the level considered acceptable. To this end, one will for instance calibrate and use formula [1].

Automatic sampling modes for uni-dimensional lots (streams)

In the particular case of one-dimensional lots so common in a process plant environment (e.g. streams of slurry or dry suspensions, crushed ore on conveyor belts, etc.), there are three identified sampling modes corresponding to different families of automatic samplers:

#1 Taking part of the flow part of the time (e.g. internal pipe bleeder)
#2 Taking part of the flow all of the time (e.g. in-pipe derivation, pressure bleeder)
#3 Taking all of the flow part of the time (e.g. cross-stream sampler).

Only mode #3—and only in the case of a proper installation of the sampler and in appropriate conditions of use—can guarantee correct samples. One of the main reasons is the following: even if a totally turbulent (i.e. random) state could artificially be imparted to the flowing regime just before the sampling point, the sole fact of introducing an obstacle to

(i) *It is important to not fall prey to the very common confusion between 'the absence of proof of bias' (demonstrated by certain statistical tests) and 'the proof of absence of bias'* the material (the collector, whatever it is), could, and will, re-structure the flow in a precise, deterministic, albeit un-predictable manner. This unknown restructuring quasi-automatically results into a preferential, therefore incorrect, sampling.

The following rule ensues:

With very few exceptions, samplers using modes #1 and #2 above are to be avoided at all costs, if one wants to be serious about sampling.

Classical stream samplers

The sine qua non of correctness creates the absolute necessity of critically distinguishing between the various types of samplers and sampling procedures available. Whatever the possible manufacturers claims might be, one will significantly benefit from using the following guidelines and examples instead.

Examples of incorrect samplers

Internal pipe bleeders

All of the internal pipe samplers, such as pipe bleeders, pressure bleeders, sample valves and Archimedes screw extractors, use modes #1 and #2 above and therefore:

These types of samplers are to be avoided at all costs in practice.

Some samplers using mode #3

Mode #3 above alone is NOT a guarantee of sample correctness. Certain conditions of installation and use must also be fulfilled.

Example 1: Cross-belt sampler

The Cross-belt sampler is a running-belt sampler consisting of a rotary, articulated arm which attempts at collecting a sample 'on the fly' from the passing material on the belt. This type uses mode #3 above, and yet, it is virtually impossible to make it work 'correctly' for many reasons, including the following:

- ➤ Generally, the selected part of the flow of material is pushed towards the collection chute rather than cut
- ➤ The finest and/or coarsest material are usually not collected in representative proportions
- ➤ If the motor is not powerful enough, visually appreciable variation in the cutting speed can hamper the correctness of the collection
- ➤ If, on the other hand, the motor is powerful enough to keep this effect to a minimum (although it is never entirely eliminated), then a part of the coarsest fragments often bounce against the wall of the collection chute and back onto the belt.

With very few exceptions, these types of samplers are to be avoided at all costs, or replaced.

Example 2: Cross-stream samplers incorrectly installed or used

Cross-stream samplers installed at the discharge of slurry pipes or conveyor belts generally use mode #3 above. Most of them are correct by design, but a flawed installation may render them incorrect in practice.

This for instance will be the case when the collector speed is not constant because the motor is moved by a manual, pneumatic or hydraulic system, or when certain limiting conditions of use are not fulfilled (more details in the next section).

Another example arises when not the entire flow is cut by the sample collector, whether it is because the cutter is not centered, or because the equipment is wrongly sized.

Such samplers must be replaced/fixed as soon as the flaw is discovered.

Example 3: Ill-designed cross-stream samplers

Also widely available on the equipment market are samplers using mode #3, which are unarguably incorrect because the flow of material (rather than the cutter opening) is imparted a momentum other than the sole acceleration of gravity, resulting in complex and uncontrollable mechanics conducive to sample incorrectness.

Such is the case, for instance, of a flexible discharge tube periodically moved by a piston, or a rotating distribution spigot, passing over or in front of a fixed opening. These last samplers attempt at imitating linear and Vezin type samplers(ii) but do so quite incorrectly. Samplers based on rotating spigots even are the most commonly proven biased by experimentation in plants around the world.

This type of sampler is to be eliminated at all costs.

In the same category, some otherwise proper Vezin type samplers are also faultily designed in that their collecting openings are not radial.

Such samplers must be replaced/fixed as soon as the flaw is discovered.

Example 4: Most manual samples

Manual sample taken through a falling flow or even from an agitated tank are never correct. The main reasons include the following:

- ➤ the modifications brought to the mechanics of fluids and solids in the vicinity of the sample collection container;
- ➤ the difficulty to cut the entire flow; and,
- ➤ the impossibility to impart the cutting movement at an exact constant speed.

All these pitfalls trigger preferential sampling.

This type of sampling is to be eliminated at all costs.

Examples of correct samplers

Cross-stream samplers

Cross-stream rectilinear sample cutters and rotary cutters with radial, revolving openings (as opposed to revolving feeders), all use mode #3 and are generally correct by design, provided certain limiting conditions of use are met.

(ii) Named after Vezin, author in 1895 of the ancestor of Gy's formula, true Vezin samplers strictly belong to the category of uniformly rotating cutter realizing a full cut of a vertical stream of material in free fall

These conditions, established by Gy both at the theoretical and experimental levels, aim at controlling the effects that the complex mechanics of the fragments bouncing on the moving sample cutting blades may have on the correctness of the sample:

- the collection opening must everywhere exceed three times the diameter *d* of the largest fragment, with an absolute minimum of 10 mm when *d* is smaller than say 3 mm, and
- a maximum allowable speed can be calculated from the retained opening.

This type of sampling is the best choice and is strongly recommended.

Manual sampling of a stopped belt

It is possible to obtain correct samples from a stopped belt by manually sampling it, provided a sample cutting template is used (made of two parallel plaques profiled to the belt curvature and rigidly assembled). It is not a routine sampling procedure because of its usually high cost, but is an excellent interim method, or as a reference to demonstrate suspected biases in other types of samplers.

This type of sampling is strongly recommended when and where needed.

Practical consequences

Risk control

It is observed that once a sample is collected, it does not possess verifiable or observable characteristics of its correctness or absence thereof. As a consequence, no risks shall be taken, and any sampler or sampling procedure suspected not to be of a correct type shall be eliminated/replaced instead, remembering if needed that in sampling, *no information is usually better than biased information.*

Result control

Unfortunately, however important it is, controlling/restoring the quality of sampling at times is an unrewarding task, often leading to large expenditures, with little room for demonstrative accounting of the improvements obtained.

Even though, as already stressed, an even marginal improvement to sampling often translates into a significant improvement of the results of an operation (plant tuning, mine grade control, etc.), tracing this improvement of results back to the improvements to sampling is only really possible in the case where the sampling review was triggered by a measurable, well identified problem, which is not the general case. More often, the resulting improvements in results are instead credited to the sudden, unexpected occurrence of better behaved ore.

Committing to correct sampling therefore demands an enhanced understanding of corresponding issues and consequences, and a lot of faith and dedication.

Economic compromise

It is also important to understand that not all sampling problems have a both completely satisfactory and economically viable solution, and that it is often necessary to introduce an element of compromise before committing large expenditures.

However, only an in-depth understanding of sampling problems and sampling theory will lead to well-informed, justifiable decisions, and the risk of under-estimating the economical impact of good sampling remains critical and misunderstood in most cases.

Numerical control

Proper dimensioning of sampling apparatus and protocols largely resort to formula [1] above. Yet, the formula will only constitute an effective tool if its experimental calibration is based on sound principles and appropriate models, which regrettably is not always the case in the industry, even nowadays.

In the favourable case where it has been properly calibrated, then the formula will provide a reliable estimate of the minimum mass required for a sample extracted from a lot or for an individual increment taken from a flow.

In the case of incremental sampling of a flow, however, another problem must also be addressed: the optimization of the sampling regime. One must not forget that the incremental method was designed to reduce the negative effects of a generally unquantifiable, albeit omnipresent segregation. Fortunately, thanks to the uni-dimensionality of the particular problem, a geostatistical analysis of experimental sampling data using the variogram curve permits a proper quantifying of this particular type of segregation along time, and can be used to determine the best sampling frequency.

Conclusions

Most popular types of sample cutters for plants have been critically reviewed in this paper, and risks and costs of the corresponding bad sampling emphasized. It is concluded that the industry has a lot of progresses to make in that direction, although improvements usually pay for themselves very quickly. It is therefore hoped that plant managers around the world will increasingly assume their duty of verifying the quality of their sampling, instead of classically waiting until bad reconciliations ring the alarm bell late in the game and trigger unfriendly audits imposed by the mine or the corporation management. ◆