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1.0 INTRODUCTION

In 1993, Parrish stated that the most common error found when doing resource/reserve audits is an error in the tonnage factor used to derive the tonnage of the ore in question. Density and/or specific gravity of the ore is directly related to the tonnage of the deposit which in turn is directly related to the amount of metal in a deposit. Recent MTS experience indicates that Parrish's 1993 comments are still valid in that many projects have insufficient data to adequately characterize the density (tonnage factors) of all of the waste and ore types while some projects have excellent databases containing well documented density determinations.

Insufficiency of data takes many forms, i.e., some projects simply have not performed any density determinations; others have not documented procedures or have used procedures that are inappropriate for the material in question. Some workers, although relatively very few, still insist on obtaining density from their favorite little black book (Cat Handbook or Pocket Ref) and forego any determinations.

The problem is, quite simply, that the density multiplied by the volume yields the tonnage of material on hand and a discrepancy in the density of 10% produces a discrepancy in the metal content of 10%. It is incomprehensible why many projects insist on not performing adequate density determinations in light of this relationship. They routinely request assay data to 3 or 4 decimal places (at least one decimal more than is reasonably attainable) and are satisfied with density values based on few actual data, estimated from their favorite black book, or worse yet, a guess at the density based on questionable data from a somewhat similar mine in an adjacent country.

This document provides a summary of the methods used in the mining industry to determine density and/or specific gravity, evaluate the pitfalls of each method, and suggest preferred methods for various materials. It does not contain all the procedures that will be encountered. There are subtle to significant variations on all of the methods discussed here. MTS has restricted discussion to methods that are most commonly, and effectively used in the mining industry, and does not discuss those sometimes-questionable procedures that are used by one project somewhere on the planet. The recommended procedures are supported by ASTM or Australian standard procedures and are thus generally accepted as good procedures.



2.0 DEFINITIONS

A few definitions are required:

Density is the mass of a material per unit volume of the material, most commonly reported in grams/cm³ in the mining industry (outside the United States). For our purposes, density is normally determined on small samples, core or hand-sample-sized blocks, and represents the rock density and does not account for fracture porosity.

Bulk density refers to the density of an in situ rock mass. Bulk density accounts for porosity of the rock as well as fracture porosity. With rare exception, the bulk density will be somewhat less than the density determined using the methods in this document because fracture porosity is rarely accounted for in density determinations, but within the industry most people equate the measured density with bulk density. The error is generally, but not always, quite small. In this document, unless specifically indicated, density is rock density that does not necessarily account for fracture or other porosity. Adjustment factors, where required, are used to convert determined density to bulk density. Bulk density implies dry bulk density; however, it always best to confirm this and precede the term with 'dry' or 'wet'. Only dry bulk density should be used in resource estimation because all assays are done on a dry basis. The same dry basis for the density and assays must be used or the estimate of resource inventory will be incorrect.

Note that iron ore is an exception. Although assays are always on a dry basis, wet density is used to estimate iron ore tonnage so there will be a slight disconnect between grade, tonnage, and contained metal. MTS has not investigated the impact on total metal, but it is likely small and this is a standard in the iron ore industry that is unlikely to change.

Specific gravity (SG) is a **unitless ratio** of the mass of a sample in air versus the mass of a sample suspended in water. More specifically, the specific gravity is a number that expresses the ratio between the weight of a substance in air and the weight of an equal volume of water at 4°C (Hurlbut, 1971). Specific gravity can be determined with a Jolly Balance using any scale of measurement that is handy: inches, meters, etc., because the units cancel during the calculation; thus, the unitless ratio. At 4°C, using pure water, SG is numerically equivalent to density in g/cm³. If the water used to determine SG is at other than 4°C, SG and density are not numerically equivalent, although the discrepancy is not large enough to be a serious consideration (producing a measurement error of <0.004) until the water is at temperatures above 30° C. Equating SG and density or attaching units to SGs are poor practices and in the extreme, damage the credibility of the report and reporter. Table 2-1 summarizes the change in water density with temperature. Water density can be estimated at any temperature from 4° to 99.9° C using:

$$\text{Equation 1: } d \text{ (g/c}^3\text{)} = 0.0 \quad * T^3 - 0.0 \quad * T^2 + 0.0 \quad * T + 0.9$$



This equation provides a very good estimate of water density within the limits prescribed ($r^2 > 0.9999$). These values can then be used to convert SG to density by accounting for water density. Densities determined in dirty, hot water, may have significantly larger discrepancies than indicated because of the increased density of dirty water.

Tonnage Factor is a term used in the United States and locally elsewhere, that expresses density in terms of cubic feet per short ton (cu ft/st) or short tons per cubic foot (st/cu ft). The conversion is:

Equation 2: $1 \text{ g/cm}^3 = 32.0373 \text{ ft}^3/\text{st} = 0.0312 \text{ st/ft}^3$

Ore is material that is reasonably believed to be able to produce metal or other valuable components at a profit.

Waste is material that cannot be reasonably believed to be able to produce metal or other valuable components at a profit.

Porosity is the naturally occurring void space in rocks. This includes such voids as open fractures, cavities remaining after leaching of components (sulfides for example), space between mineral grains in sedimentary rocks, or any other void that is an integral part of the rock.

Fracture porosity is porosity due to fracturing and faulting of the entire rock mass.

Immersion refers the process of immersing a sample in water or other liquid of known density to determine the mass of the sample suspended in the liquid and thus the volume of the sample. At 4° C, the mass of water displaced, in grams, is equivalent to the volume of the sample in cm^3 because water, by definition, has a density of 1 g/cm^3 at 4°C.

Dry density is the density of the material in question after it has been thoroughly dried. For most ore deposits, this is the important density value because grades (assays) are determined on dry samples. These are not true bulk densities because fracture porosity is not typically accounted for.

Wet density is the density of the material in question as it is removed from the ground. Although not important for most base and precious metal deposits, wet density is used almost exclusively in iron ore deposits because iron ore is generally not dried prior to shipping from the plant.

A few abbreviations are needed:

DD	Dry Density
WD	Wet Density
DBD	Dry Bulk Density
WBD	Wet Bulk Density
Ma	Mass of sample as obtained
Md	Mass of dry sample
Mdw	Mass of wax coated dry sample



M _{dws}	Mass of submerged wax coated dry sample
D _{H₂O}	Water density
D _{wax}	Wax density (or other coating)
M _w	Mass of wax

Table 2-1: Density of Water at Various Temperatures (CRC Handbook of Chemistry and Physics 55th ed.)

Temp (°C)	Density Pure Water (g/cm ³)	Absolute Difference	% Difference
0	0.9999	0.0001	0.01
4	1.0000	0.0000	0.00
10	0.9997	0.0003	0.03
15	0.9991	0.0009	0.09
16	0.9990	0.0010	0.10
17	0.9988	0.0012	0.12
18	0.9986	0.0014	0.14
19	0.9984	0.0016	0.16
20	0.9982	0.0018	0.18
21	0.9980	0.0020	0.20
22	0.9978	0.0022	0.22
23	0.9976	0.0024	0.24
24	0.9973	0.0027	0.27
25	0.9971	0.0029	0.29
26	0.9968	0.0032	0.32
27	0.9965	0.0035	0.35
28	0.9963	0.0037	0.37
29	0.9960	0.0040	0.40
30	0.9957	0.0043	0.43
40	0.9922	0.0078	0.78



3.0 SAMPLES

Density determinations are physical measurements of samples of the rock in the mineral deposit. The most common sample type is a short piece of core from exploration holes on a property. Other sample types include blocks of rock collected at the surface, excavated surface (or underground mine) samples, rock chips, and powders.

No matter what the type, samples chosen for density determinations must be representative of the material to be mined and selection of those samples can be difficult. In order to perform the determinations, core must be somewhat competent; in some deposits, the areas of interest are clay-rich or friable which limits the sample selection. Typically, this will lead to a selection bias because only the most competent, and least representative, samples are chosen for the determinations; these typically have a higher density than the more broken pieces, leading to a global overestimate of density for that rock type. In some cases, it is appropriate to adjust density data for this bias. In many cases, that factor can be determined by collecting surface or underground samples of similar material and comparing those data to drill core data. On one project that I am aware of, densities determined on core were adjusted downward by 2 to 9% to account for the selection bias based on mining experience.

Another problem is collecting samples that adequately represent the porosity of the in situ material. This is particularly difficult when large, open fractures are present. Samples to be used for density determinations will most likely not have open fractures and analysis of those samples will result in a bias in the data that is rarely accounted for. The determined density may be biased high by 1 to 10% (possibly more) compared to the actual bulk density of rock, but for the most part, the bias is typically on the order of 1 to 3%. Geological observations are required identify rock units that carry this risk.

Some materials like wet saprolite or friable kimberlite are exceedingly difficult to sample and significant creativity is required. And, the answer is likely to be wrong. It is best to collect lots of data and use averages. The error will be minimized, but bias will not be removed. It may not be possible to effectively remove bias in wet saprolite or friable kimberlite.

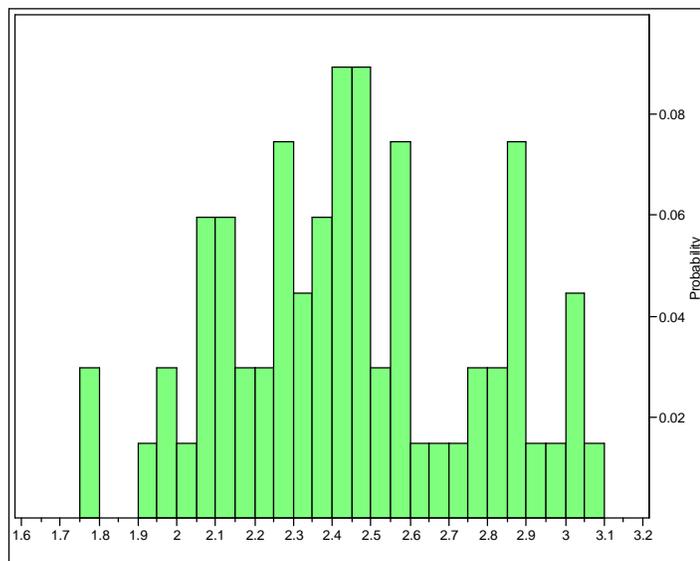
The number of measurements of density required for Mineral Resource estimation is also difficult to determine. In some deposit types, (e.g. potash, trona, etc.) density of the ore will be uniform over very large distances. Waste will be mined only until the ore is reached by shaft or ramp thus large numbers of waste rock densities are not necessary. Ore with uniform density will be mined from the time that it is intersected onward. A single sample may be adequate to estimate the density over much of the deposit. However, if only a single sample is collected, no estimate of the uncertainty of the measurement can be made. For that reason, it is desirable to collect at least three samples of each rock type, so that the uncertainty of the mean can be calculated. For major ore units like potash, the 95% confidence in the mean should be no larger than ± 2.5 percent of the mean value (i.e. the 95% confidence interval is no larger than 5 percent of the mean value). Otherwise, the density is not known to three significant figures as it is usually stated (e.g. 3.01 rather than 3.0 g/cm³). In some cases, ore

density is nearly constant over large distances and density is assumed to be the same for the entire deposit. Potash in Saskatchewan is an example where density of the potash ore is assumed to be 2.08 g/cm³.

On the other end of the spectrum are skarn deposits which can have significant mineralogical and thus density changes over centimeter to meter ranges. Ideally, each assay would have a corresponding density determination. This is rarely necessary because density rarely varies as abruptly as grade does (but, skarns are sometimes an exception).

As a general rule, a minimum of 35 samples of each ore and waste type is needed to adequately characterize the density of each of the waste and ore types. This number of samples will produce a sufficiently narrow confidence interval and will also provide a reliable estimate of the mean. In addition, it may reveal multimodal density distributions in a particular rock type that need to be addressed by refining geologic observations to identify the sub-populations that have different average densities. Figure 3-1 shows data from a single ore type in an iron ore deposit. Two populations are obvious, one with an average density of 2.4-2.5 g/cm³ and a second with an average density of about 2.9 g/cm³ and there may be another population at about 2.05 g/cm³ and another at 3.05 g/cm³.

Figure 3-1: Bimodal (Multimodal?) Density in Soft Ore from an Iron Ore Deposit (units are g/cm³)



Sampling for density must provide good geographic coverage of the area of interest. Otherwise, a significant pocket of low- or high-density material may go undetected, and the local resource estimate will consequently suffer. Those samples must be collected from throughout the deposit.

This minimum is a guide and is only applicable to deposits where density changes little from rock type to rock type or from area to area. In many deposits, density changes are



so commonplace that a systematic sampling program is required. Many projects collect a density sample on either side of each lithological change and at specified distances down holes (5 or 10 m is common). This procedure will generally generate sufficient data to adequately estimate the densities for each ore and waste type (Waste rock type densities must be estimated in order to adequately estimate the tonnage of waste to be moved.). In some deposits, each assay must have an associated density determination in order to adequately model the density. Saprolite deposits typically exhibit strong vertical trends and should be tested a 1 to 5 m intervals in every hole if accurate local estimates of tonnage are required.

Density models should be constructed whenever sufficient data are available. These models will more accurately represent the variation of density across the deposit than will models that assign average density rock (ore and waste) type or an average is used across the deposit. In some deposit types, such as potash, changes in density across the deposit are negligible; hence, no model is necessary. Others, saprolite deposits for example, have strong vertical density gradients and significant data are required to adequately account for the vertical gradient.



4.0 METHODS

This section describes several of the methods for density determination commonly used in the mineral industry today. Other methods exist, heavy liquids, for example, but those are not routinely used for determination of densities of mineral deposits.

4.1 Sample Drying

In most of the following methods, drying of samples is required. Standards Association of Australia (1977a) and Standards Australia (2005a) discuss standard procedures for drying samples. In all cases, a dry sample is a sample that has been dried until dry. That is, it has been dried in a temperature-controlled oven and the mass measured on an hourly basis until three subsequent mass determinations are equal. This normally takes 8 to 24 hours at $105\pm 5^\circ\text{C}$ (normal drying temperature) and may take days at 50°C .

Clay-rich samples may experience mineralogical changes above 45°C and should thus be dried at 45°C or less to eliminate volume changes due to mineralogical changes when hydration water is driven from the sample at higher temperatures. In most samples, the change in density due to mineralogical changes is likely negligible, but the use of higher temperatures for quicker drying of clay-rich must be tested and the volume change quantified before higher temperatures are routinely used.

4.2 Immersion Methods

All immersion methods involve weighing a sample in air and then weighing the sample while it is immersed in a liquid of known density, typically water, but alcohol or other liquid are acceptable if the density is known or can be determined. The simplest procedure is the venerable Jolly Balance. The Jolly Balance relies on a torsion spring with a pointer as the measuring device and a meter stick for the scale. A sample is placed in the device, displacement is recorded in millimeters and the sample is then suspended in water and this displacement is recorded. The ratio of the displacements is the specific gravity and the units cancel. Today, density and specific gravity determinations typically rely on electronic digital balances that weigh in grams. An example of a typical immersion setup is shown in Figure 4-1. Note that the balance has a hook under the load cell that allows it to weigh suspended masses. Not all balances are set up that way and there is a work around discussed below.

In its simplest form, density determination requires determination of the mass of a dry sample in air (on top of the balance) and suspended in water. Suspending the sample requires a basket or similar attachment device that is suspended from the balance into a container of water (Figure 4-1). The balance is tared with the basket suspended in water and the sample is then placed in the basket.

If a balance with a center hook is not available, a frame like the one in the left photograph in Figure 4-2. The sample is weighed in air on top of the balance and the water container and basket apparatus are placed on the balance and the balance tared. The sample is



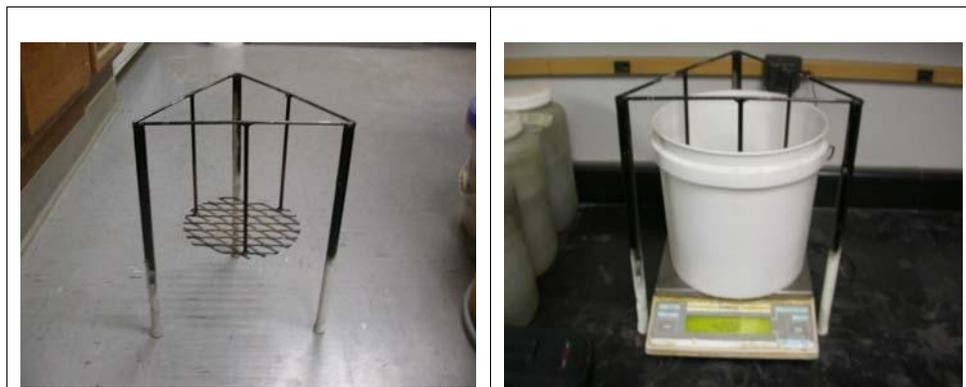
then placed in the basket. The volume displaced will be equivalent to the mass reported on the balance.

Densities can be determined more or less directly if one remembers that the difference between the dry weight of the sample and the immersed weight of the sample is equivalent to the volume of water displaced at 4° C. The correction for the water temperature is generally simple, but at temperatures between 15 and 25° C, the correction is much less than 1% and can be ignored assuming that clean distilled water is used. Indeed, current ASTM procedures do not call for water temperature corrections, but best practice is to apply a correction factor for all determinations. At water temperatures above 25° C, the correction should be applied. Throughout this discussion, the corrections for water temperature are included where appropriate.

Figure 4-1: Setup for Determination of Density by Immersion Method. (The balance on the table is connected to a basket in the bucket by a wire through the base of the balance.)



Figure 4-2: Apparatus for Balance Without a Center Hook (McLellan Labs)





4.2.1 Direct Immersion Methods

Simple Direct Immersion

The simplest method is to simply weigh the sample in air and then weigh it while it is immersed in water. The density is then (Lipton, 2001; Abzalov, 2013):

$$\text{Equation 3: } D = \frac{m_{ia}}{m_{ia} - m_{iw}}$$

Assuming that the units used are grams, results will be in g/cm³ because:

$$\text{Equation 4: } m_{ia} - m_{iw} = r \cdot v \cdot c^3 \cdot w \cdot a^4 \cdot C$$

This procedure is appropriate only for dense, nonporous materials. Any porosity will negate the value of this type of determination by over estimating the density. The overestimation is proportional to the porosity of the rock.

ASTM (1996) method C97-96 and Standards Australia (2005b) method AS 4133.2.1.2-1993 are similar methods that require saturation of the sample after it has been dried and weighed. This is a recommended procedure for significantly nonporous materials.

Surface Saturated Immersion

This method is useful for some materials and as a check on a coated method. The sample is dried to dry and weighed. The sample is then immersed in water for five to ten minutes and then transferred to the density apparatus and weighed in water. Theory has it that for samples with little porosity and low permeability will absorb water only for a few mm and the interior pores will not be affected.

Dry density is calculated by:

$$\text{Equation 5: } D = \frac{D_M}{D_M - (S_c \cdot I_n \cdot \frac{D_M}{M - (S_c \cdot M - D_M)})}$$

The limited data available to MTS suggest that this method is not totally reliable, or possibly, the operators were not totally reliable. In either case, some of the data have obvious errors which limit confidence in any conclusions based on the data.

4.2.2 Coated Immersion Methods

Porous materials necessitate special procedures. McKinstry (1948) recommends coated immersion procedures (wax or shellac) for specific gravity determinations. MTS concurs with that recommendation. These procedures require that the sample be coated with wax, shellac, spray Krylon®, plastic wrap, etc. in order to perform



adequately. By using a balance that determines mass in grams, densities rather than specific gravities can be determined.

The wax-coat immersion procedure for density determination is as follows (see ASTM, 2016; Method C914 – 09 (Reapproved 2015)):

-) Brush samples clean with an air jet,
-) Weigh (as-received mass),
-) Oven dry overnight at a maximum temperature of 100°C or until dry,
-) Allow the sample to cool to room temperature in a desiccator,
-) Weigh (for dry mass),
-) Dip in wax, weigh (for waxed mass),
-) Weigh while suspended in water (for buoyant mass),
-) Measure water temperature (for density corrections).

The following formula can be used to calculate the density of the water to correct for variations of water density resulting from water temperature in the T = 16-22° C range only:

Equation 6: $D_H = 1.0 - 0.0 * T$

or

Equation 7: $D_H = -0.0 * T^2 - 0.0 * T + 1.0$

for all temperatures. This is an approximation seen in some literature that slightly underestimates water density in the 4-20° range but is acceptable in the 20-30° range. Better is Equation 1 above which is a least squares regression of the data in Table 2-1.

Use Equation 8 to calculate the density of the wax to correct for wax coating. The procedure is the same as above for unknown samples, but relies on a standard sample of known density, typically an aluminum block or cylinder, to establish the density of the wax. The density of the block must be known. The block is coated and the density of wax determined. The density of the wax is (ASTM (2015b; Method D1188 – 07 (Reapproved 2015)):

Equation 8: $D_w = \frac{(D_c M - D_u M) - \left(\frac{D_u M}{D_c} \right)}{D_c M - D_u M}$

We can use the following formula to calculate the dry density (ASTM, 2015):

Equation 9: $D = \frac{M_D}{(M_W - M_S) - \left(\frac{M_W - M_D}{D_w} \right)}$

Which ignores the density of water which is acceptable to ASTM as it is “... true to within 3 parts in 1000 for water at room temperature.” Although ASTM accepts density with no



water temperature correction, best practice is to adjust for water temperature, but unfortunately, most projects do not control or record water temperature.

If wet density is required, M_{Arock} can be substituted for M_{Drock} in Equation 9.

To account for water density Abzalov (2013) offers Equation 10:

$$\text{Equation 10: } D = \frac{M_D}{(M_W - M_{Sr}) / D_H - (M_S - M_D) / D_w}$$

ALS uses Equation 11 to account for water density:

$$\text{Equation 11: } D = \left(\frac{D \cdot M}{m - Ir} \right) * W \quad d$$

Equation 12 is useful to calculate the moisture content of the rock before processing:

$$\text{Equation 12: Moisture \%} = (M_{Arock} - M_{Drock}) / M_{Drock} * 100$$

where:

- T = Temperature of water
- D_{H2O} = Density of water
- D_{wax} = Density of wax
- M_{Arock} = Mass of sample as-received
- M_{Drock} = Mass of dried sample
- M_{Wrock} = Mass of waxed sample
- M_{Srock} = Submerged (buoyant) mass of waxed sample
- WD = Density of sample as-received (wet density)
- DD = Density of dried sample

This procedure works well for samples with millimetre-sized pores. Shellac or lacquer can also be used for microporous materials. The volume of shellac or lacquer will be too small to significantly affect the density determination so no corrections are generally required.

For samples with pores as large as 1 to 2 cm, samples can be sealed with plastic wrap or sealing tape rather than wax. This procedure works well if the amount of plastic wrap or tape is kept to a bare minimum. No corrections are normally needed if the amount of sealing material is minimal. MTS has tested this on several occasions and found the density difference to be very small. An example is discussed below, but, best practice is to adjust for sealing material.

On a recent project, MTS reviewed data generated using cling wrap rather than wax as a sealant. The operator did not account for the cling wrap when calculating density. Because the data were all available, MTS calculated density accounting for the cling wrap and not accounting for it. Figure 4-3 summarizes the data which shows that the raw (no adjustment for cling wrap) is biased about 0.02 g/cm³ higher than the adjusted

data. There is a small proportional effect in that very large samples (sample mass >700 x cling wrap mass) exhibit a bias of 0.01 g/cm^3 and very small samples (sample mass <math><50 \text{ x cling wrap mass}</math>) exhibit a bias of

For samples with large vugs, volumetric methods are generally required because it is difficult to adequately seal the samples to account for the vugs.

Figure 4-3: Raw versus Adjusted Density

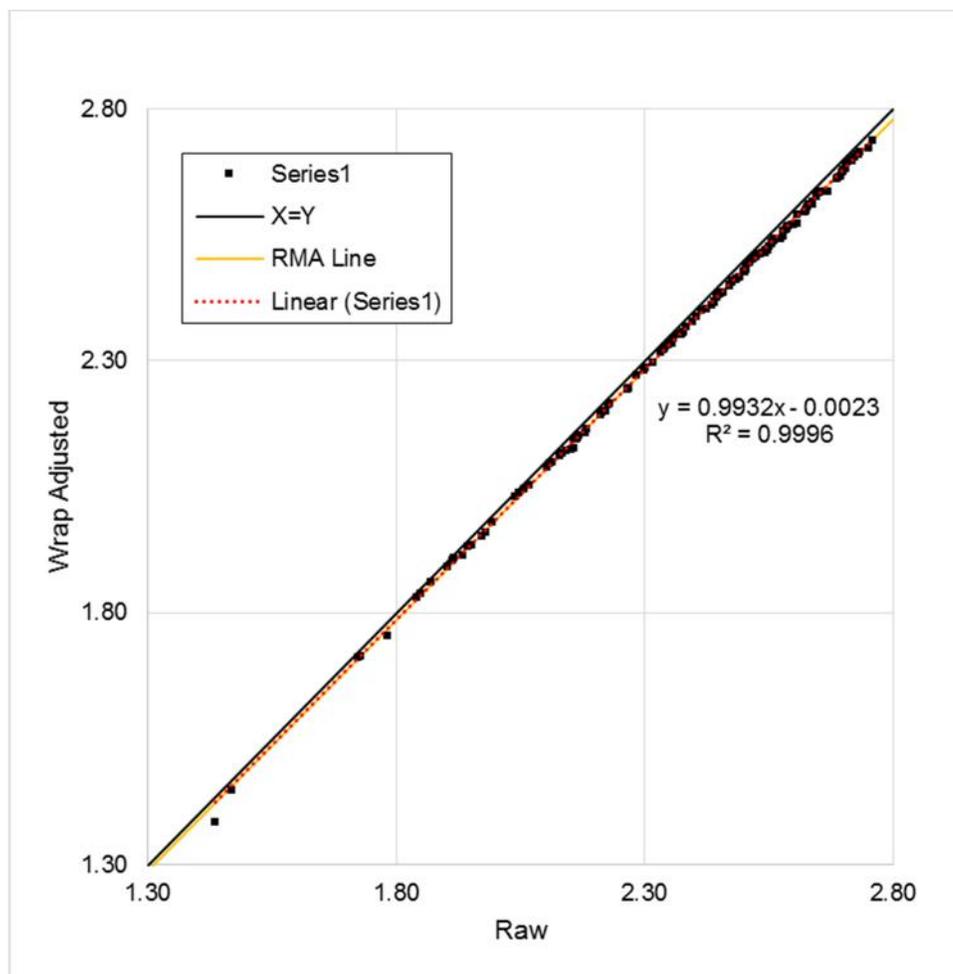
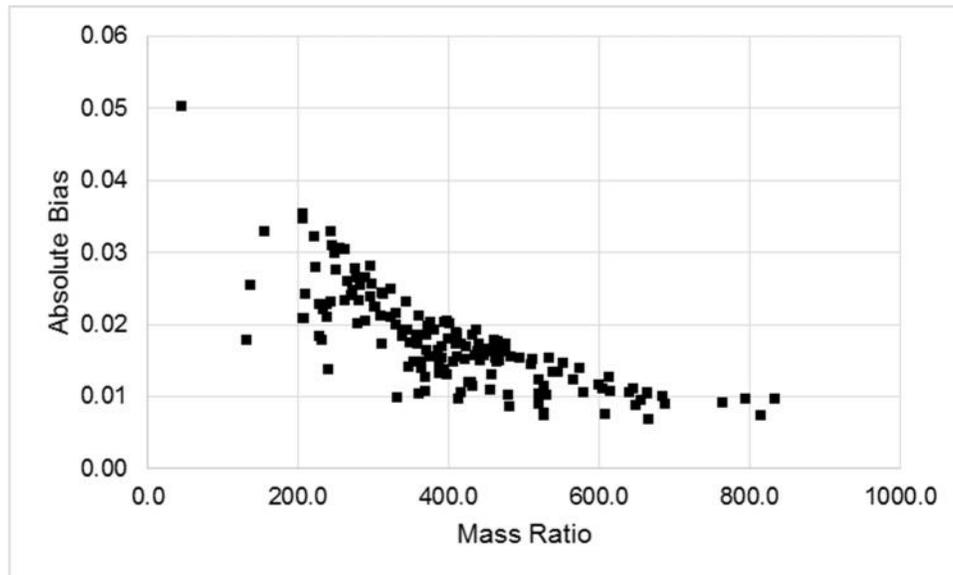


Figure 4-4: Absolute Bias versus Mass Ratio



4.2.3 Variations

For various reasons, variations on the immersion methods are sometimes required. An example is pyroclastic kimberlite, which typically decrepitates as it dries. These materials must be weighed as received, sealed in wax, and weighed while immersed in water as soon as possible after removing them from the core barrel. The samples are then slowly dried at low temperature and weighed. The moisture content is calculated by the difference between as-received weight and the dry weight accounting for the mass of wax. Density is calculated by Equation 9.

Immersing soluble materials such as potash can be somewhat problematical, but if done quickly, the amount of material that dissolves is minimal. The water must be replaced between each sample; however, to avoid changing the density of the water with dissolved salt. It is sometimes useful to use saturated brine as an immersion medium. Density of the immersion medium can be determined by filling a graduated container with a known volume and weighing the mass of the liquid.

Another variation is the use of crushed material, drill cuttings or analytical reject material for example, for the sample. The material must be wet screened prior to use to remove dust which can trap air in the sample and provide buoyancy. The sample is dried, weighed, and then immersed. This is essentially a pycnometer procedure that will possibly work adequately on nonporous materials, but may significantly overestimate the density of porous materials because pores are destroyed during crushing. It is not a recommended procedure to support Mineral Resource estimation.



4.3 Volumetric Methods

Several volumetric methods are commonly used and are generally directed at specific problems. Several of the methods are discussed below.

4.3.1 Direct Measurement

Direct measurement of core or cut block dimensions is a common procedure used for very porous material, but can be used to check the results of immersion procedures. Core samples for this type of procedure are cut as nearly perpendicular to the core axis as possible and precision calipers are used to measure the length and diameter of the core (dial calipers are best). The length of the core must be measured at several locations around the perimeter of the core and averaged. Similarly, the diameter must be measured at several locations and averaged. The volume of core is then calculated by the formula:

$$\text{Equation 13: } V = p * r_i^2 * h$$

The sample is dried and weighed in air. The density is then:

$$\text{Equation 14: } D = \frac{sg \quad m}{v}$$

This procedure works well on all types of uniform core and is especially useful for very porous materials that are not amenable to immersion procedures. Standards Australia (2005b) method As 4133.2.1.1 – 1993 is a standard procedure for caliper measurement of samples.

4.3.2 Excavations

This type of determination takes several forms and is useful whenever materials of interest are exposed at the surface. McKinstry (1948) and Parrish (1993) both recommend weighing the ore from an excavation of known dimensions. These determinations are particularly useful for soft materials such as saprolite that are difficult to core.

Graduated Sand Procedures

Standards Association of Australia (1997b) and ASTM (2016) describe variations of the graduated sand procedure. This procedure involves excavating a small hole and determining the volume of the hole by filling it with graduated sand. The general procedure is:

-) Carefully clean and level the area to be sampled (Figure 4-5a),
-) A metal frame is carefully leveled and held in place with nails (Figure 4-5b).
-) A 15 cm deep hole is excavated through the opening in the metal frame (Figure 3-1Figure 4-5c, d).



-) Care must be taken to collect and bag all of the material from the hole (Figure 4-5d).
-) The completed hole is smoothed and all material from the hole is bagged (Figure 4-5d).
-) The graduated sand apparatus is placed in the recess in the frame and the hole is filled with graduated sand. When the excavation is filled, the valve on the apparatus is closed (Figure 4-5f).
-) The material collected from the hole is taken to the laboratory where it is weighed in its as-collected state, dried at $105 \pm 5^\circ \text{C}$ until dry, and reweighed. The volume of sand is calculated by weighing the sand container and subtracting the volume of the inverted funnel spout on the container. The unit mass of sand removed from the container is proportional (calibrated) to the unit volume of sand. Wet density is then:

Equation 15:
$$W = \frac{A R M}{V_t}$$

Dry density is:

Equation 16:
$$D = \frac{D M}{V_t}$$

Figure 4-5 is from a project in Brazil and the material is saprolite. The procedure is time consuming and labor intensive, but produces, in our opinion, the best density data from small excavations. Procedures using water, described next, are functional, but for some reason, are error prone. The graduated sand method has potential errors, but is less prone to errors than water-based methods.

A variation of the graduated sand method is a graduated glass bead method described by Balco and Stone (2003) and Sheldrick (1984) is applicable to laboratory measurements:

-) A metal container is partially filled with very small ($260 \mu\text{m}$) glass beads,
-) the sample is placed in the container on the glass beads,
-) the container is then filled completely with glass beads,
-) the mass of the container with beads and sample is determined,
-) the sample is removed and the mass of beads is determined.

The mass of beads required to fill the container with the sample is subtracted from the mass of beads required to fill the container without a sample. This is equivalent to the volume of the sample. The mass of beads required to fill the volume is divided by the volume of the container (mass of water, in grams, required to fill the container) which provides the “graduation” required to convert the mass of beads to volume.

Both references use this method for irregularly shaped rock and soil samples, but it is applicable for most rock materials. MTS views this as a check method for volume



determination. It should be quick and reasonably painless but care must be taken to get glass beads into and out of large pores in the rock. I have not done this method, but both references indicate that it should be done multiple times for each sample (three minimum) and the data averaged.

Figure 4-5: Photographs of the Procedures for determining In Situ Density of Rock Samples using the Graduated Sand Procedure (see text for explanation)





Drive Cylinder Method

Another procedure that is useful in soil and saprolite is the slide hammer (drive cylinder) procedure. Samples are collected from the ends of the tube to produce a exposures in undisturbed soil or saprolite using ASTM (2010; Method D 2937–10) which calls for driving a thin-walled tube of known volume into undisturbed soil with a slide hammer (Figure 4-6a). Once the tube is filled, it is excavated (Figure 4-6b, c, d). Material captured in the tube is carefully shaved from the end of the tube level with consistent volume. The sample is removed from the tube, weighed, dried, and reweighed.

Moisture and dry density are then calculated using Equation 12 and **Equation 16** respectively. This method is not widely used in the mining industry but is used in civil engineering and construction. MTS considers it to be adequate to support Mineral Resource estimation and short-term mine planning and recommend that it be considered for all soft saprolite situations. It is prone to errors if not very carefully done so it is important to be certain that the method be done exactly to the specifications each time it is done.

Figure 4-6: Photographs of the Slide Hammer (Drive Cylinder) Method





Water Based Methods

Many methods using water to determine the volume of an excavation have been devised and used. United States Department of the Interior (1989) method USBR 7221-89 and ASTM D5030/D5030M – 13a discuss a useful procedure that can be modified for specific projects. All of these procedures involve carefully excavating a pit, lining it with a waterproof liner, and filling it with a measured amount of water. Excavations range from small 15 x 15 x 15 cm pits to pits meters in breadth and depth. In all cases, all of the material excavated from the pit must be carefully collected, weighed as-received, dried, and weighed dry. Pits are generally lined with a plastic liner and then filled with water. For some reason, water volumes are difficult to measure and/or record, thus, failures are common with this type of procedure. Figure 4-7 shows an apparatus that works well with water-filled pits for density determinations. The procedure is as follows:

-) Frame shown in Figure 4-7 is constructed of wood or metal. The dimensions are not critical, but 50 x 50 cm is a good compromise.
-) The area where the sample is to be collected is carefully cleaned and leveled.
-) The frame is placed on the site and very carefully leveled. This is a critical point.
-) A plastic liner is placed in the frame and filled to the top of the frame with water (V_1) which is carefully measured. This volume will be used to correct for surface imperfections.
-) A hole is excavated within the limits of the frame. The depth of the hole should be at least half the frame dimension, so for this example, the hole should be at least 25 cm deep. Deeper is better as the larger volume will minimize measurement errors.
-) All of the material from the hole is carefully bagged for drying and weighing.
-) The hole and frame are lined with plastic and filled to the top of the frame with water (V_2) which is carefully measured. The volume of material removed from the hole (V) is then:

Equation 17: $V = V_2 - V_1$

The sample is taken to the laboratory where it is weighed, dried to dry, and reweighed. Wet density is then calculated using **Equation 15**.

Dry density is calculated using **Equation 16**

This procedure was used successfully on a project in Indonesia. The process is time consuming and labor intensive, but if records are carefully kept and water is carefully measured, will produce very reliable results.

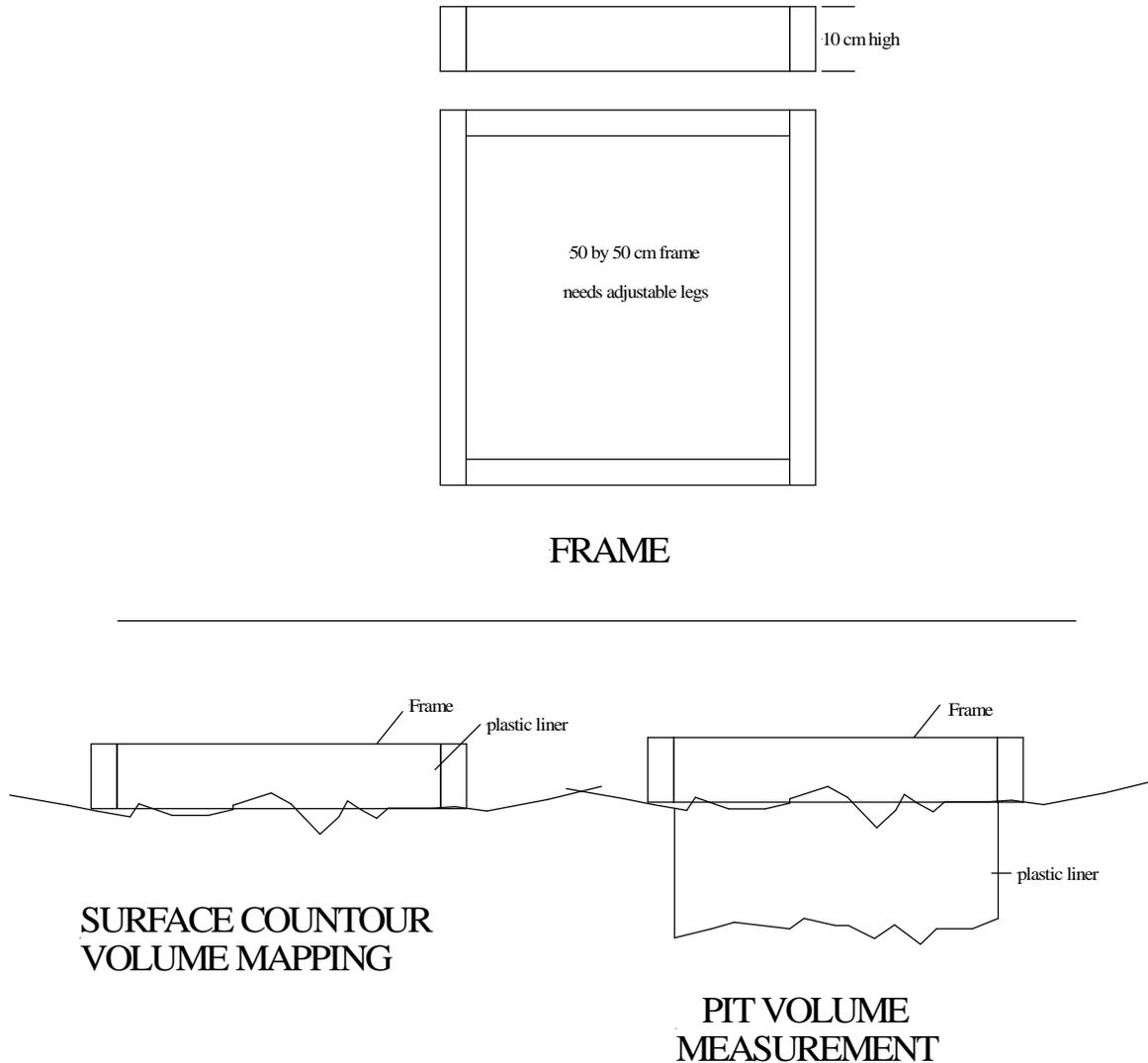


Other Excavation Procedures

One other commonly used procedure is to excavate a large hole, 25 x 25 x 10 m (or larger) with mining equipment and carefully survey the excavation. The sample is trucked to a scale where it is weighed and several small samples are taken to determine the moisture content. The moisture content is then used to correct for dry density. This procedure can produce very reliable results, but it can also produce very unreliable results if volume is not accurate or the truck scale (weigh bridge) has not been calibrated in ten years. This is a time consuming and expensive method to determine density, but it has been used successfully in numerous cases. It has also failed in numerous cases. Failures are typically due either to poor surveying or poor mass determination, or both.

This procedure will produce a bulk density that includes fracture and vug porosity. This type of procedure can be used to estimate correction factors for selection bias in friable or fractured rocks resulting from choosing only the hard, competent bits in core.

Figure 4-7: Apparatus and Steps for Water-Filled Pit Density Determinations



4.4 Displacement Techniques

Displacement techniques generally rely on measuring the amount of liquid displaced by a sample to determine the volume of the sample. In theory, these methods should work well, but in practice, they tend not to work very well unless exceptional care is taken when doing the procedures. The procedures involve immersing a sample in liquid in a graduated container. The volume of a sample is then the difference between the original liquid volume and the final liquid plus sample volume. The sample is then weighed, dried to dry and re-weighed. Density is calculated by **Equation 16**.



Problems arise when reading the meniscus of the liquid. The meniscus must be read properly or errors will occur.

Another method is to fill a container to the top with water, immerse the sample and collect the overflow in a graduated container. This method works as well as any, but problems arise with reading the meniscus of the liquid in the graduated container. The water that is displaced can be weighed which is more accurate than direct reading methods but for some unknown reason, prone to data recordation problems.

Another method of density analysis using displacement to measure the volume of half or whole core samples is as follows:

Weigh the following in order:

-) 1 liter graduated cylinder with 1 liter of water (up to mark) = A
-) 1 liter graduated cylinder approximately one-half full of water = B
-) 1 liter graduated cylinder approximately one-half full of water plus the sample = C
-) 1 liter graduated cylinder plus the sample and water added to make up 1 liter = D

The density is then calculated as follows:

-) The mass of the sample in grams:

$$M = C - B$$

-) Volume of sample in ml (cm³):

$$V = M + A - D$$

-) Density of sample in g/cm³:

$$D = M / V$$

This procedure has been used successfully and has the added advantage in that when the sample is added to the half-full graduated cylinder, the volume can be determined by difference as a check on the volume determined by weighing the sample plus water which is normally more accurate than direct reading of the volume.



4.5 Mineralogical Techniques

Mineralogical techniques include two broad categories; density based on modal mineralogy and density based on geochemical analyses. These techniques are useful, for the most part, only in massive sulfide or vein deposits where the mode can be estimated or the geochemistry can be used to estimate mineralogy, and, most importantly, porosity is negligible.

4.5.1 Modal Mineralogy

The mode of a sample can be estimated from hand samples, thin sections, or mine faces. If the mineralogy is simple, the mode can be used, in conjunction with mineral density data, to estimate the density of the material in question. This procedure is not very reliable, but can be used as a check on other procedures. In cases where the mode is estimated from masses (e.g. normative mineralogy from assays) care must be taken to translate these into mineral volumes in order to apply the proper weighting to each mineral when calculating the density. The modal approach is most commonly used when there is a very large contrast between ore and waste rock. A modal fit will typically overestimate density in cases where a rock's porosity is not zero.

4.5.2 Geochemical Methods

Numerous mines use geochemical assay results to estimate the density of every assayed sample. The procedure involves collection of several hundred samples that have both density determinations and geochemical analyses. The density is then correlated with the geochemistry, and an equation is empirically derived using some or all of the geochemical parameters to estimate the density.

The simplest method employs multiple regressions of the geochemical data to the density data. The following equation is an example from a massive sulfide deposit in Canada:

$$SG = [162,540 + 301(\text{wt}\%S)] / [60,200 + 2.51(\text{wt}\%Zn) + 0.318*(\text{wt}\%Zn)(\text{wt}\%S) + 6.46(\text{wt}\%Cu) + 0.419(\text{wt}\%Cu)(\text{wt}\%S) - 349(\text{wt}\%Pb) + 0.195(\text{wt}\%Pb)(\text{wt}\%S) - 622(\text{wt}\%S) + 0.654(S)^2]$$

This equation relates sulphur (S), zinc (Zn), copper (Cu), and lead (Pb) assays to the density. There is no standard procedure; each deposit is unique but the general procedure is to determine the density of a sample (or SG) and then perform the geochemical analysis. Once 50 or so determinations are completed, the multivariate equation is fit to the data. The equations can be complex and they must be carefully checked before implementation. The implementation must also be checked. In some cases, the equations are based upon samples from only the upper parts of a deposit. As deeper parts of a deposit are explored and developed, the accuracy of the equations must be verified. Density sometimes changes with depth and the equation may change if mineral ratios change dramatically because of mineral zoning or other reasons. In all



cases, equations of this type must be continuously checked by comparing the equation to results from new sampling.

In the Sudbury Basin, specific gravity is calculated using the following (Vale Inco "Alcock") formula:

$$\text{SGCALC} = 100 / (100 / 2.88 + 0.0166 * \text{Cu} - 0.1077 * \text{Ni} - 0.328 * \text{S})$$

MTS had the opportunity to check this formula against new SG data on multiple occasions and found that it works well at any depth. There are local failures, but those failures are not typically significant.

4.6 Pycnometer and Related Procedures

4.6.1 Liquid Pycnometers

The pycnometer is a device used for measuring fluid density, also known as a specific gravity bottle. It uses working fluid such as water, acetone, or mercury (or even a gas) to find a volume. The name comes from the Greek *puknos*, a word meaning "density." Operation of a pycnometer is described in ISO 1183-1:2004.

A typical pycnometer consists of a flask with a close-fitting ground glass stopper with a fine hole through it, allowing accurate measurement of volume. The flask is weighed empty, weighed after filling with water, and then weighed after filling with a liquid whose density is desired. The density of the liquid can easily be calculated. A sample in the form of a powder can be combined with water or a liquid of known density and put into the pycnometer. The weight of the powder and the weight of the displaced liquid can be determined, and from them the density of the powder.

Pycnometers (ASTM, 1993) are not widely used in the mineral industry because they provide the density of the crushed or pulverized material, not the overall density including porosity. Any porosity is destroyed when the samples are crushed or pulverized. If the rock porosity is zero, pycnometers provide acceptable density data, but porosity is rarely zero.

Pycnometers can also be used to determine the density of liquids. An important example is when brines are used as the immersion medium for density determinations; the density of the brine must be known. To determine the density of liquids in a pycnometer, the following procedure, from Yoder and Leber (2003), is used:

The pycnometer that will be used in the density determination must first be calibrated:

-) Examine the pycnometer to be used. Unless the glassware is visibly dirty, do not clean it.
-) Place the pycnometer in a drying oven for fifteen to twenty minutes to insure that all residual moisture has been removed from the glass. Let cool before weighing.



-) Weigh the empty dry pycnometer on an analytical balance and record the mass. As you manipulate the pycnometer, be sure not to touch the glass with your hands as residue and oils from your hands will impact the accuracy of the measurement of the mass.
-) Fill the pycnometer with water of known temperature. Take the mass of the filled pycnometer. The difference between the mass of the empty pycnometer and the pycnometer when it is full yields the mass of the liquid that is within the pycnometer. The literature value for the density of water at the temperature observed can be used to determine the volume of the pycnometer using the equation:

$$V = M_{H_2O} / D_{H_2O}$$

Once the exact volume of the pycnometer being used is known, the density of the unknown fluid can now be determined.

-) After emptying the pycnometer, place it in the drying oven again for at least an hour. When all the moisture has been removed, allow the glassware to cool in a desiccator.
-) Weigh the dried, cooled pycnometer on an analytical balance.
-) Fill the pycnometer with the unknown fluid. Weigh the pycnometer containing the fluid and again take the difference between this mass and the mass of the empty pycnometer.
-) Knowing the mass of the unknown fluid and the volume of the pycnometer, the density of the unknown fluid can be calculated using $D = M/V$.

4.6.2 Gas Pycnometer

Gas pycnometers are commonly employed to determine density of powdered geological samples. They are useful only for nonporous samples and will overestimate the density of a sample by the amount of porosity in a sample. They therefore have no use for samples that have significant porosity which severely limits their overall usefulness for geological samples. In general, MTS is of the opinion that they should not be used to determine density used to support Mineral Resource estimates.

The following discussion of the function of a gas pycnometer is from Wikipedia (2009). A gas pycnometer is a laboratory device used for measuring the density or more accurately the volume of solids, be they regularly shaped, porous or non-porous, monolithic, powdered, granular, or in some way comminuted, employing some method of gas displacement and the volume:pressure relationship known as Boyle's Law. The simplest type of gas pycnometer (due to its relative lack of moving parts) essentially consists of two chambers, one (with a removable gas-tight lid) to hold the sample and a second chamber of fixed internal volume - referred to as the reference volume or added volume. The device additionally comprises a valve to admit a gas under pressure to one



of the chambers, a pressure measuring device - usually a transducer - connected to the first chamber, a valved pathway connecting the two chambers, and a valved vent from the second of the chambers. In practice the sample may occupy either chamber; that is gas pycnometers can be constructed such that the sample chamber is pressurized first, or such that it is the reference chamber that starts at the higher pressure. The working equation of a gas pycnometer where the sample chamber is pressurized first is as follows:

$$\text{Equation 18: } V_s = V_c + \frac{V_r}{1 - \frac{P_1}{P_2}}$$

where V_s is the sample volume, V_c is the volume of the empty sample chamber (known from a prior calibration step), V_r is the volume of the reference volume (again known from a prior calibration step), P_1 is the first pressure (i.e. in the sample chamber only) and P_2 is the second (lower) pressure after expansion of the gas into the combined volumes of sample chamber and reference chamber.

Pycnometers (of any type) are recognized as density measuring devices; however, they are in fact, devices for measuring volume only. Density is merely calculated as the ratio of mass to volume; mass being invariably measured on a discrete device, usually a balance. The volume measured in a gas pycnometer is that amount of three-dimensional space inaccessible to the gas used, i.e. that volume within the sample chamber from which the gas is excluded. Therefore the volume measured considering the finest scale of surface roughness will depend on the atomic or molecular size of the gas. Helium is most often prescribed as the measurement gas, not only is it of small size, it is also inert and the most ideal gas.

4.7 Miscellaneous Methods

Numerous other procedures have been used with variable success.

One method that has been used extensively is weighing core boxes. **This method is only applicable when core recovery is 100%** and when the core diameter is very uniform. Each box of core must be weighed and intervals of similar lithologies, alteration, etc. can then be added. Volume is calculated for the length of the interval and average diameter of the core. Density is then the mass divided by the volume. This method is not recommended, but it has been used successfully on a limited number of projects. It has also failed on a number of projects. It can be used as a procedure to check, in general, the results of more robust procedures.

With the advent of downhole probes that can be used in small diameter holes, it is possible to use downhole tools to estimate the *in situ* density in many mineral exploration projects. These procedures are not widely used in the mineral industry and where they have been used, in MTS' experience, the data are not as reliable as data generated by more traditional methods. Downhole densitometers must be recalibrated very frequently in order to assure reproducible results. Even then, accuracy can be compromised by



changes in the drill hole surface (rugosity) and shape. In situ measurements must also be corrected for moisture contents in order to obtain dry bulk density values for use in estimating the mineral resource. This is not to say that high-quality data cannot be generated. A well calibrated downhole tool is capable of producing acceptable quality density data in a uniform hole.

The CoreLok™ method has been successfully used by at least one mining operation. This method involves placing a sample in a plastic, puncture resistant bag, which is placed inside another plastic bag. The sample is then placed in the chamber of the CoreLok™ apparatus. The apparatus will then be evacuated to 29.7 in. Hg. The sample is then immersed in water and cut open. This allows water to enter the bag and fill all void spaces in the sample, saturating it. Once the water has completely filled the bag, the sample and bag are weighed under water. Knowledge of the weight of the bag, sample weight, and the combined weight of the bag and sample under water allows for calculation of the maximum specific gravity.



5.0 QUALITY ASSURANCE-QUALITY CONTROL

As with any type of analytical method, density determinations must include an appropriate quality assurance-quality control program. When possible, a minimum of 5%, preferably 10%, of the samples should be sent to a second laboratory for check density determinations using a coated immersion procedure. The check laboratory should be chosen with the same care as for any check analytical facility. Comparisons using different procedures, i.e. performing the primary determination using a coated immersion procedure and checking 5% of the samples by measuring the length and diameter of the core, are very useful checks and will normally identify problems.

Some operations employ round bar stock of known density, such as aluminum, ceramic, and steel rods, to check the calibration of equipment. These are highly recommended.

Examining drill recovery and RQD data may reveal which rock types are most likely to be prone to systematic bias caused by biased sample selection. These can sometimes be followed up by using a method, such as a large pit or normative mineralogy, to provide a check on density. If the mean density of pieces selected for density is higher than the mean by these other methods, there is a strong indication of a systematic error (bias), because the pit and modal methods should only match the density measurements if the rock porosity is zero.

Biased density data are just as catastrophic to a resource estimate as biased assay data. Extreme care must be taken to prevent or adjust biased data.



6.0 SPECIFIC RECOMMENDATIONS

6.1 Density Determinations on Core

The following is a protocol for the determination of density for samples from most deposit types. It is based largely on my experience.

6.1.1 Sample Selection

Samples will be selected by individual core loggers while the core is being logged. Because the grade of material present in an interval is not known when the core is logged, samples will be collected based on the core loggers identification of lithological boundaries. Sampling should begin near the collar of the hole and continue down the hole on 5 to 10 m intervals, respecting lithological boundaries. Shorter intervals are appropriate where complex ore-waste intervals or variable ore types are present. The length of the sample (along the centerline of the core) must be recorded along with the rock type involved. There is some benefit to follow a set of rules for selecting core pieces for density. Measurements, i.e., the samples are collected every 5 m, respecting lithological boundaries. The benefit is that every time a sample location is moved, i.e., not on 5 m intervals, a reason can be logged, and this provides a gauge on the possible selection bias for a particular rock type. Numerous shifts in sample locations are a red flag for selection bias for a particular rock type.

Samples should be whole core between 15 and 20 cm in length with shorter samples selected only when longer samples are not available. Half-core is acceptable, but the smaller the sample, the larger the relative error. Samples should be labeled and placed in a plastic bag by the core loggers. A tag or block must be placed in the core box to indicate where the sample was collected. That block should have the From-To interval, reason for sampling and sampler.

6.1.2 Sample Preparation

Samples should be carefully cleaned to remove any loose material attached to the core. This can be accomplished, for most samples, by placing the sample under running water and gently brushing the sample. The sample should then be weighed and the “wet” mass recorded. The sample is then dried in an oven at temperatures no higher than $105^{\circ} \pm 5^{\circ} \text{C}$. Higher temperatures can induce changes in the clay mineralogy and thus in the density of the rock in question. The samples should be dried for at least 12 hours or until dry to ensure that all water has been removed from pores in the sample. The most reliable drying method is to dry to constant weight. In this approach, the sample (usually while in the drying tray, which has a known weight) is weighed, returned to the drying oven, and after some time, weighed again. The process is repeated until there is no downward trend in the sample weight. Standards Association of Australia (1977a) and Standards Australia (2005a) discuss standard procedures for drying samples.



Note that some clay minerals lose hydration waters at temperatures below 50° C with some significant losses above 75° C. Loss of hydration water may involve volume changes so, clay-rich units should be carefully tested to determine whether, or not, drying at this temperature causes volume changes. If volume changes are apparent, the temperature should be reduced to 50° C and the time increased. The sample must be dried to dry no matter what temperature is used.

6.1.3 Analytical Procedure

Analysis of the sample begins by weighing and recording the weight of the dry sample in air. The sample is then dipped in a hot, molten wax of known density (Pure beeswax has a density of about 0.96; paraffin has a density of 0.4 to 0.9 depending on the source and specific composition.). Wax is highly flammable, no open flames or sparks should be allowed within five meters of the container and the area should be ventilated and free of other flammable material, in case the wax ignites. A fire extinguisher should be kept within easy reach. It is best if the temperature of the molten wax is only a few degrees above its melting point. This will provide a thicker, more water-resistant coat, and less wax will soak into the rock sample. Also, the low temperature will ensure the wax solidifies rapidly when the sample is lifted out of the molten wax.

The weight of the waxed sample is then determined and recorded. This weight will allow the density of the sample to be adjusted to compensate for the weight and buoyancy of the wax. In the case of paraffin or thin films, the effect of the mass is usually negligible, but some published methods stipulate this correction and best practice is to do the correction. The sample is then weighed while completely submerged in water (but not in contact with the bottom or side of the water vessel) and the weight recorded. The temperature of the water should be recorded to correct for temperature variations. For cold water, this correction is also negligible. The density can then be calculated, correcting for the wax coating and temperature using the equations in Section 4.1.2.

6.1.4 Specific Case Protocols

In cases where the ore is contained in intensely argillized, clay-rich zones and in extremely broken zones (rubble) that are not amenable to the protocol in 8.1.3, the following modifications to the protocol may be required.

Clay-rich Zones

Clay-rich zones should be handled similarly to the protocol above, but they cannot be dried prior to wax sealing and they are very fragile. The samples should be handled and cleaned gently; they will tend to disintegrate in water. These samples should be weighed wet and then immediately sealed in wax to retain their water content and to allow the samples to be handled. The wet density should then be determined as above. The sealed sample should then be opened and dried slowly at a temperature <35° C to



prevent melting and loss of wax which begins to melt at about 37° C. After the sample has dried, the weight should be determined and recorded. This will allow the wet density to be corrected to a dry density.

Broken (rubble) Zones

The density of broken (rubble) zones is extremely difficult to determine. A possible solution is to carefully measure the length of a broken zone and then weigh the core from that zone. This will allow for direct calculation of the density of the sample, but it is necessary to have 100 percent core recovery and a very accurate measurement of the length of the core. This may be accomplished by only using intervals between driller's blocks, but **there will always be uncertainty about the recovery.**

Alternatively, it is possible to determine an adjustment factor to use for this type of material when solid (unbroken) material is adjacent to broken (rubble) zones by determining the density of the solid material volumetrically (using a pycnometer or other method) and decreasing the density by the porosity determined by saturating the dried sample (assuming that it does not disintegrate in water). Volumetric density determinations are performed by cleaning, drying, and weighing the sample followed by placing the sample in a container of water and very accurately measuring the volume of the water displaced by the sample. The density is then calculated by dividing the weight of the sample by the displaced volume of water.

This type of material is difficult, and no procedure will produce completely reliable results. If the material is exposed at the surface, the most reliable determinations will be produced by large-scale (mine scale) excavation techniques.

Vuggy Zones

Vuggy zones are common within ore zones and have distinctly lower bulk densities than the surrounding zones without vugs. These samples must be prepared somewhat differently than the non-vuggy samples. This type of material will be prepared by first drying the sample and then sealing the sample with wide packaging tape before it is sealed in wax. The tape will insure that the decreased density due to vugs will be accounted for in the final density determination. Density will then be determined using the coated immersion procedure.

Care must be used with this method because if the tape is too thin, it will deform when the sample is dipped in wax. If the tape is too thick, it will not faithfully follow the contour of the core. This is something of a last resort procedure that will provide useful, but not totally reliable data.

A better method, if the core is competent is to carefully cut the ends of the samples perpendicular to the core axis and then use calipers to measure the average length and diameter of the core. This method is generally more reliable than the tape and immersion method, but requires very competent core.



6.1.5 Additional Considerations

At the time of logging, we know very little about the details of metal distribution within ore zones. It is possible that most of the metal is contained in very small parts of intervals or that it is evenly distributed within the interval. Because we require that a full diameter core be used for the density determination, the samples are typically pulled prior to assaying, and it is necessary to assay the sample after the density has been determined. Wax can be removed from the sample by boiling the sample in water (tape can be difficult). The cleaned sample can then be assayed and the assay value proportioned back into the interval if it is substantially above or below the value determined for the interval. Recorded sample and interval lengths are necessary to perform this calculation.

6.2 Density Determinations of Unconsolidated or Soft Surface Material

The following procedure has been used effectively to determine the *in situ* bulk density of near surface or underground, broken or soft rock.

6.2.1 Site Selection and Preparation

An appropriate site is selected based upon the rock units that need to be sampled. The area is cleaned and all loose material is removed so that undisturbed bedrock is exposed. The cleaned area should be on the order of 2 by 2 meters to insure that no loose material can contaminate the sample. The sample area should be carefully leveled and surface irregularities minimized. The area should then be cleaned with a broom.

6.2.2 Surface Contour Volume Mapping

In order to obtain an accurate measurement of the rock sample volume, the irregularities of the surface need to be mapped. This is done by placing a wooden frame on the surface of the rock and then very carefully leveling it. A thin plastic sheet is then placed in the frame and smoothed to minimize bunching of the plastic. Water is then used to fill the frame and the volume of the water is carefully measured and recorded. This procedure is repeated three times to get an average volume. If any one of the volume measurements is significantly different than the other measurements, the process is repeated until the volume is considered reliable.

6.2.3 Sample Excavation

The plastic liner is carefully removed from the frame and the outline of the inside of the frame is carefully marked on the rock, immediately below the frame. The outside of the frame is carefully marked to allow the frame to be reset over the hole after the sample is excavated. The frame is removed and a portable rock saw is used to cut the sample



edges along the line marking the inside of the frame. Once a cut is begun, it must be completed because loose material will fall into the hole and be removed if the groove is re-entered with the saw. Eight cuts, four for the outline, and four interior cuts allow for easy removal of the sample. The position of the saw cuts and the number of cuts must be recorded. The sample is then carefully removed from the pit and placed in poly sample bags.

6.2.4 Pit Volume Measurement

The frame is re-set over the pit, carefully oriented exactly as it was for the surface mapping exercise. The pit is lined with plastic and filled with a known volume of water until the water just overflows the frame. The volume of water is then recorded.

6.2.5 Sample Weighing and Drying

The sample bags are weighed and then placed in an oven to dry. The samples are then re-weighed until a constant weight is achieved, possibly as much as several days to a few weeks to completely dry. The final weight of the sample is then recorded.

6.2.6 Density Calculations

The sample volume is calculated by subtracting the surface map volume from the pit volume. The density is then the ratio of the sample weight to the sample volume. The volume lost to the saw cuts should be calculated and factored back into the final density calculation.

6.3 Saprolite and Other Weathered Materials

Density of saprolite and similar weathered materials can generally be determined using the procedure described in section 6.2, but MTS found the calibrated sand method described in section 4.4.2 to be more reliable if the material is exposed at the surface. It does; however, require significant manpower and time for each sample which limits the number of determinations that can be made in a day.

The slide hammer method is a very workable, useful procedure for exposed saprolite. The method is prone to small errors, but it is very easy and rapid. Multiple samples per hour are possible so small errors will tend to be hidden in the mass of data. As of date of this report (April 2020), the slide hammer sampler is available from Humboldt Construction Materials Testing Equipment (www.humboldtmfg.com/density-drive-sampler-2.html).

In some cases, saprolite density can be determined on drill core, but care must be taken to preserve the integrity of the core. Saprolite, especially wet saprolite, is typically soft and the core is easily distorted by rough handling. The most reliable density estimates



for saprolite combine extensive drill core sampling with a program of surface sampling using the calibrated sand or slide hammer procedures.

Note that density in saprolite increases from the surface downward in a rather predictable way. That predictability can be used to model the density in saprolite if sufficient data are available to produce the model. Recent work in saprolite-hosted gold deposits indicates that density can be effectively modeled using a linear regression relating percentage (proportion) of depth through the entire saprolite and density. This type of proportional model is easily constructed if the block modeling software can determine proportions from a stack of blocks.



7.0 REFERENCES

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