Metallurgical Testing of Iron Ore from the Labrador Trough

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SGS Minerals
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Iron Ore Characterisation

- Chemistry
- Mineralogy
- Comminution
- Physical Separation
  - Gravity
  - Magnetic
  - Flotation
Advanced Exploration

Iron Ore Characterisation

- Chemistry
- Mineralogy
- Comminution
- Physical Separation

# Samples: +++

Major, Trace, Element Metal Content

Magnetic Content

- Satmagan
- Magnetic
- Gravity
- Heavy Liquid (HLS)
- Davis Tube (DT)
Minerals of different density are separated by floating or sinking in a heavy liquid of fixed density.

Specific gravity of the fluid is in the range 2.95-3.33.

Performed on different size fractions to find the optimum grind size to maximize Fe content of the concentrate...

... or to find where the Fe losses occur in Wilfley table tailings
A glass separation tube is positioned between poles of a powerful electromagnet at an angle of ~45° (adjustable) that is agitated back and forth and rotated by a motorized system.

Magnetic particles are collected inside the tube in the zone of intense magnetism and all non-magnetic minerals are washed out.

Performs a perfect magnetic separation for concentrate quality assessment and magnetite content estimation.
- Study the effect of grind on concentrate quality

<table>
<thead>
<tr>
<th>Head Grade (%)</th>
<th>Feed Size</th>
<th>Concentrate Grade (%)</th>
<th>Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fe</td>
<td>SiO₂</td>
<td>Sat</td>
</tr>
<tr>
<td>31.9</td>
<td>54.2</td>
<td>37.1</td>
<td></td>
</tr>
<tr>
<td>31.9</td>
<td>54.2</td>
<td>37.1</td>
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<tr>
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<td>54.2</td>
<td>37.1</td>
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<td>23.6</td>
<td>66.0</td>
<td>26.6</td>
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<tr>
<td>25.6</td>
<td>62.8</td>
<td>29.2</td>
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<tr>
<td>25.6</td>
<td>62.8</td>
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</tr>
</tbody>
</table>
Measures the magnetite content of iron ore sample from the magnetic susceptibility of the sample

Satmagan value (or Recoverable Fe) can be compared and calibrated with Davis Tube Results
Iron Ore Characterisation

Advanced Exploration

- Chemistry
- Mineralogy
- Comminution
- Physical Separation
- Qemscan

# Samples: +
- Examine staged crushed, sized fractions from 3000 um to -75 um
- Provides bulk modal mineralogy (BMA) and iron deportment
- PMA provides mineral release curves and grind size targets
1. Direct Shipped Ore (DSO)
2. Metamorphic Specularite-Magnetite
3. Taconite

Bulk Mineral Analysis (BMA)
Free and Liberated classes only

Red : DSO  
Blue : Hem-Mag  
Green : Tac
Particle Mineral Analysis (PMA)

- Size-by-size grade-recovery curve
- Fe recovery against silica content
Old Scoping Study Practice

- Master composite sample
- Designed on a minimum throughput
- One Single Average Value for next 5 years: 2,850 TPH

2 different hardneses:
- Moderate
- Soft
- Very Soft

2 different minerals:
- Hematite
- Magnetite

Plant Throughput (TPH):

Year
1  2  3  4  5

1,000  2,000  3,000  4,000
- Master composite samples
- Some variability composite samples
PEA/Scoping Study

Iron Ore Characterisation

- Chemistry
- Mineralogy
- Comminution
- Physical Separation

Master Composite
- Bond Low Energy Impact Test (CWI)
- JK Drop-weight Test (DWT)
- Bond Rod and Ball Mill Work Index (RWI/BWI)

Variability Composite
- SAG Power Index (SPI)

# Samples: +
Consists of two pendulum hammers striking equal blows simultaneously on opposite sides of specimen. Height of pendulum is raised until sufficient energy to break specimen is reached.

Determines the Crusher Work Index (CWI) in kWh/t used to calculate the net power requirement for sizing crushers.

Single specimen

20 rocks of 50-75 mm (approx. 10 kg)
JK Drop-weigh Test

Developed by Julius Kruttschnitt Mineral Research Center (JK MRC)

Single particle (impact) and Tumbling (abrasion)

Rocks of 13-63 mm (approx. 75 kg)

- Consists of dropping a variable weight onto different size rock specimens from various height.

- Measures: 1) Appearance function (or breakage pattern) for five coarse size fractions at different energy inputs (0.1 to 2.5 kWh/t); 2) Abrasion resistance of 37.5 to 53 mm particles; 3) Ore density of 30 specimens in water.

- Impact and abrasion reduces to three parameters: A, b and ta used for JKSimMet software for AG or SAG Milling.

- Extensive JK database
For rod mill test, the test is a dry grindability test performed in a standard rod mill and run in closed circuit with a screen, with a circulating load of 100% until steady state is reached. The closed-screen size ranges from 4 to 65 Mesh (typical is 14 Mesh).

For ball mill test, the test is a dry grindability test performed in a standard ball mill and run in closed circuit with a screen with a circulating load of 250% until steady state is reached. The closed-screen size ranges from 65 to 270 Mesh (typical is 100 Mesh).

Measure net gr/rev created during each cycle and converted to Work Index in kWh/t, which is used to calculate the net power requirements of rod or ball mills (primary or secondary) with Bond’s Third Theory of Comminution.
- Master composite samples
- Some variability composite samples
- Average throughput will be 2,854 TPH
- Short fall in Year 1 and 4 vs Target

**PEA/Scoping Study**

- 2 different hardnesses:
  - Moderate Soft
  - Very Soft
- 2 different minerals:
  - Hematite
  - Magnetite

**Plant Throughput (TPH)**

- Year 1: 2,000 TPH
- Year 2: 3,000 TPH
- Year 3: 3,000 TPH
- Year 4: 2,000 TPH
- Year 5: 2,000 TPH

Red line indicates target throughput.
Pre-Feasibility

- Variability samples
- Variability composite samples

2 different hardnesses

2 different minerals

Very Soft
Moderate Soft
Soft
Very Soft

Hematite
Magnetite

VS Hem
Soft Hem
MS Mag
Soft Mag
Iron Ore Characterisation

Pre-Feasibility

Chemistry

Mineralogy

Comminution

Physical Separation

Variability Samples

SAG Power Index (SPI)

SAG Mill Comminution (SMC)

Mod Bond Test (MBI)

Master or Variability Composite

MacPherson Autogenous (AWI)

# Samples: ++
Developed by SGS & J. Starkey

Batch Test

5 kg of 40-65 mm rocks or dill core

Measure Variability

- Develop to use a simple power-based model like the Bond Work Index
- Measures the time in minutes required to grind a 2 kg sample from 80% minus ½ inch (12.7 mm) to 80% minus 10 Mesh (1.7mm) in the 12” x 4” SPI Test Mill.
- Link to ore hardness determines power for AG or SAG milling which was calibrated from existing plant operations (277 surveys from 30 concentrators)
- Over 22,000 SPI samples processed on wide variety of ore in SGS database
- Extensive quality assurance system
SMC Test

Developed by Steve Morrell

Abbreviated DWT – faster and cost effective

Single particle

30 kg of Crushed Rocks or ¼ Drill Core Sample

- Performed on one single size from one of the following size fractions:
  1. +26.5 - 31.5 mm (Recommended)
  2. +19.0 - 22.4 mm
  3. +13.2 - 16.0 mm (issue with limited quantity)

- Generates the Drop-Weight Index (DWI) in kWh/m³ which is directly related to $A x b$

- Provides also the Mia (AG/SAG), Mih (HPGR) and Mic (Crusher) work index for power-based calculation in addition to approximate values of $A$, $b$ and $ta$. 
Developed by SGS
Locked Cycle
Stage-crushed feed:
1.2 kg of -3.36 mm (6 Mesh)
Fast and cost effective with less sample

- Open circuit dry batch test using only 1.2 kg of - 3.36 mm sample in a standard Bond ball mill
- Used for target screen size of 65 to 200 mesh
- Calibrated against the standard Bond Ball Mill Work Index (1:10)
- Large SGS database
- Extensive quality assurance system
MacPherson Autogenous Test

Developed by Arthur MacPherson
Continuous
Small scale SAG mill
Requires 175kg of 32 mm

- Continuous test performed in a 18 inch mill with 8% ball charge in closed circuit with a 14 mesh screen. The 14 mesh oversize is sent back to the mill.
- Fully automated to regulate the feed rate and mill level at 25% volume. Test is run for a minimum of six hours and one hour after reaching steady state.
- MacPherson Autogenous Work Index (AWI) is calculated from power draw, feed rate and product size distribution.
- Large SGS database
Iron Ore Characterisation

Chemistry

Mineralogy

Comminution

Physical Separation

Gravity

Magnetic

Flotation

Wilfley Table
Material is separated by combining longitudinal oscillations with a perpendicular water flow across the table. Particles segregate and follow a parabolic path based upon their specific gravity.

Many adjustable parameters: motor speed, stroke length, water addition rate and angle impact separation of different minerals.

Generate three products: concentrate, middlings and tails. Middlings are circulated until the fresh feed runs out.

Can be used to generate a grade-recovery curve by taking multiple concentrate cuts.
## Wilfley Table Results

| Stream        | Weight | Assays, % |           |          |           |          |          |          |          |          | LOI | Sum | Fe | Sat |
|---------------|--------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|------|-----|----|-----|
|               | kg     | %         | SiO₂      | Al₂O₃     | Fe₂O₃     | MgO       | CaO       | Na₂O      | K₂O       | TiO₂     | P₂O₅ | MnO | Cr₂O₃ | V₂O₅ |
| Wilfley Conc  | 9.03   | 33.1      | 5.22      | 0.17      | 98.3      | 0.05      | 0.03      | 0.04      | < 0.01    | 0.02     | 0.04 | 0.08 | < 0.01 | < 0.01 |
| Wilfley Tails | 18.3   | 68.9      | 72.2      | 0.14      | 26.5      | 0.19      | 0.06      | < 0.01    | 0.02      | < 0.01   | 0.07 | 0.08 | 0.02  | < 0.01 |
| Calc. Head    | 27.3   | 100       | 50.1      | 0.15      | 50.2      | 0.14      | 0.05      | -         | -         | -       | 0.06 | 0.08 | -     | -     |
| Direct Head   |        |           | 50.9      | 0.14      | 49.4      | 0.14      | 0.03      | < 0.01    | < 0.01    | 0.01     | 0.06 | 0.08 | < 0.01 | < 0.01 |

| Stream        | Weight | Distribution, % |           |          |           |          |          |          |          |          | LOI | Sum | Fe | Sat |
|---------------|--------|-----------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|------|-----|----|-----|
|               | kg     |                 | SiO₂      | Al₂O₃     | Fe₂O₃     | MgO       | CaO       | Na₂O      | K₂O       | TiO₂     | P₂O₅ | MnO | Cr₂O₃ | V₂O₅ |
| Wilfley Conc  | 9.03   |                 | 3.45      | 37.5      | 64.7      | 11.5      | 19.8      | -         | -         | -       | 22.0 | 33.1 | -     | -     |
| Wilfley Tails | 18.3   |                 | 96.6      | 62.5      | 35.3      | 88.5      | 80.2      | -         | -         | -       | 78.0 | 66.9 | -     | -     |
| Calc. Head    | 27.3   | 100.0           | 100.0     | 100.0     | 100.0     | 100.0     | 100.0     | -         | -         | -       | 100.0 | 100.0 | -     | -     |
Iron Ore Characterisation

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- Comminution

Physical Separation

- Gravity
- Magnetic
- Flotation

LIMS
LIMS – Low Intensity Magnetic Separation

- Materials is subject to a low-intensity magnetic field (~900-1000 Gauss)
- More representative results of industrial process than Davis Tube
- LIMS weight recovery function of magnetite content and grind size.
- Two to three stages of LIMS are typically required
- Magnetite concentrate may require regrinding and further LIMS stages to achieve saleable concentrate quality

Continuous drum
Varies (> 1kg)
Iron Ore Characterisation

- Chemistry
- Mineralogy
- Comminution

Physical Separation

- Gravity
- Magnetic
- Flotation

Rougher & Cleaner Batch Test
Locked-cycle Test (LCT)
Mineral Flotation Test (MFT)
Rougher & Cleaner Test

Batch

Requires 1 or 2 kg – 10 Mesh
Done on Iron or LIMS concentrate

- Consist of floating 1 or 2 kg of ore in Denver D1 4.4L cell at 35% solids for rougher test and 10-20% for cleaner test.

- Rougher test: Produce a concentrate/tail sample for downstream. Examine the effect of primary grind size, pH and reagent scheme.

- Cleaner test: Examine the effect of cleaner configuration and regrind size. Goal is to increase concentrate quality i.e. lower the silica or sulfide content.

- For iron ore, flotation is inversed (float the silica or sulfide and tails are the iron concentrate)
Variability samples

Average throughput will be 2,845 TPH

Short fall in Year 1, 4 and 5 versus Target

Pre-Feasibility

2 different hardnesses

2 different minerals

VS Hem
Hematite

Soft Hem
Magnetite

Moderate
Soft

Very
Soft

MS Mag

Soft Mag
Might require more variability samples (1 sample per Mt)
Bulk and ROM samples

2 different hardnesses
- Very Soft
- Soft
- Moderate
- Very

2 different minerals
- Hematite
- Magnetite

VS Hem
Soft Hem
MS Mag
Soft Mag
Feasibility

Iron Ore Characterisation

- Chemistry
- Mineralogy
- Comminution
- Physical Separation

Variability Samples
- SAG Power Index (SPI)
- SAG Mill Comminution (SMC)
- Mod Bond Test (MBI)

# Samples: +++
Ore Hardness + Geological Info ➔ Geostat ➔ Hardness Estimate for Each Block ➔ Block Model

Variogram

- Variance vs. distance m
- Data, model, sill

Geostatistical Distribution
Geometallurgical Dataset

Table 3:
- 0.001 ≤ SPI < 5.000
- 5.000 ≤ SPI < 10.000
- 10.000 ≤ SPI < 15.000
- 15.000 ≤ SPI < 25.000
- 25.000 ≤ SPI < 35.000
- 35.000 ≤ SPI ≤ 100.000

High Ore Variability

Known Ore Feed
Reduced Variability
Feasibility

- Might require more variability samples
  (1 sample per Mt)
- Bulk and ROM samples
- Back to original average target of 2,850 TPH

2 different hardnesses
- Very Soft
- Soft
- Moderate
- Very Soft

2 different minerals
- Hematite
- Magnetite

Might require more variability samples
(1 sample per Mt)
Bulk and ROM samples
Back to original average target of 2,850 TPH
Iron Ore Characterisation

Chemistry
Mineralogy
Comminution
Physical Separation

Gravity
Magnetic
Flotation

Bulk/ROM Samples
Pilot Plant
- Fully integrated flowsheet from grinding to gravity circuit, LIMS and/or flotation circuits
- Vendor testing to produce marketable iron ore concentrate and representative tailings for vendor and environmental testing
Pilot Plant Testing Consideration

- Unusual Ore Behaviour
  - Significantly different grindability characteristics (blending)
  - Fall outside ‘normal range’, such as extremely soft and hard ores

- Unusual Circuit, or Operating Conditions
  - Single-stage AG (common in iron ore industry)
  - Introduction of metallurgical separation units such as coarse magnetic separation
  - Operation conditions falling outside typical range

- SAG Milling
  - Very ore dependant
  - Very sensitive to feed size distribution
  - Check if enough coarse rock to grind the finer ones without producing excessive critical size build up?

- Should be Conducted when in Doubt
Integrated Geometallurgical Simulator (IGS) is a tool that simulates comminution and flotation circuits either separately or as combined processes.
7 years of forecasting for one major iron ore producer
Better model accuracy since 2008