DENSE MEDIUM SEPARATION – AN EFFECTIVE AND ROBUST PRE-CONCENTRATION TECHNOLOGY

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ABSTRACT

With energy costs increasing and ore grades diminishing, the role of pre-concentration in hard rock mining operations has been gaining greater interest. To maximize energy conservation, the pre-concentration process should be conducted at as coarse a crush size as possible while minimizing losses of pay metals. Dense medium separation (DMS) is a robust process that can be conducted at particle sizes as coarse as 300 mm and as fine as 500 µm with high separation efficiency, depending on liberation characteristics of the value minerals. The DMS process involves three steps: feed preparation, dense medium separation, and ferrous-based media recovery. This paper discusses each of these processing steps, but focus will be given to the dense medium separation stage. Various types of DMS equipment are reviewed. Pilot plant campaign case studies conducted at the SGS Lakefield site are presented, which have included a variety of mineral systems such as spodumene, sulphide-bearing gold ores, and complex sulphide ores. These case studies demonstrate that for amenable ores, mass rejection of 20-60% is possible while maintaining recoveries of greater than 90% in most cases.

KEYWORDS

Dense medium separation, pre-concentration, lithium, sulphide ores, ferrosilicon, magnetite, dense medium cyclone, Wemco drum, TriFlo, dense media recovery, densifier, densification.

INTRODUCTION

Pre-concentration is a process of rejecting mass of gangue while ensuring recovery of valuable minerals prior to more intensive, downstream processing. Pre-concentration has been practiced in industry for many years, and is gaining greater interest as the industry copes with processing lower grade, more difficult ores, typically requiring finer grind sizes and higher energy costs.

The benefits of pre-concentration are as follows:

- Lower mining costs: allows non-selective mining;
- Lower process capital and operating costs: reduced grinding, flotation, fines disposal, etc. stages;
- Increased ore reserves: potential to treat lower grade ore;
- Increased mine production without expansion of the existing plant or concentrator;
- Reject can be a by-product, e.g., underground backfill or aggregate, and reduces overall tailings impoundment;
- Improved efficiency of downstream processes, e.g., silica removal in electric arc furnace feed, removal of softer sliming minerals prior to grinding;
- Can be applied to brownfield operations and greenfield projects;
- A 'green' process option:
    - Reduced processing energy consumption
    - Reduced mill feed
    - Increased stage metal recovery (higher grade feed)
    - Increased mill metal output
    - Plant has a small footprint and can be installed underground, reducing surface plant, tailings dump and tailings pond requirements
    - Can be applied to retreatment of old tailings dumps to recover metal values and reduce environmental impacts (e.g., dissolved metal runoff, acid drainage, etc.).

Pre-concentration generally involves physical separation, where gravity separation and ore sorting processes have been the most effective. Dense medium separation (DMS), synonymous with heavy medium separation (HMS), is a form of gravity concentration technology involving float-sink separation that historically has been used predominantly in the coal and diamond processing industries. Many other industries have used DMS, which include iron ore, complex sulphides, base metal oxides, precious metals, and various industrial mineral industries such as fluorspar, lithium, garnet, and other gemstones.

Other technologies considered for pre-concentration have mainly included optical ore sorters and jigs. DMS has several advantages over these technologies, which include:

- High separation efficiency at coarse particles sizes up to 300 mm;
- Separations achievable to 0.2 SG density differential between two minerals, e.g., sylvite (1.99 SG) and halite (2.17 SG) in the potash industry;
- Simple process control (i.e., medium density control); and
- Simple machinery (e.g., screens, pumps, cyclone or bath).

DMS TECHNOLOGY

The DMS process relies on a medium of specific density (specific gravity) that is between the density of the minerals targeted for separation. The form of the medium has changed throughout the years, but today is almost exclusively ferromagnetic powders such as magnetite or ferrosilicon. Once the minerals are submerged in the medium, they either float or sink, and a separator is required to remove the floats and sinks.

Two types of separators are utilized for DMS processing. The original form of separator employs baths and is a 'static' type separator. These machines are used to process a very broad range of feed particle sizes, as coarse as 300 mm and as fine as +6 mm or +12 mm, depending on the application. The development of cyclone technology introduced the 'dynamic' type separator that is used to process finer feeds, and recent large cyclone developments allow treating materials with top sizes as coarse as 100 mm and as fine as 0.5 mm.

Major developments in the dense medium technology include: (Wills, 1988; Hillman, 2003)

- 1858 – Bessemer (UK): First dense medium process patent to remove coal impurities by 'immersion in a tank or bath containing a fluid, the specific gravity of which is greater than the pure coal and less than the substance to be separated there from';
- 1921 – Chance (USA): First commercial plant. Cone separator, sand suspended in water medium;
- 1922 – Conklin (USA): Bath, iron ore medium;
- 1928 – Lessing (UK): Bath, calcium chloride medium;
- 1931 – de Vooys/Barvoys (Netherlands): Bath, barium sulphate and clay medium. Single compartment, -200/+12 mm feed, 3 products. Dual compartment, -250/+30 mm and -30/+6 mm feeds;
- 1937 – Tromp (Netherlands): Bath, magnetite medium, -100/+15 mm and -15/+6 mm feeds, 3 products;
- 1940 – Dutch State Mines (DSM, Netherlands): Cyclone for separation of very fine tailings particles developed to use shale an as operating medium in Barvoys baths;
- 1945 – DSM (Netherlands): Cyclone, magnetite medium, raw coal (bath fines), -10/+0.5 mm;
- 1950's – Tromp (Netherlands): Shallow bath, magnetite medium;
- 1950's – Wemco (USE): Bath (drum), magnetite medium, -200/+6 mm feed, 3 products;
- 1950's – Drewboy: Bath, magnetite medium; and
- 1950's – Teska (USA): Bath, magnetite medium.

The deep bath type dense medium separators of the early 1920's to 1940's, which used scraper chains for product removal, have been replaced by drum and wheel designs from the 1950's to present. Coarse feed bath separators currently used in the minerals processing industry are predominantly of the Wemco, Drewboy, and Teska types.

- Late 1950's – Dynawhirlpool (DWP, USA): 2 product, gravity-fed separator;
- Late 1960's – Vorsyl (UK), 2 product, pump-fed separator;
- Late 1960's – 3 Product Cyclone (Russia);
- Late 1970's – TriFlo (Italy): 3 product, gravity-fed separator;
- Early 1980's – Larcodems (LARge COal DEnse Medium Separator, UK) – 2 product gravity-fed separator;
- Early 1980's – 3 Product Cyclone (China): Pump-fed separator;
- Late 1980's – 3 Product Cyclone (China): Gravity-fed separator;
- Early 1990's – TriFlo (Italy): 4 product, 2 medium density, gravity-fed separator; and
- Mid 1990's – Larcodems (UK): 3 product, gravity-fed separator.

The chronology of the development of dynamic dense medium separators is depicted in Figure 1.

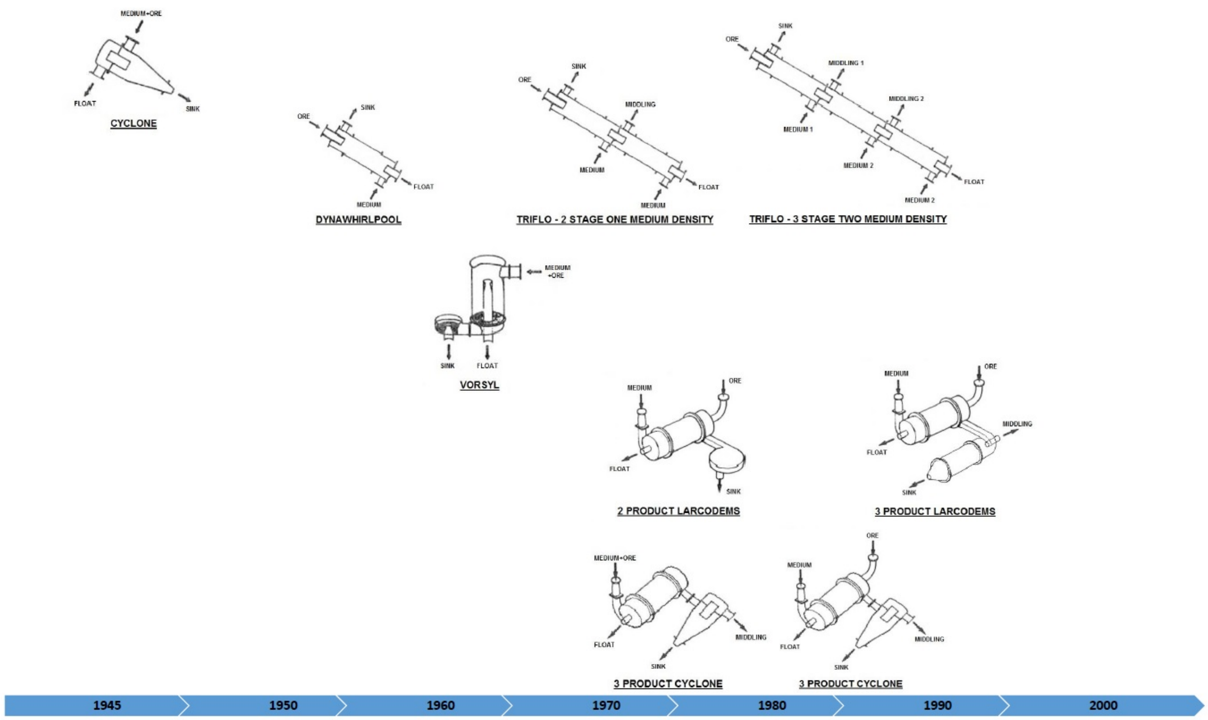

Figure 1 - Dynamic Dense Medium Separator Development

DMS LABORATORY TESTING

To determine if an ore is suitable for pre-concentration using DMS (or other gravity separation techniques), a laboratory scale testing program is generally initiated. Laboratory scale testing usually involves heavy liquid separation (HLS). At SGS, two modes of HLS testing are practiced. One mode involves the use of methylene iodide (CH_2I_2) which is diluted with acetone to reduce the specific gravity (SG) of the liquid phase to the target SG. With an SG of 3.3, the range of HLS testing using methylene iodide can be from 3.3 to 0.8 (i.e., the specific gravity of acetone), which far exceeds the requirements of most mineral systems. For higher densities, SGS uses another mode involving sodium polytungstate, with a specific gravity of 2.89. Tungsten powder is added to the sodium polytungstate solution to raise the SG further, and is used for separation SG's between 3.3 and 4.0.

The first step of the HLS test is to prepare the ore sample to mimic that which will feed the DMS media process. This requires crushing the sample to the desired size and also screening out the fines. It is common to test multiple crush sizes at this stage of the test program to assess the mass rejection/value recovery relationships at different sizes. The most common crush size being tested is 100% passing 1/2" (12.5 mm), but other top sizes such as 1", 3/4", 3/8" (9.5 mm), 1/4" (6.35 mm), and 6 mesh (3.35 mm) are also common. As the size of the fines is generally constrained (10 mesh (1.17 mm), 20 mesh (0.85 mm), and 32 mesh (0.50 mm) are most common), testing at crush sizes finer than 6 mesh is not usually practical. However, if the grain sizes of the ore are considered large enough, testing at crush sizes coarser than 1/2" is encouraged, as the effort for size reduction in practice will be less.

The main goal of HLS testing is to separate the sample into several density fractions to evaluate the tradeoff between recovery of value minerals and rejection of gangue minerals at different medium specific gravities. It is also common to separate the sample at multiple size fractions, to allow for evaluating the size at which the value mineral(s) are liberated. Each test product is weighed and assayed, allowing completion of a mass balance. Analysis of the mass balance provides insight into whether the separation was successful. It is the custom at SGS to present the data in terms of value metal recovery versus weight recovery to sink. Other methods for depicting the data such as a Tromp curve are also common.

An example of data available from HLS testing of a gold bearing sulphide ore is provided in Figure 2. The sample used in this example was crushed to 100% passing 1/2", screened at 500 µm, and the -1/2"/+500µm fraction was separated at SG's ranging from 3.20 to 2.65. The gold was associated with arsenopyrite, and there was an almost perfect correlation between the gold and arsenic recoveries. The recovery is calculated based on sum of the fines fraction and sinks fraction from each separation stage. This example of HLS testing is the most ideal case, where the recovery of gold increased dramatically with small increases in mass pull. The gold recovery approached 100% at a low mass recovery. A distinct plateau was formed which indicates that any further increase in recovery would require a significantly higher mass pull. In this case the apex in the curve occurred at an SG of 2.80, and this is the point where separation by DMS would be practised. At this point of separation, the mass rejection (i.e., 100% - mass pull) was approximately 70% and gold recovery was approximately 98%. The head grade of this sample was approximately 14 g/t and increased nearly three-fold to a concentrate grade of approximately 40 g/t.

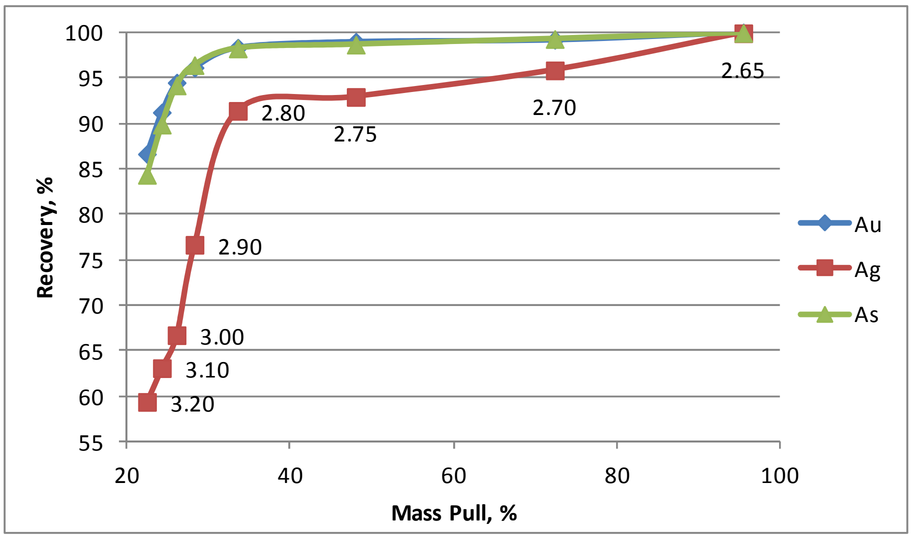

Figure 2 – HLS Data Example #1 – Gold Bearing Sulphide Ore

The data from most applications show similar trends, with recovery of the value minerals increasing with increasing mass recovery. However, many applications don't show such a distinct separation, and the minerals are not liberated sufficiently to be separated efficiently from the gangue matrix. Figure 3 presents data from an application involving a complex CuPbZn ore where recoveries of approximately 97% were attained, but at a high required mass pull of approximately 75%. The ore upgrading ratio in this case was very low, at approximately 30%, and DMS was thus not considered to be a good option.

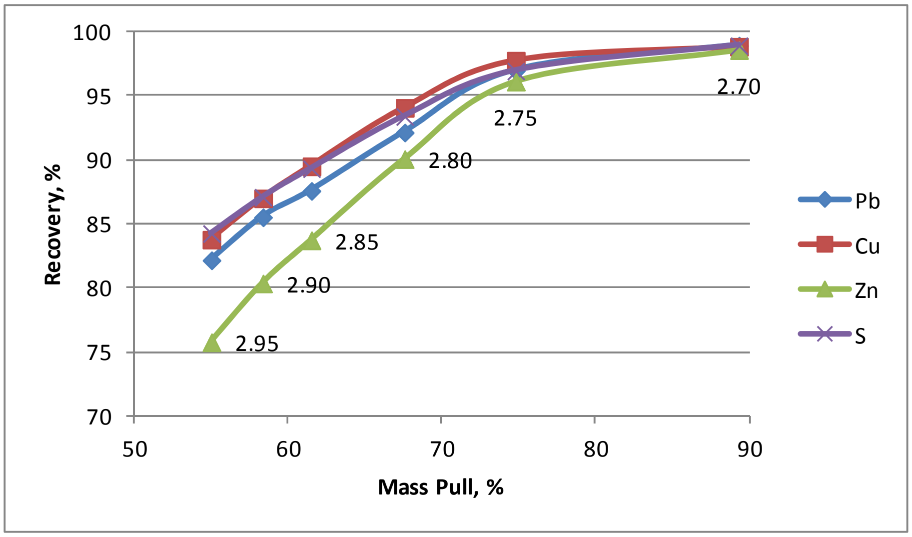

Figure 3 – HLS Data Example #2 – Complex Sulphide Ore

DMS OPERATION

While DMS circuit configurations can vary depending on objectives and the nature of the value and gangue minerals, each DMS flowsheet consists of the feed preparation, dense medium separation, and media recovery circuits. This section discusses each of these areas in more depth.

Figure 4 depicts a typical DMS flowsheet, showing the standard processing units of feed preparation (to ensure that the correctly sized feed is presented to the separation vessel(s)), dense medium separation (to separate particles of different minerals based on their density differences), and media recovery (to recover the heavy media for recycle and re-use).

While Figure 4 depicts a common single-pass flowsheet, each material of interest can be processed using customized sequence of separation stages (i.e., reprocessing of the float / sinks streams at different densities and with or without intermediate size reduction stages). Consequently, each material to be treated can utilize a specific flowsheet, developed through systematic testing, to allow the most effective trade-off between value recovery/waste mass rejection and cost.

Figure 5 depicts a photograph of the pilot-scale (3 tph capacity) DMS plant at SGS Lakefield. SGS Lakefield also uses a smaller capacity pilot-scale DMS plant (~1 tph capacity), which can be integrated with the 5 tph plant to allow continuous testing of a second (repass) DMS stage.

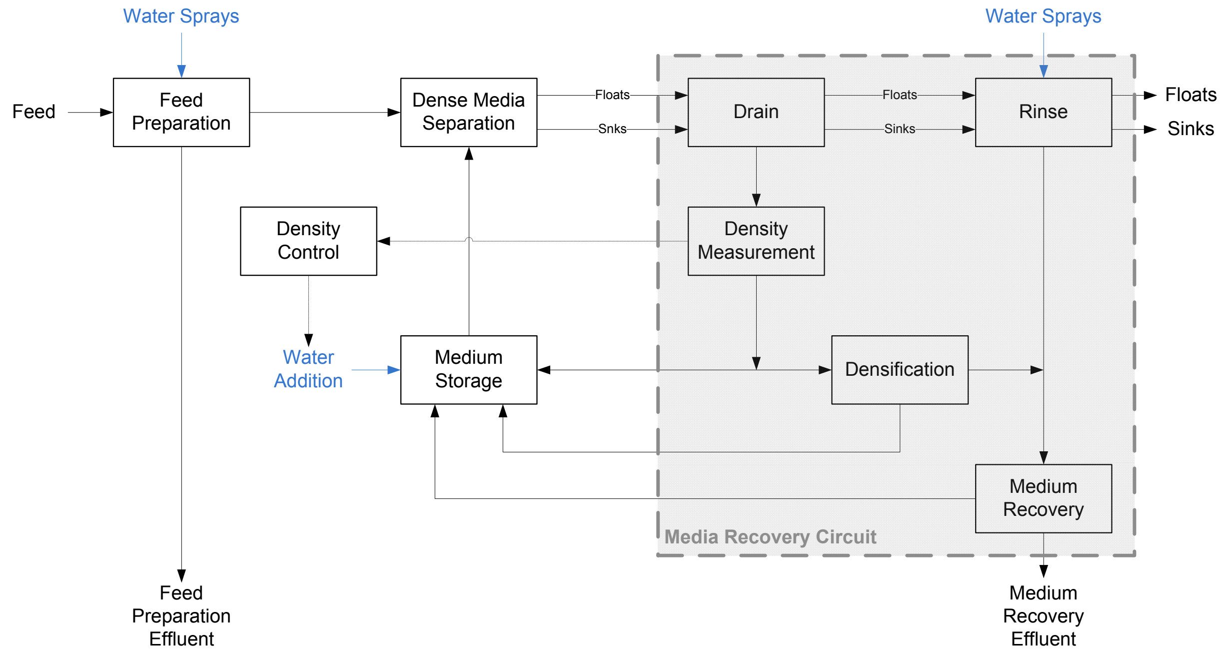

Figure 4 - Dense Media Separation Flowsheet

Figure 5 – SGS 5 tph DMS Pilot Plant

Feed Preparation

Feed preparation involves the processes of size reduction and classification to ensure a suitable particle size range is presented to the dense medium separation vessel. This is critical to ensure an efficient dense medium separation. The main objectives of the feed preparation process are to ensure maximum liberation of minerals by crushing/breaking/scrubbing/attritioning, the removal of fines/slimes (which hinder the separation process), and the control of the particle size range to which each separation vessel will be presented.

ROM material is typically reduced in size using conventional crushing techniques such as gyratory crushing, jaw crushing, cone crushing, and/or HPGR. The crushed product can be scrubbed at a pulp density of 50% solids or less to break up clays and agglomerated particles and/or attritioned at a higher pulp density to break down the friable gangue minerals for further rejection by screening. At SGS Lakefield, feed material is generally prepared by stage crushing with a jaw crusher / cone crusher in combination with classification screens for dry screening. Classified material is often directed to a wet scrubbing or wet attritioning stage, the discharge of which is wet screened to remove generated slimes. The material is deslimed at a fine cut-off size, typically 0.5 mm to 1.0 mm depending on processing objectives. The coarse fraction is directed to the DMS stage. Dense medium cyclones can typically treat particles with a top size of up to 100 mm, while coarser fractions generally up to 300 mm can be treated in open-bath separators, or with Drewboy machines which can treat much larger rocks. Assuming liberation is adequate, the intermediate size is generally constrained by cyclone and/or pumping limitations, whereas the overall top size is generally constrained by downstream handling limitations.

Slimes tend to create inefficiencies in dense medium separations through increased slurry viscosity in the separation vessel, which hinders the movement of smaller particles, resulting in misplaced material in the floats stream. In addition, slimes can contaminate the circulating medium, resulting in difficulty in density measurement and control.

The criteria for determining the minimum cut-off size are two-fold. Firstly, below a minimum size (e.g., 0.3 to 1.0 mm), the dense medium separation efficiency decreases to an unacceptable level, affecting recovery. This is referred to as the breakaway size. The breakaway size of a cyclone is related to its diameter, where larger cyclones have a larger effective lower treatment size. Secondly, it is often desirable from an economic perspective to process the fine material via a different beneficiation scheme (e.g., froth flotation), or to reject it entirely depending on trade-off between recovering the value contained in the fines and the additional cost of processing. It is important that proper drainage of the feed preparation screen oversize stream is ensured, prior to mixing with the circulating medium, to avoid medium dilution and in turn difficult density control. The installation of water sprays and weir bars on the screening surface can vastly improve the efficiency of screening and dewatering.

At SGS Lakefield, for projects that require scrubbing, pre-crushed feed is transferred to a feed hopper (with capacity dependent on feedrate), which discharges at a controlled rate via a horizontal conveyor or vibratory feeder onto an inclined conveyor belt that feeds a Scrubber unit. A Titan Process Equipment 30”x58” overflow scrubber is used for disaggregation, desliming, and to remove any adhered fines. Scrubber discharge overflows onto a 48” Kason screen deck, where fines are directed to a Thickener for further processing or to the tailings containment bunker. The screen oversize is directed to the DMS plant. Figure 6 presents a photograph of the Scrubbing circuit, with the Scrubber Feeding System shown on the left and the Scrubber/Kason Screen arrangement shown on the right.

Figure 6 - Scrubbing Equipment at SGS Lakefield

For projects that do not require scrubbing or other pre-treatment, the crushed feed can be fed directly onto a horizontal screen deck, which is part of the DMS plant, for rejection of the fines fraction (slimes) prior to feeding the oversize into the cyclone feed pumpbox.

Dense Medium Separation

The primary purpose of the DMS plant is to concentrate the valuable minerals in the DMS plant feed and to generate a reject stream. (Either the concentrate or reject stream, or both, can be subjected to further processing stages.) In the case of pre-concentration, the reject stream is generally discarded to minimize the downstream processing requirements. The separating vessels are the heart of the DMS Plant (Weiss, 1985). DMS vessels can be categorized into two broad categories. Static, open-bath vessels (e.g., drums) are used for the separations at coarser particle sizes, while dynamic separators are generally employed for finer size ranges. Open-bath vessels make use of the natural settling velocity of particles in a heavy medium slurry (at standard gravity), whereas dynamic vessels, namely centrifugal devices, make use of centrifugal forces to enhance the settling forces acting on the particles, thereby effectively increasing the settling velocity of the particles (and in turn increasing the capacity of the process). Cyclones are the most common centrifugal dense media separation devices in most industries. However, multi-stage separators are gaining traction outside of North America where the Chinese 3-product separator is processing 2.5 billion tonnes per annum of coal. The trend is moving towards medium 'free' gravity fed separators where only the medium is pumped into the separation vessel via one of the inlets. This reduces power and maintenance costs (i.e., no cyclone feed pump is required).

Discharge from the feed preparation screen is mixed with the dense medium slurry. The ore/medium slurry is then directed to the separation vessel(s), either via gravity or by pumping. Feeding by gravity ensures a consistent head pressure, while feeding by variable speed pumping allows for variation and control of the pressure to the separating vessel.

SGS Lakefield employs a Wemco-style drum separator with 75 mm internal diameter and 90 mm internal length, which can treat particles up to 32 mm. Separation is accomplished by the continuous removal of the sinks product via perforated lifters fixed to the inside of the rotating drum. The sinks stream, propelled by the lifters, empties into the sinks launder at a certain position in the lifter trajectory. The floats product overflows the discharge end of the drum.

The principle of operation of dense medium cyclones is similar to that of a conventional hydrocyclone. For pump-fed cyclones, the ore is suspended in a dense medium and is introduced tangentially to the cyclone under pressure. Particles denser than the slurry will move to the wall of the cyclone and travel down to the apex and ultimately through the cyclone underflow, while less dense particles will travel into the vortex and ultimately up through the cyclone overflow (Wills, 1988). Therefore, the centrifugal forces present in the cyclone are meant to be kept to a minimum. It is the experience at SGS that the density of separation in the cyclone is 0.06 SG greater than the medium SG.

The cyclone feed pressure must remain relatively low compared to classification hydrocyclones. In DMS, the cyclone feed pressure is generally held within 9 to 14 times the cyclone diameter. This pressure is required to maintain the stability of the medium, while excessive cyclone feed pressure would impart higher g-forces on the particles of both the ore and medium and would cause separation by size, similar to the principle of a classification hydrocyclone. Classification of the medium would cause density gradients in the cyclone (comparable to the particle size gradients present in a hydrocyclone) resulting in an ineffective separation.

The DMS cyclone pilot plant utilized by SGS Lakefield is a Dowding Reynard & Associates of America pump-fed cyclone plant, equipped with a dense medium cyclone (200 mm). The feed-sized material (typically -12.5+0.5mm) discharges from the vibrating screen deck into the DMS plant mixing box where it is mixed with slurry from the circulating medium tank. Depending on the desired operating density range, pure ferrosilicon, pure magnetite, or a blend of ferrosilicon and magnetite are used as the heavy media. The separation by density occurs in the cyclone, with denser particles reporting to the cyclone underflow and less dense particles reporting to the cyclone overflow. The density of the separation is controlled by adjusting the ratio of water to medium in the suspension. Both floats and sinks products pass over a medium recovery screen. The screen consists of a drain section, which allows the majority of the heavy medium particles to drain directly into the circulating medium (also known as correct medium) section of the plant, followed by a rinse section fitted with water sprays to wash ferrosilicon and/or magnetite particles from the products into the dilute medium section. DMS floats and sinks are captured in bulk bags for batch transfer, or are continuously directed to further processing stages. Figure 7 depicts the SGS Lakefield DMS plant in operation (left side) and the DMS cyclone discharging onto the sinks and floats drain/rinse screens. (In this case the sinks and floats report to a common screen, which is partitioned into two separate sections.)

Figure 7 - SGS Lakefield DMS Plant (left) and Cyclone Operation (right)

Dense Medium Recovery and Control

The medium recovery portion of a DMS plant consists of two circuits: the circulating medium circuit and the dilute medium circuit. The sinks and floats streams from the separation vessels each report to horizontal vibrating screens fitted with screen panels of an aperture size finer than that of the feed preparation screen. The first portion of the screen is used to drain the dense medium. The screen undersize then reports to the circulating medium tank through a demagnetizing coil, where it is mixed with the fresh incoming feed. The second portion of the screen is fitted with water sprays to rinse any remaining ferromagnetic particles from the solid particles in the two streams, before exiting the circuit. The screen undersize from the rinse section of the screen reports to the dilute medium circuit, where it is then directed to a low intensity magnetic drum separator for recovery of the ferromagnetic dense media particles.

The circulating medium is pumped through a demagnetizing coil to break up any magnetically flocculated particles into an agitated holding tank, from where the flow of circulating medium into the feed pumpbox is regulated. Medium in the circulating medium circuit is maintained at a density slightly higher that is required for the separation. This is generally accomplished via a densifier or the use of splitters to control the relative proportion of medium reporting to the each of the circulating medium and dilute medium circuits. The densifier has the dual purpose of water removal and the rejection of non-magnetic particles, with the underflow returning to the circulating medium circuit and the overflow reporting to the dilute medium circuit. A slurry density meter is used to measure the density of the circulating medium reporting to the holding tank, and a water stream of variable flowrate is used to control the amount of water introduced into the circulating medium circuit and in turn the operating density of the circuit. Media cleaning is often accomplished with the presence of a bleed stream into the dilute medium circuit, particularly when densifers are not used.

Dilute medium is pumped to a magnetic separation stage, which is the primary step in media recovery. Wet low intensity permanent magnetic drum separators are almost exclusively used for this role, and typically in two stages to maximize medium recovery and mitigate the impact of magnetic separator feed fluctuations. The primary drum collects the majority of the medium, while the secondary drum is used as a scavenger. Criteria to consider in the design and operation of a magnetic separation circuit include the volumetric flowrate of dilute medium, the pulp density of the dilute medium, and the percent magnetics in the dilute medium. These factors influence the performance of the magnetic separators, and pulp levels and magnet positions in the separators must be controlled to enable an acceptable balance between maximized medium recovery and minimized dilution of the magnetic concentrate. A densifier can also be employed in a dilute medium circuit.

Densification and Dense Medium Control Strategies

The control of the medium density is a major factor in the operation of the dense medium separation process. The medium density must be kept in close tolerance to the target or set-point density to avoid displacement of near density material which will affect the yields and product grades. The density should be controlled to a precision of two decimal points or ± 0.005SG.

Control of the medium density requires removal of water added to and retained in the circulating or correct medium circuit. The main source of water entering the system is from the ore feed which has been wet screened and retained water due to medium solids adhering to the float and sink products. Other sources of water entering the circulating medium circuit include rinse screen water sprays and medium pump gland water. Thus, to be able to control the medium density, the system must remove water from the circulating medium circuit.

It has been established that the most effective mode of control is that the system removes more water than enters the circuit and control is established by adding water. This is referred to a positive water addition. The medium density is controlled by the operation of the densification and medium recovery circuits. In lower operating density separations, e.g., coal operating at 1.4 to 1.8 SG, the dilute medium circuit magnetic separator is sufficient to remove water from the circulating medium and enable density control. For higher density mineral separations operating at 2.5 SG and higher, centrifugal densifiers are usually required to maintain good density control.

Both dilute and correct medium densification are used, though the trend is for the latter which provides rapid water removal from the circulating medium after a DMS plant shutdown or process upset condition. There are two basic types of densifier: a pipe densifier and a cyclone densifier. The pipe densifier has a typical cyclone feed inlet with a long cylindrical section with a tangential outlet and operates as a de-watering rather than a thickening device. The cyclone densifier is a typical hydrocyclone and operates as a thickening rather than a dewatering device. The cyclone is better suited to dilute medium densification (i.e., thickening), and the pipe densifier to correct medium densification (i.e., dewatering).

Table 1 and Table 2 show the typical mass balances of a pipe densifier and cyclone densifier operating in the circulating medium circuit, respectively.

Table 1 – Pipe Densifier Mass Balance

Stream	Flowrate (m^3/hr)	G	Magnetics Recovery, %
Feed	20	.65	100
Overflow	6	.15	3
Underflow	14	.30	97

Table 2 – Cyclone Densifier Mass Balance

Stream	Flowrate (m^3/hr)	G	Magnetics Recovery, %
Feed	20	.65	100
Overflow	14	.25	53
Underflow	6	.60	47

Comparing of the two mass balances, the pipe densifier rejects significantly less magnetics to the overflow than the cyclone densifier, and this greatly reduces the dilute medium circuit magnetics loading and in turn the size of the wet drum magnetic separator required. An additional advantage of correct medium densification using a pipe densifier is reduced magnetics classification and reduced fine magnetics losses from the dilute medium circuit wet drum magnetic separator.

Both types of densifier will reject lower density contaminant minerals from the circulating medium (e.g., silicates and clays). However, in higher density mineral separations, such as sulphides, it is recommended that a circulating medium bleed to the dilute medium circuit is incorporated to remove fine high density non-magnetics which can build up in the circuit and affect the medium density and viscosity.

Measurement of Separation Efficiency

While laboratory heavy liquid separation testing is done under near-ideal conditions, the dynamic conditions of a continuous dense medium separation process introduces natural inefficiencies, with higher density particles misplaced into the floats stream and lower density particles misplaced into the sinks stream. The degree of inefficiency increases relative to the proportion of particles in the feed whose density is near the density of the separation (i.e., near density material). The efficiency of the separation process can be determined through the generation of partition curve (also known as a "Tromp" curve), consisting of the effective separation density (which can be different than the operating slurry density) on the x axis and the percentage of feed material of a given density that reports to the sinks stream on the y axis. Refer to Figure 8. The ideal separation (i.e., no misplaced material) is represented by a vertical line, where 100% of the particles having a density higher than the separation density and 0% of the particles having a density lower than the separation density report to the sinks stream. The "D_{50}" value is the separation density at which a particle has a 50% probability of reporting to either the float or sink stream. The sharpness of separation is displayed by the slope of the curve, which can be quantified by the "Probable Error of Separation" ("Ep"), and is defined as half of the density difference between the D_{75} and D_{25}, where a lower Ep indicates a higher separation efficiency. For the case in Figure 8, the data is from a tracer test where the D_{50} SG was determined to be 2.75 at an Ep of 0.02 (which indicates the SG difference between the D_{75} and D_{25} was only 0.04).

The partition curve for a particular vessel under a specific set of operating conditions can be determined by tracer testing, in which a set of solids of specific sizes (e.g., 2 mm, 4 mm, 8 mm, and so on), each with a precise known specific gravity indicated by its colour, is introduced into the feed stream of the separation vessel. The tracers are collected from each of the floats and sinks streams and counted, such that the percentage of tracers of a certain specific density can be determined. This type of testing is done immediately prior to and often during the pilot scale testing of materials, as a means of determining the efficiency of the separation vessel at the conditions established for the testing program. Any issue identified through tracer testing should be corrected prior to testing the sample.

The partition curve can be constructed after the separation of the sample has been completed, by collecting representative samples from the floats and sinks streams during the separation and performing heavy liquid tests on each sample to assess the degree of misplaced material in each of the floats and sinks streams. The partition curve of the reconstituted feed can then be constructed.

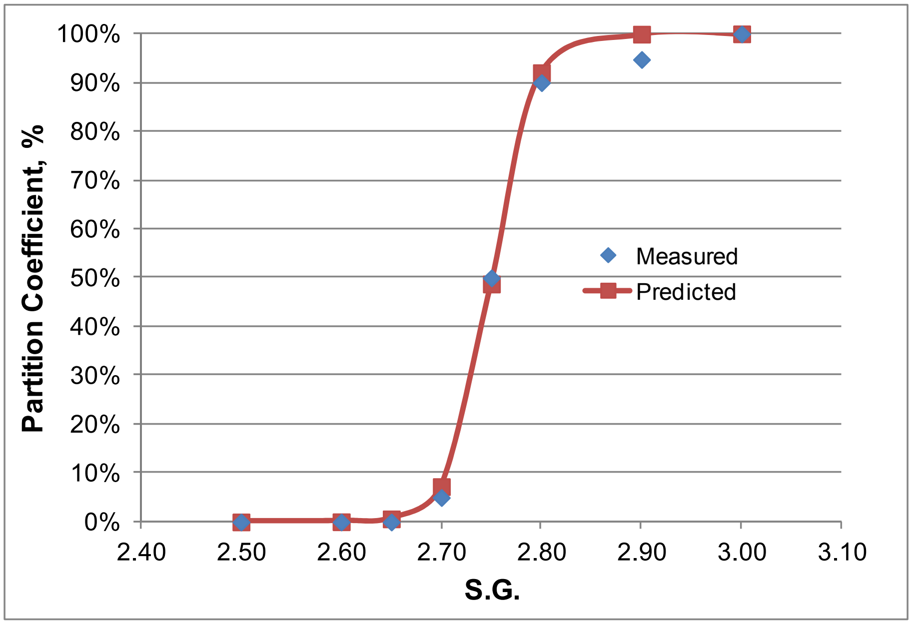

Figure 8 – Tromp Curve example, Tracer Test

CASE STUDIES

Hard Rock Lithium

Nemaska Lithium – Whabouchi Project, Quebec, Canada

SGS Lakefield executed a DMS flowsheet development study on a spodumene ore, with the dual goals of pre-concentration to reduce the requirement for downstream (flotation) processing and the production of a saleable concentrate. DMS pilot-scale testing was completed in several stages and consisted of the unit operations of crushing, scrubbing, screening, dense medium separation, magnetic separation, filtration, and dewatering. A larger, 25 tonne, sample was initially tested in various stages, along with intermediate size reduction and further concentration by magnetic separation. Based on the data generated from the various stages of DMS piloting, a simplified flowsheet which was deemed more practical for large-scale implementation was tested on a smaller sample.

The larger sample was processed in a total of eight DMS stages to determine the effectiveness of various upgrading stages, both by DMS and by magnetic separation, as well as the impact of separation at three different feed top sizes. Overall, a combined concentrate representing 13% (weight basis) of the feed mass was produced at an average grade of 6.0% Li_2O. Lithium distribution to this concentrate was slightly below 50%. A middlings fraction was produced representing 45% of the feed mass (weight basis) at an average grade of 1.6% Li_2O, which is similar to the grade of the initial DMS plant feed. The lithium losses to tailings were slightly less than 10%, at a mass rejection of over 40%. The overall results summary is provided in the table below.

Table 3 - Overall Results Summary – DMS Processing of 25 tonne Sample (8-Stage DMS Flowsheet)

Combined Products	Wt (t)	Wt %	Grade (% Li_2O)	Li Distribution %
Feed	23.42	100.0	1.64	100.0
Tailings	9.90	42.3	0.36	9.2
Concentrate	3.06	13.0	6.04	48.1
Middlings (PP Feed)	10.47	44.7	1.57	42.7

Based on the information gained from the processing of the 25 tonne sample, a mine representative sample was processed via a simplified flowsheet that would be more practical in industrial operation. An initial DMS stage was conducted at a particle top size of 3/8", intended as an initial scalping unit to remove coarse rejects (DMS#1 floats). The concentrate was then upgraded in the second DMS stage, with no intermediate size reduction, to produce a final grade concentrate (DMS#2 sinks). The DMS#2 floats stream was then crushed to a top size of 6 mesh, followed by two further stages of processing. The DMS#3 sinks was of final concentrate grade, while the DMS#4 sinks was considered middlings to be further processed downstream in a flotation plant along with the minus 0.5 mm fines fractions from all DMS stages. The DMS#4 floats stream was considered final tailings. Magnetic separation of the DMS#2 and DMS#3 sinks streams was also conducted to generate data related to the potential for further upgrading of the DMS plant concentrates.

Figure 9 depicts the simplified flowsheet tested, and Table 4 shows the final mass balance of all streams, according to the numbering system shown in the processing flowsheet.

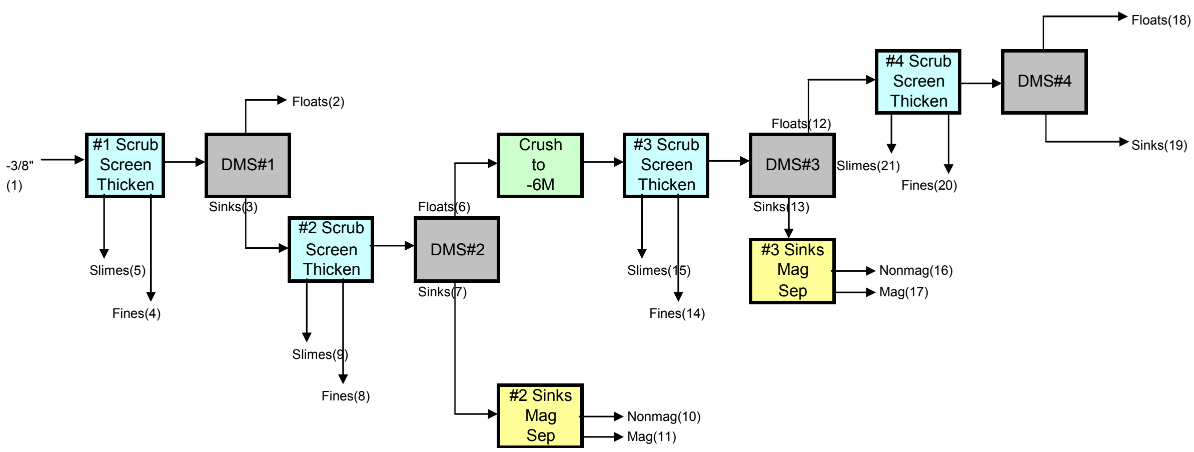

Figure 9 – DMS Processing Flowsheet – Mine Representative Sample

Table 4 – Mine Representative Sample – Detailed Mass Balance

Stream #	Stream ID	Stream Type	Wt (t)	Wt %	Grade (% Li_2O)	Li Distribution %
1	DMS Feed	Feed	4.42	100.0	1.61	100.0
2	DMS #1 Floats	Tailings	1.32	29.8	0.31	5.7
3	DMS #1 Sinks	Intermediate	2.04	46.1	2.75	79.0
4	DMS #1 Fines	PP Feed	0.89	20.2	1.02	12.8
5	DMS #1 Slimes	Tailings	0.17	3.9	1.02	2.5
6	DMS #2 Floats	Intermediate	1.67	37.8	2.16	50.9
7	DMS #2 Sinks	Concentrate	0.29	6.6	6.22	25.7
8	DMS #2 Fines	PP Feed	0.06	1.3	2.32	1.9
9	DMS #2 Slimes	Tailings	0.01	0.3	2.32	0.4
10	DMS #2 Nonmag		0.28	6.4	6.28	25.2
11	DMS #2 Mag		0.01	0.2	4.21	0.5
12	DMS #3 Floats	Intermediate	0.81	18.3	1.49	17.0
13	DMS #3 Sinks	Concentrate	0.21	4.7	6.59	19.1
14	DMS #3 Fines	PP Feed	0.60	13.6	1.60	13.6
15	DMS #3 Slimes	Tailings	0.05	1.2	1.60	1.2
16	DMS #3 Nonmag		0.20	4.5	6.65	18.6
17	DMS #3 Mag		0.01	0.2	4.93	0.5
18	DMS #4 Floats	Tailings	0.20	4.6	0.12	0.3
19	DMS #4 Sinks	PP Feed	0.56	12.6	1.97	15.4
20	DMS #4 Fines	PP Feed	0.04	1.0	1.82	1.1
21	DMS #4 Slimes	Tailings	0.01	0.1	1.82	0.2

A further simplified processing flowsheet consisting of only two DMS processing stages was considered. The mass balances showing both scenarios (2 and 4 stages) are summarized in Table 5. Both balances are exclusive of magnetic separation.

With only two stages of processing, a concentrate representing 7% of the feed mass would be produced at a grade of 6.2% Li_2O and a Li distribution of 25%. With the inclusion of the final two stages (DMS#3 and DMS#4) in the flowsheet, the production of final concentrate increased to 11% (weight basis) at a grade of 6.4% Li2O and a Li distribution of 45%. The Li losses to tailings increased by 2% and the grade of the middlings (i.e., flotation pilot plant feed) decreased from 1.8% to 1.5% Li_2O with the inclusion of DMS#3 and DMS#4 stages. A comparison of the overall integrated process, including flotation performance with the two different flotation feeds, would determine the optimal processing flowsheet configuration.

Table 5 – Comparison of Two-Stage and Four-Stage DMS

4 Stages

Combined Products	Wt (t)	Wt %	Grade (% Li_2O)	Li Distribution %
Combined Tailings	1.77	40.0	0.42	10.4
Combine Middlings	2.15	48.7	1.48	44.9
Combined Concentrates	0.50	11.3	6.37	44.8
Feed	4.42	100.0	1.61	100.0

2 Stages

Combined Products	Wt (t)	Wt %	Grade (% Li_2O)	Li Distribution %
Combined Tailings	1.50	34.0	0.41	8.6
Combine Middlings	2.62	59.4	1.78	65.7
Combined Concentrates	0.29	6.6	6.22	25.7
Feed	4.42	100.0	1.61	100.0

Other Lithium Project's in Quebec

SGS has been involved with other lithium projects in Quebec. One of the projects involved a 20 tonne sample was stage crushed to 100% passing 6 mm, similar to company's other operation. Following completion of laboratory HLS testing to confirm amenability of the ore to DMS operation, pilot plant processing was completed. The other operation utilizes a two-stage DMS process, with both stages operated at the same SG. To compare this method of processing with the SGS customary lithium processing technique of two-stages at different SGs, the ore was split into two samples, weighing 3 and 17 tonnes, with each processed differently for comparison purposes.

The results from the two-stage DMS operation at different SGs are summarized in Table 6, while the results from operation at the same SG are summarized in Table 7. The overall results from both cases were very similar, with approximately 72% of the Li recovered by DMS into a concentrate of approximately 6.5% Li_2O in both cases, representing very favourable metallurgy.

Table 6 – Two-Stage DMS Operation – Different SG

Product	Wt. (kg)	Wt. %	Assay, %					Distribution, %			
			Li_2O	Li	SiO_2	Al_2O_3	Fe_2O_3	Li	SiO_2	Al_2O_3	Fe_2O_3
DMS #4 Sink	2293.9	14.2	6.53	3.03	64.2	25.8	1.21	71.9	15.2	27.8	27.7
DMS #4 Float	647.9	4.0	1.25	0.58	74.3	15.3	1.03	3.9	5.0	4.7	6.6
DMS #1 Sink	2941.8	18.2	5.37	2.49	66.5	23.49	1.17	75.8	20.2	32.5	34.3
DMS #1 Float	6009.5	37.2	0.13	0.06	77.5	13.0	0.36	3.7	48.2	36.6	21.3
DMS #1 Fines	4249.2	26.3	1.00	0.47	72.0	15.4	1.05	20.5	31.6	30.9	44.4
Feed (calc)	16142.2	100	1.29	0.60	59.9	13.2	0.62	100	100	100	100
Feed (dir)			1.51	0.70	73.6	16.1	0.63				

Table 7 – Two-Stage DMS Operation – Same SG

Product	Wt. (kg)	Wt. %	Assay, %					Distribution, %			
			Li_2O	Li	SiO_2	Al_2O_3	Fe_2O_3	Li	SiO_2	Al_2O_3	Fe_2O_3
DMS #3 Sink	416.9	14.7	6.48	3.01	64.1	25.8	1.26	72.0	15.3	28.3	27.2
DMS #3 Float	49.4	1.7	1.46	0.68	72.6	16.9	0.94	1.9	2.1	2.2	2.4
DMS #2 Sink	466.3	16.4	5.95	2.76	65.0	24.9	1.23	73.9	17.4	30.5	29.6
DMS #2 Float	1159.1	40.8	0.20	0.09	78.0	12.8	0.50	6.1	51.8	39.1	29.7
DMS #2 Fines	747.4	26.3	1.00	0.47	72.0	15.4	1.05	20.0	30.8	30.4	40.6
Feed (calc)	2839.1	100	1.32	0.61	61.4	13.4	0.68	100	100	100	100
Feed (dir)			1.51	0.70	73.6	16.1	0.63				

Complex Sulphide Ores

Complex sulphide ore operations, e.g., Nanasivik Mine, have used DMS to pre-concentrate the ore. Two such projects conducted at SGS Lakefield which investigated the use of DMS are Canadian Zinc Corp's Prairie Creek Project and an operating mine in Central America.

Canadian Zinc Corp – Prairie Creek, Northwest Territories, Canada

During this project, fairly small scale DMS operations were conducted to produce pre-concentrate in support of the flotation laboratory testwork program conducted at SGS. One case involved a sample of approximately 600 kg while another involved approximately 400 kg. The results from the DMS operations are summarized in Table 8 and Table 9. In both cases the feed was screened at 800 µm and oversize reported to the DMS cyclone for separation at a separation SG of 2.80. In the first case, the fines fraction was included in the analysis and, in combination with the DMS sink stream, recoveries of approximately 97% and 98% were obtained for copper, lead, and zinc. Similarly for the second study, which did not include analysis of the fines, recoveries (relative to DMS feed) of approximately 92%, 97% and 95% were realized for copper, lead and zinc, respectively.

Even with the high recoveries obtained, reasonable mass rejections of 27.8% and 37.1% (based on DMS feed) were obtained.

Table 8 – Canadian Zinc Prairie Creek Study #1

Product	Mass		Assay, %, g/t					Distribution, %				
	kg	%	Cu	Pb	Zn	Au	Ag	Cu	Pb	Zn	Ag	Au
DMS Sink	183.5	43.5	0.47	17.4	19.8	0.04	226	61.6	66.1	58.4	50.8	61.3
DMS Floats	120.9	28.7	0.038	0.67	1.41	0.02	16.5	3.3	1.7	2.7	16.7	2.9
-20 mesh	117	27.8	0.42	13.3	20.7	0.04	207	35.1	32.2	38.9	32.4	35.8
Head (calc.)	421	100	0.33	11.5	14.8	0.03	161	100	100	100	100	100

Combined Products

Product	Mass		Assay, %, g/t					Distribution, %				
	kg	%	Cu	Pb	Zn	Au	Ag	Cu	Pb	Zn	Ag	Au
Sink	184	43.5	0.47	17.4	19.8	0.04	226	61.6	66.1	58.4	50.8	61.3
Sink + -20 mesh	301	71.3	0.45	15.8	20.2	0.04	219	96.7	98.3	97.3	83.3	97.1

Table 9 – Canadian Zinc Prairie Creek, Study #2

Sample	Wt. (kg)	Wt. %	Assay, g/t, %					Distribution, %				
			Cu	Pb	Zn	Au	Ag	Cu	Pb	Zn	Au	Ag
DMS 3rd Pass Sink	324.0	55.4	0.91	24.3	31.1	0.05	358	92.3	96.6	94.7	75.6	93.1
DMS 3rd Pass Float	18.4	3.1	0.12	1.72	3.45	<0.02	36.6	0.7	0.4	0.6	1.7	0.5
DMS 2nd Pass Float	25.8	4.4	0.07	0.96	2.01	<0.02	24.6	0.6	0.3	0.5	2.4	0.5
DMS 1st Pass Float	217.1	37.1	0.095	1.00	2.05	<0.02	33.8	6.5	2.7	4.2	20.3	5.9
Head (calc)	585.3	100	0.55	13.9	18.2	0.04	213	100	100	100	100	100
Head (dir)*			0.53	16.3	19.5	0.05	231					

*Assay's includes -0.8mm fines that were not assayed.

Combined Products

Sample	Wt. (kg)	Wt. %	Assay, g/t, %					Distribution, %				
			Cu	Pb	Zn	Au	Ag	Cu	Pb	Zn	Au	Ag
DMS 3rd Pass Sink	324.0	55.4	0.91	24.3	31.1	0.05	358	92.3	96.6	94.7	75.6	93.1
DMS 2nd Pass Sink	342.5	58.5	0.87	23.1	29.6	0.05	341	93.0	97.0	95.3	77.3	93.6
DMS 1st Pass Sink	368.3	62.9	0.81	21.5	27.7	0.05	319	93.5	97.3	95.8	79.7	94.1

Other Pb-Zn Project – Central America

The Pb-Zn mine in Central America was in the process of a mine expansion, and higher tonnages of lower grade feed were reporting to the mill, thereby affecting performance. DMS was investigated to determine its potential to increase the head grade to the mill and improve performance. The first stage of the testwork involved HLS testing that compared two grind sizes, -1/2" and -1/4", and determined the optimal SG for separation. The two crush sizes were found to perform similarly, and the -1/2" case was selected for further testing. The initial HLS test was performed at a starting SG of 3.2, but the weight rejection was lower than expected, and it was suspected that a dense gangue mineral was present. Thus, the 3.2 SG sink was processed further at higher SGs of 3.8 and 3.5 with the goal of a higher mass rejection. The results from the HLS testing are summarized in Figure 10. The target for mass rejection was 15% and an SG of separation of 3.0 was selected for DMS operation.

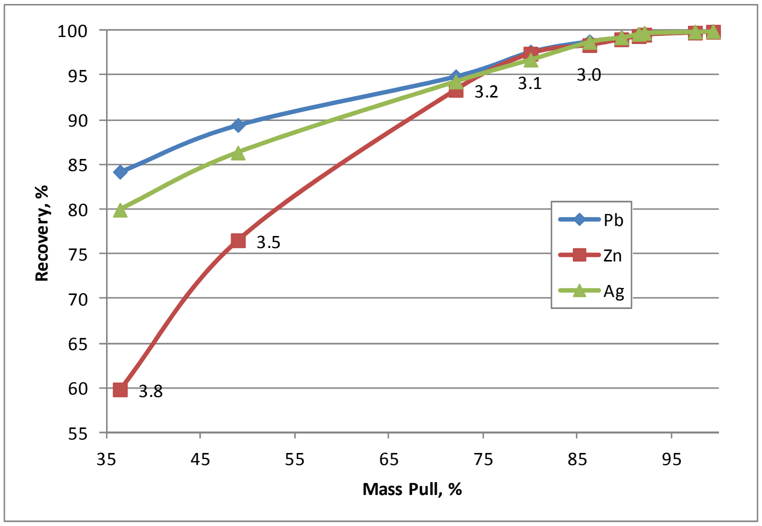

Figure 10 – HLS Test Results

The DMS process was tested on a bulk sample, operated at a separating SG of 3.0, to confirm the results from the HLS test. The results are summarized in Table 10. The mass rejection target of 15% was attained, at 16.3%, and recoveries for lead, zinc, and silver were similar to the HLS testing results. Higher mass rejections and, in turn, upgrading is possible at higher separation SG, but this may reduce the overall recovery.

Table 10 –DMS Results

Product	Wt. (kg)	Wt %	Assays, %, g/t			Distribution, %		
			Pb	Zn	Ag	Pb	Zn	Ag
Sink	179.6	59.8	1.71	4.10	48.3	65.3	67.4	56.5
Float	48.8	16.3	0.13	0.51	7.4	1.3	2.3	2.4
Fines	71.7	23.9	2.19	4.63	88.2	33.4	30.4	41.2
Head (Calc)	300.1	100	1.57	3.64	51.2	100	100	100
Head (Dir)			1.43	3.14	40.3			

	Wt %	Assays, %, g/t			Distribution, %		
		Pb	Zn	Ag	Pb	Zn	Ag
Comb Sink+ Fines	83.7	1.85	4.25	59.7	98.7	97.7	97.6

Sulphide Gold Ores – Banks Island Gold, British Columbia, Canada

The Banks Island Gold project is comprised of three main ore deposits: the Tel, Bob and Discovery Zones. Samples from each deposit were tested at SGS. Two of the deposits, Bob and Discovery, were subjected to both HLS and DMS testing. The mineralogical characteristics of the two deposits were distinctly different, which caused different HLS and DMS responses. Both samples were crushed to 100% passing 1/2" and screened at 500 µm prior to being fed to the DMS cyclone. The results from DMS processing of the Bob and Discovery Zone samples are summarized in Table 11 and Table 12, respectively, and compared against the HLS test results in Figure 11. Overall, the results from DMS processing were very good, attaining high gold recoveries with high mass rejections.

Table 11 – DMS Mass Balance, Bob Zone

Sample	Wt (kg)	Wt %	Assay, g/t			Distribution, %		
			Au	Ag	S	Au	Ag	S
DMS Sink	14.7	38.3	24.6	81.6	11.4	89.9	81.1	84.5
DMS Float	20.3	52.9	0.88	6.2	0.68	4.4	8.5	7.0
Fines	3.4	8.7	6.78	46.0	5.04	5.7	10.4	8.5
Head (Calc)	38.4	100	10.5	38.6	5.17	100	100	100
Head (Dir)			13.4	45.8	5.40			

Sample	Wt %	Assay, g/t			Distribution, %		
		Au	Ag	S	Au	Ag	S
Sink + Fines (calc)	47.1	21.3	75.0	10.2	95.6	91.5	93.0
Sink + Fines (dir)		21.7	73.0	10.5			

Table 12 – DMS Mass Balance, Discovery Zone

Sample	Wt (kg)	Wt %	Assay, g/t, %			Distribution, %		
			Au	Ag	S	Au	Ag	S
DMS Sink	45.3	58.9	8.63	10.0	7.72	84.2	79.6	83.3
DMS Float	23.1	30.0	0.48	1.7	0.63	2.4	6.9	3.5
Fines	8.5	11.1	7.31	9.0	6.53	13.4	13.5	13.2
Head (Calc)	76.9	100	6.04	7.4	5.46	100	100	100
Head (Dir)			9.41	6.8	5.74			

Sample	Wt %	Assay, g/t		Distribution, %			
		Au	Ag	S	Au	Ag	S
Sink + Fines (calc)	70.0	8.42	9.8	7.53	97.6	93.1	96.5
Sink + Fines (dir)		10.5	11.3	7.98			

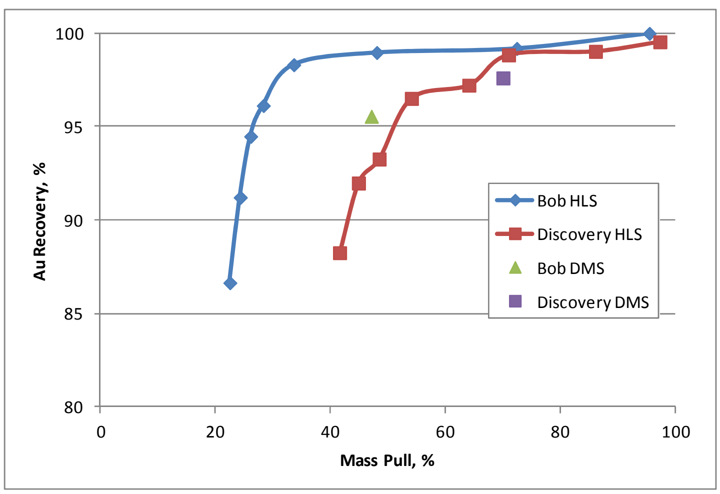

Figure 11 – Banks Island Gold DMS Results

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