Modeling of Taconite Comminution and Liberation Simulation

METE 6010
Modeling and Simulation of Mineral Processing Plants
Module 8

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Problem Description

This problem originated from a research program sponsored by Minnesota Power.

The grinding circuit of the Fairlane Plant, located at mile 4 on county road 17, south of Eveleth, was chosen to be the subject of this study. The plant processes a blend of Taconite ore that is mined by Eveleth Mines at the Thunderbird North Mine, from four mining horizons denominated Middle Upper Cherty, Lower Upper Cherty, Top Lower Cherty and Bottom Lower Cherty, which present a magnetite content above cutoff grade. The plant produces pellets containing not more than 5.30% SiO_2 and 78 to 82% of the particles in the pellets should pass the 45 microns screen.

The study carried out in the Fairlane Plant provided with an excellent opportunity to test, in practice, the procedures and models for liberation. The preliminary characterization of the mineralogical texture of the ore was carried out by fractionation of a narrow size sample obtained from the plant into a few grade intervals. This procedure provided enough information to estimate the density of the two relevant phases in the ore, Magnetite and Chert, and, through the measurement of interphase area per unit volume of phase, a good estimate of the geometrical texture parameter φ, at that size range, was obtained.

The bulk of the experimental work consisted of the measurement of the size spectra, by standard sieving, and the liberation spectra, by image analysis, in every stream in the secondary grinding circuit of the Fairlane plant. These data were used to develop appropriate models for use with MODSIM, and to test the application of the liberation models.

Flowsheet Description

The simplified flowsheet of the plant's secondary grinding circuit is shown in Figure 1. The grinding circuit feed is mainly the concentrate stream of Cobber Magnetic Separators, which concentrate Rod Mill discharge in the primary grinding stage. For this particular circuit, Ball Mill grinding is performed in closed circuit with both classification and concentration. The Ball Mill is 12.81 meters long by 5.185 meters in diameter (42 by 17 feet), and is equipped with rectangular lifters that are 76.2 millimeters high. Grinding media is fed to the Ball Mill at a rate of 2724 kilograms (6000 pounds) per day. The nominal mill charge represents 36% filling by volume, and the grinding media is constituted by 60% of 50.8 millimeters (2 inches) balls and 40% of 38.1 millimeters (1.5 inches) balls. The Ball Mill revolves at 12 *RPM*, which is 64% of critical speed.

Most of the concentration is carried out in wet magnetic drum separators which are fed directly with the ball mill discharge stream. This separation is designated as Rougher, and its concentrate/magnetic stream is the major component of the cyclone feed stream. The Rougher tails are subject to further concentration, and the concentrate of the Scavenger separation is returned to the grinding circuit through the cyclone feed stream.

The major classification stage is performed in four KREBS hydrocyclones assembled in a cluster. The hydrocyclones are 660 millimeters (26 inches) in diameter. The circular inlets measure 241.3 millimeters (9.5 inches). Vortex finder diameter is 279.4 millimeters (11 inches) and the spigot-vortex finder distance measures 2082.8 millimeters (82 inches). Spigot diameter is 114.3 millimeters (4.5 inches). The cyclone underflow is recirculated to the ball mills and the cyclone overflow constitutes the product of the secondary grinding circuit. The cyclone overflow is fed to a hydro-separator, and the concentrate product of the hydro-separator is screened in fine, double deck, vibrating screens, with primary opening of 150 microns (0.006 inches) and secondary opening of 100 microns (0.004 inches). The screens oversize is split in two fractions. One fraction is fed to a re-grind circuit. The other fraction, representing approximately 5/6 of the screens oversize, is returned to the grinding circuit through a wet magnetic drum separator. The major role of this separation stage is dewatering, and a magnetic/concentrate stream is produced that contains mostly solids. This is then recirculated to the ball mills. The tail stream is mostly water, which is recirculated to the cyclones. This separation stage is designated as the Dewatering Drum.

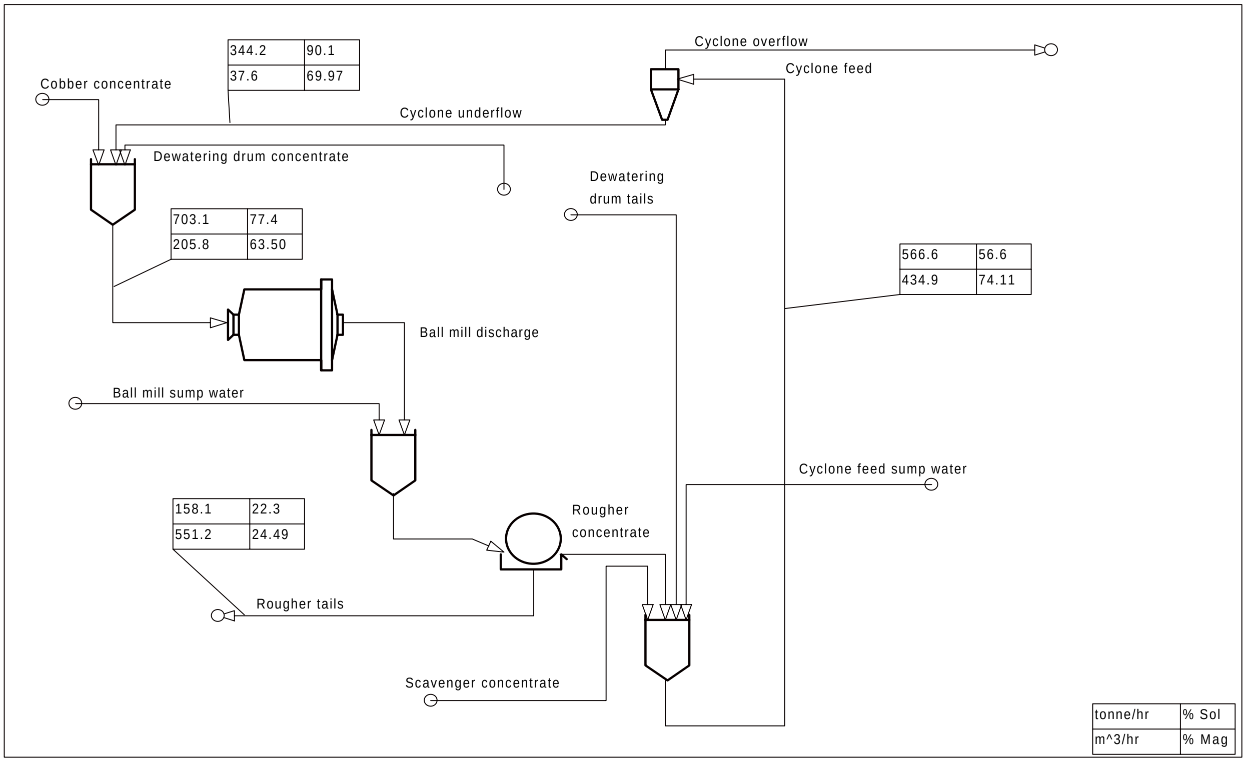

Figure 1 MODSIM simulation of the Fairlane Plant grinding circuit.

Simulation Data

The experimental work started with the sampling of the Fairlane Plant secondary grinding circuit streams. This was followed by solids contents measurement, which was the only measurement carried out at the plant site. The particle size distributions were carefully determined in each stream and a sample from each size range below 1000 microns was separated for image analysis. These were mounted, ground, polished and coated. A set of images from each specimen was acquired. The images were processed for chord length distribution and linear grade distribution measurements. A larger narrow size sample from the Ball Mill Discharge was used for texture and phase characterization by fractionation.

Sampling of the Fairlane Plant grinding circuit was carried out on 11/16/1993. The selected streams were sampled in the order given below, according to the location of the sampling points in the plant, to minimize the time necessary for sampling. The corresponding abbreviated names, as used in the tables and figures, are listed along the stream names.

- Cobber Concentrate, Cob.Conc.

- Cyclone Feed, Cyc.Feed
- Cyclone Underflow, Cyc.Under
- Cyclone Overflow, Cyc.Over
- Dewatering Drum Concentrate, D.D.Conc.
- Dewatering Drum Tails, D.D.Tails
- Ball Mill Discharge, B.M.Disch.
- Rougher Concentrate, Rough.Conc.
- Rougher Tails, Rough.Tails
- Scavenger Concentrate, Scav.Conc.

The samples were collected with sample cutters in all streams. Three rounds were carried out following the sequence above, with no time interval between rounds. Each round consumed an average 20 minutes time. The samples from each round were added, producing one composite sample for each stream. The pressure head in the cyclone cluster was measured for each round. There are four cyclones in the cluster and two cyclones were operating at sampling time while the other two were standing by. Pressure heads in each round were 843.6, 949.1 and 949.1 g cm^{-2} (12.0, 13.5 and 13.5 PSIG), in that order. The samples were collected from open streams, and in most cases the sample cutter used was long enough so that the sample obtained was representative of the entire stream. The exception was the sample collected at the ball mill discharge, where the flow rate was too high so that the cutter could not be held steadily during sampling, neither could it be inserted deeply enough into the stream. However, an effort was made to obtain the best possible sample. The Cyclone Feed sample was drawn with a probe from the cluster feed head. The sampling at that particular point is routinely performed at the plant, and the probe depth to obtain a representative sample from well-mixed slurry had previously been established.

Each sample was immediately weighed after sampling, and the wet weight noted. The samples were then filtered, dried and cooled to room temperature. The solids weight was then measured and noted. The solids content by weight, for each stream, is shown in Table 1. The samples were then bagged and labeled, completing the work at the plant site.

Table1 Measured solids content in the sampled streams

Stream	Weight Wet, g	Weight Dry, g	Solids, %
Cobber Concentrate	6647.7	4224.0	63.54
Cyclone Feed	2229.5	1091.5	48.96
Cyclone Underflow	4536.4	3627.0	79.95
Cyclone Overflow	5763.6	1833.0	31.80
Dewatering Drum Conc.	3463.6	2104.5	60.76
Dewatering Drum Tails	13500.0	562.5	4.17
Ball Mill Discharge	7247.7	4954.6	68.36
Rougher Concentrate	4472.7	2951.0	65.98
Rougher Tails	9311.4	562.5	6.04
Scavenger Concentrate	2632.0	213.5	8.11

Taconite Characterization - Size Analysis and Liberation Measurements

The samples were separated in narrow size intervals by screening. This was carried out in a disliming, wet screening stage, followed by dry screening. Each sample was first wet screened at 150 microns. The undersize fractions, (-150 microns), were wet screened with a 38 microns sieve, until no particles passed through. After filtering and drying, the dislimed fractions, (+38 microns), were dry screened with the aid of a ROTAP™, into several narrow size fractions. Each narrow size sample was weighted and bagged individually with the proper identification label, to follow specimen preparation for image analysis. The resulting size distributions and the size intervals used are shown in Table 2. The size distributions around the two major nodes in the circuit, namely the rougher concentration and the hydrocyclone classification, must be consistent so that the units can be parameterized properly. The raw measured size distributions are not exact, and the error is due to sampling inaccuracy that is inherent to sampling high flowrate streams in industrial plants. Material balance smoothing was carried out around the two nodes using MASSBAL, a material balance smoothing package developed by Kenwalt Systems. The amount of smoothing required was minimal, indicating that the sampling procedure was good. The resulting smoothed size distributions in the corresponding streams are shown in Table 3.

The grade distribution in each feed stream sample were measured by image analysis, and corrected for stereological bias. These grade distributions are shown in Tables 4 through 7, and are required for simulation in MODSIM.

Finally, the liberation spectra were also measured in all internal streams. Since these are not feed streams, they are not required for MODSIM simulation. Nevertheless, the measured overall liberation spectrum in each internal stream can be entered in MODSIM for comparison with simulation results. These spectra are shown in Table 8.

Table 2 Measured cumulative size distributions in the sampled streams

Size, microns		Fairlane Plant grinding circuit sampled streams									
Upper	Lower	B.M.	Cob.	Cyc.	Cyc.	Cyc.	D.D.	D.D.	Rough.	Rough.	Scav.
9600	8000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
8000	6300	1.0000	0.9991	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
6300	5600	0.9999	0.9955	0.9996	1.0000	0.9994	1.0000	1.0000	1.0000	1.0000	1.0000
5600	4750	0.9998	0.9922	0.9996	1.0000	0.9992	1.0000	1.0000	0.9997	1.0000	1.0000
4750	3350	0.9995	0.9836	0.9996	1.0000	0.9988	1.0000	1.0000	0.9995	1.0000	1.0000
3350	2800	0.9984	0.9357	0.9993	1.0000	0.9966	1.0000	1.0000	0.9981	0.9993	1.0000
2800	2000	0.9969	0.8872	0.9986	1.0000	0.9937	1.0000	1.0000	0.9968	0.9991	1.0000
2000	1400	0.9925	0.7742	0.9967	1.0000	0.9844	1.0000	1.0000	0.9921	0.9982	1.0000
1400	1000	0.9831	0.6538	0.9914	0.9999	0.9661	0.9998	1.0000	0.9832	0.9964	0.9995
1000	710	0.9691	0.5356	0.9828	0.9997	0.9403	0.9993	0.9997	0.9703	0.9939	0.9981
710	500	0.9466	0.4340	0.9662	0.9993	0.8988	0.9983	0.9993	0.9497	0.9898	0.9967
500	355	0.9150	0.3606	0.9445	0.9987	0.8429	0.9967	0.9986	0.9206	0.9841	0.9953
355	250	0.8699	0.2986	0.9037	0.9963	0.7663	0.9914	0.9956	0.8762	0.9681	0.9910
250	180	0.8103	0.2478	0.8398	0.9901	0.6671	0.9813	0.9834	0.8119	0.9367	0.9858
180	106	0.7304	0.2116	0.7620	0.9752	0.5419	0.9520	0.9114	0.7317	0.8932	0.9715
106	75	0.5560	0.1668	0.5883	0.8862	0.3308	0.7607	0.5209	0.5622	0.7826	0.7973
75	53	0.3151	0.1379	0.4442	0.7692	0.1414	0.5063	0.2849	0.3725	0.6892	0.5662
53	45	0.2524	0.1107	0.3290	0.5979	0.0925	0.3610	0.1908	0.2758	0.5991	0.4025
45	38	0.2432	0.1003	0.2915	0.5426	0.0780	0.3262	0.1705	0.2510	0.5615	0.3441
38	0	0.2208	0.0805	0.2496	0.4908	0.0573	0.2967	0.1463	0.2165	0.5285	0.2990

Table 3 Adjusted cumulative size distributions in the streams corresponding to the two main circuit nodes

Size, microns		Cumulative Size Distributions in Stream					
Upper	Lower	Cyc. Feed	Cyc. Over	Cyc. Under	B.M. Disch.	Rough. Conc.	Rough. Tails
9600	8000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
8000	6300	1.0000	1.0000	0.9999	1.0000	1.0000	1.0000
6300	5600	0.9996	1.0000	0.9993	1.0000	1.0000	1.0000
5600	4750	0.9996	1.0000	0.9993	0.9998	0.9982	1.0000
4750	3350	0.9996	1.0000	0.9993	0.9996	0.9980	1.0000
3350	2800	0.9993	1.0000	0.9987	0.9983	0.9966	0.9993
2800	2000	0.9984	1.0000	0.9972	0.9971	0.9953	0.9991
2000	1400	0.9961	1.0000	0.9932	0.9926	0.9905	0.9982
1400	1000	0.9895	0.9999	0.9822	0.9840	0.9813	0.9964
1000	710	0.9790	0.9997	0.9645	0.9715	0.9679	0.9939
710	500	0.9593	0.9994	0.9312	0.9516	0.9464	0.9897
500	355	0.9333	0.9989	0.8875	0.9234	0.9161	0.9840
355	250	0.8884	0.9966	0.8128	0.8802	0.8705	0.9679
250	180	0.8233	0.9906	0.7064	0.8182	0.8057	0.9364
180	106	0.7412	0.9763	0.5769	0.7395	0.7238	0.8926
106	75	0.5697	0.8903	0.3457	0.5709	0.5500	0.7813
75	53	0.4121	0.7804	0.1547	0.3797	0.3500	0.6872
53	45	0.3082	0.6047	0.1009	0.2829	0.2602	0.5973
45	38	0.2752	0.5474	0.0849	0.2739	0.2461	0.5619
38	0	0.2394	0.4937	0.0617	0.2430	0.2155	0.5291

Table 4 The measured volumetric grade distributions, by weight, in the Cobber Concentrate stream

Conditional, on size, volumetric grade distributions, weight % Size intervals in microns.											
volumetric grade interval, %	-1000 +710	-710 +500	-500 +355	-355 +250	-250 +180	-180 +106	-106 +75	-75 +53	-53 +45	-45 +38	-38
0	0.00	0.00	0.08	0.00	0.00	0.41	5.12	7.34	6.51	2.45	14.13
0 - 10	0.09	0.09	0.01	3.54	11.94	10.86	7.97	4.18	8.00	6.59	4.08
10 - 20	1.08	0.03	2.44	6.68	3.01	5.98	4.60	4.87	6.77	2.97	3.04
20 - 30	26.62	25.86	45.49	22.42	12.25	8.83	6.69	4.32	5.20	0.00	0.00
30 - 40	45.84	58.60	20.53	31.95	19.88	9.26	3.84	0.35	0.02	0.14	1.19
40 - 50	24.98	7.48	23.94	14.83	18.09	12.22	0.00	0.95	0.00	0.38	0.00
50 - 60	1.13	7.59	3.92	13.69	4.25	5.53	0.41	0.06	0.05	0.17	0.03
60 - 70	0.11	0.20	3.55	6.56	5.86	5.28	0.17	0.07	0.05	0.83	0.09
70 - 80	0.02	0.06	0.01	0.29	8.26	9.49	8.76	0.00	0.48	2.84	0.00
80 - 90	0.07	0.09	0.00	0.03	16.37	25.95	26.27	26.01	13.68	10.31	12.58
90 - 100	0.05	0.00	0.00	0.00	0.08	6.19	36.16	51.06	59.21	61.08	60.87
100	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.79	0.01	12.24	4.00

Table 5 The measured volumetric grade distributions, by weight, in the Dewatering Drum Concentrate stream

Conditional, on size, volumetric grade distributions, weight % Size intervals in microns.										
volumetric grade interval, %	-1000 +710	-710 +500	-500 +355	-355 +250	-250 +180	-180 +106	-106 +75	-75 +53	-53 +45	-45 +38	-38
0	0.03	0.00	0.03	0.00	0.96	0.01	4.52	1.35	0.53	0.24	3.18
0 - 10	0.08	0.10	0.07	5.53	21.18	15.00	5.30	3.12	0.21	0.39	0.00
10 - 20	32.53	6.73	3.92	5.22	22.64	31.47	4.96	1.31	4.70	0.45	0.60
20 - 30	65.47	58.90	38.12	39.32	43.58	24.95	8.27	6.01	1.08	1.55	0.00
30 - 40	1.01	32.35	48.76	39.76	9.31	22.93	4.19	2.06	1.54	1.93	0.15
40 - 50	0.13	1.18	8.55	9.59	1.69	4.81	24.41	2.00	3.92	0.18	0.12
50 - 60	0.14	0.14	0.09	0.00	0.41	0.05	4.72	0.00	1.53	0.08	0.09
60 - 70	0.15	0.15	0.16	0.22	0.15	0.00	5.14	0.03	1.58	0.04	0.35
70 - 80	0.15	0.16	0.14	0.29	0.07	0.00	6.22	4.40	2.04	0.28	0.21
80 - 90	0.15	0.14	0.16	0.06	0.00	0.03	23.30	19.88	2.57	16.35	18.40
90 - 100	0.16	0.15	0.00	0.00	0.01	0.01	8.98	48.22	80.18	42.73	56.85
100	0.00	0.00	0.00	0.00	0.00	0.74	0.00	11.62	0.13	35.79	20.06

Table 6 The measured volumetric grade distributions, by weight, in the Dewatering Drum Tails stream

Conditional, on size, volumetric grade distributions, weight % Size intervals in microns.									
volumetric grade interval, %	-500 +355	-355 +250	-250 +180	-180 +106	-106 +75	-75 +53	-53 +45	-45 +38	-38
0	6.77	63.71	69.25	70.86	39.51	35.22	36.85	25.32	67.92
0 - 10	70.12	12.95	24.27	14.59	27.77	27.00	29.91	34.28	0.20
10 - 20	21.63	21.93	4.80	10.48	23.75	20.73	0.86	9.24	3.05
20 - 30	0.37	0.26	0.60	2.92	7.52	0.70	8.63	1.00	0.36
30 - 40	0.14	0.14	0.10	0.14	0.00	2.35	1.64	1.34	0.53
40 - 50	0.15	0.15	0.52	0.15	0.76	7.11	3.05	1.16	0.07
50 - 60	0.16	0.16	0.31	0.17	0.14	2.07	0.80	1.85	0.51
60 - 70	0.16	0.16	0.00	0.16	0.11	0.29	3.29	1.64	0.53
70 - 80	0.17	0.17	0.11	0.17	0.10	4.44	5.69	5.38	4.62
80 - 90	0.17	0.17	0.00	0.17	0.17	0.03	7.63	10.45	16.00
90 - 100	0.18	0.18	0.03	0.18	0.18	0.00	1.65	8.34	6.21
100	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00

Table 7 The measured volumetric grade distributions, by weight, in the Scavenger Concentrate stream

Conditional, on size, volumetric grade distributions, weight % Size intervals in microns.								
volumetric grade interval, %	-355 +250	-250 +180	-180 +106	-106 +75	-75 +53	-53 +45	-45 +38	-38
0	0.00	0.00	0.09	3.55	5.04	5.65	0.51	4.05
0 - 10	32.11	17.89	26.07	16.56	3.47	0.76	6.10	3.75
10 - 20	32.96	38.90	32.89	4.50	4.97	3.33	3.44	0.84
20 - 30	34.05	19.03	14.04	10.87	4.18	4.20	0.00	0.07
30 - 40	0.35	19.91	11.83	11.12	6.11	1.66	2.09	0.66
40 - 50	0.05	2.98	0.47	7.54	0.53	0.05	0.21	0.88
50 - 60	0.00	0.65	2.22	4.27	0.53	0.54	0.27	0.08
60 - 70	0.04	0.09	2.82	4.27	2.01	0.08	0.19	0.99
70 - 80	0.13	0.00	2.92	3.56	7.68	0.66	1.61	0.20
80 - 90	0.15	0.16	6.63	13.11	23.99	9.20	8.01	13.99
90 - 100	0.16	0.16	0.00	20.63	41.48	73.87	76.72	49.73
100	0.00	0.23	0.00	0.00	0.00	0.00	0.84	24.77

Table 8 The measured overall liberation spectra in the internal streams.

Volumetric grade distributions, weight % Internal stream identification..						
volumetric grade interval, %	B.M. Disch.	Cyc. Feed	Cyc. Over	Cyc. Under	Rough. Conc.	Rough. Tail
0	8.24	1.40	3.33	0.41	0.91	52.83
0-10	6.77	1.59	2.99	0.97	3.15	19.23
10-20	4.61	2.93	5.56	0.98	2.51	9.93
20-30	12.10	12.83	1.67	13.88	10.96	4.43
30-40	12.65	9.51	7.59	19.65	13.13	2.55
40-50	2.88	4.33	2.00	6.78	6.00	0.18
50-60	3.19	3.61	0.57	6.29	3.58	0.20
60-70	2.88	5.20	1.48	7.08	3.42	1.29
70-80	4.71	5.40	2.53	2.95	6.46	0.92
80-90	18.76	14.18	14.91	14.23	12.72	4.23
90-100	15.57	29.75	36.08	23.96	34.02	2.81
100	6.13	9.26	21.28	2.84	1.71	0.86

Texture and Phase Characterization

Normally, the distributions used for modeling and simulation are in terms of particle grade, i.e., weight fraction of phase, and distributions by weight rather than volume. The conversion from volume to weight fractions is easily accomplished if the density of the phases is known. Furthermore, the liberation model requires, at the very least, a representative geometrical texture parameter, which describes the change in interphase area per unit volume of phase as particle composition changes. The representative geometrical texture parameter can be obtained by optimization, when the liberation spectra in the feed and product streams of a size reduction operation are known. The value of the parameter φ at a given particle size can be measured directly from the ore by image analysis, from particles in narrow size and narrow grade intervals like the ones produced here. Narrow size particles are easily obtained by screening. However, particle samples in narrow grade intervals require some fractionation procedure. The Taconite ore is not suitable for magnetic fluid fractionation, due to the strong ferromagnetism of the magnetite. The fractionation procedure used here is the standard heavy liquid fractionation, using organic liquids and a 125 ml separation funnel. A sample of the -710+500 microns Ball Mill Discharge weighing 56.8 g was prepared for dense liquid fractionation. The heavy liquids used were Tetrabromoethane, ρ = 2.954 g/cc, and Diodomethane, ρ = 3.325 g/cc. Diodomethane diluted with Triethyl Orthophosphate was used to give a separation density at ρ = 3.112 g/cc. After fractionation, the particles were weighed and their average density measured in a helium pycnometer. Each sample was mounted, and imaged. If we denominate as phase A all the silicates present, mainly Chert, and phase B all iron oxides, mainly Magnetite, the densities of phases A and B can be calculated by plotting the fractionated

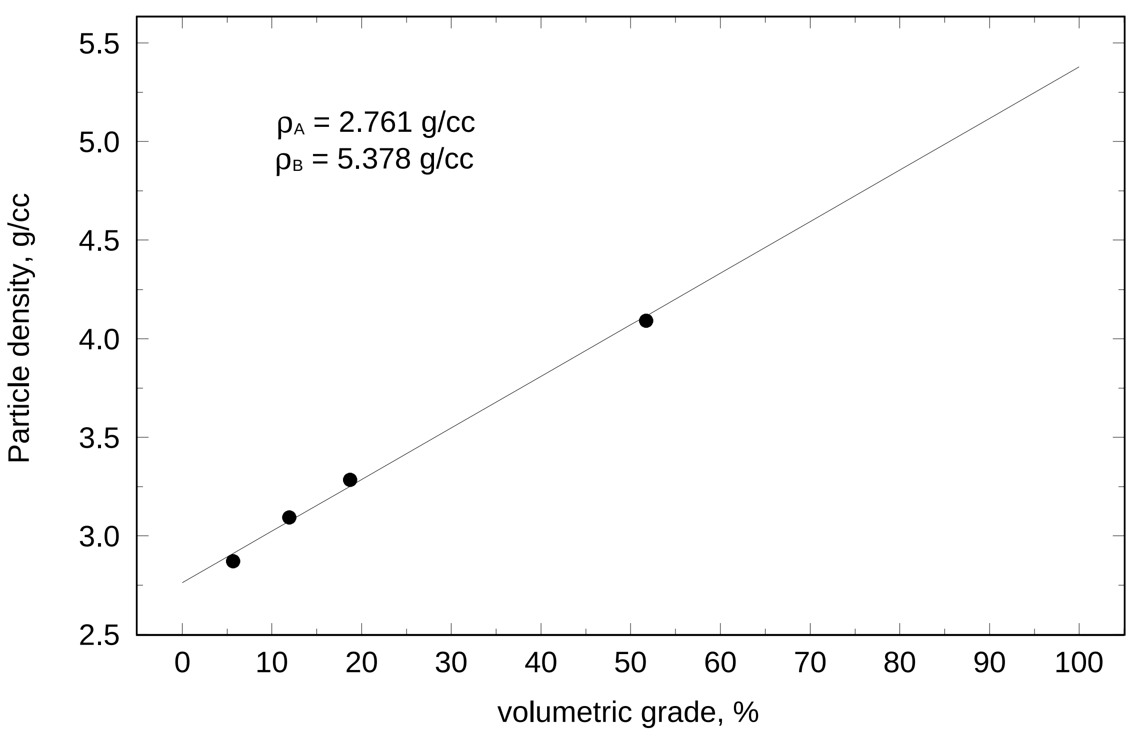

Figure 2 Phase apparent density determination in Taconite ore.

sample densities, as measured by use of a pycnometer, against the corresponding volumetric grade as measured by image analysis. This is shown in Figure 2. The straight line indicates that the ore is essentially binary with respect to density. In Figure 1, the density of phases A and B are calculated from the intercept and the slope of the line that fits the measured points. Linear regression yields ρ_A = 2.761 g/cc and ρ_B = 5.378 g/cc, completing the phase characterization procedure.

Since the particles were already fractionated for phase density determination, it is possible to use the images to measure the value of the textural parameter φ at this size range. For this, the average chord length for both phases and features was measured from the fractionated particle sample specimens. The average chord lengths were used to calculate the surface area per unit volume of both phases and the features as well. With these values, the interphase area per unit volume of phase S_vAB and S_vBA could be calculated. The geometrical texture parameter $\varphi(-710+500\mu)$, is calculated by plotting the product of representative particle size and interphase area per unit volume of phase against the volumetric grade of the corresponding phase. Here, the representative particle size is 595.82 microns. The resulting plot is shown in Figure 3, and linear regression yields $\varphi(-710+500\mu)$ = 45.06.

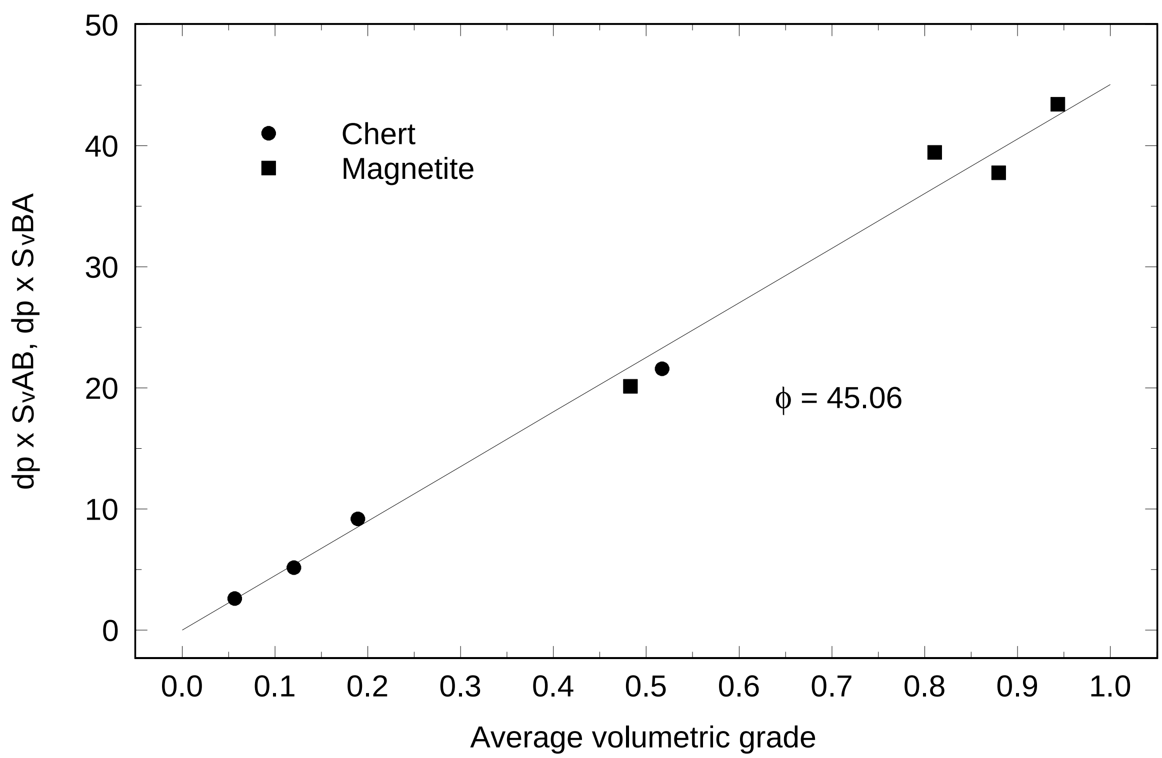

Figure 3 Determination of texture parameter for liberation simulation

Unit operations models

The flowsheet setup for the simulation of the grinding circuit is shown in Figure 1. The main feed stream is the Cobber Concentrate. The Dewatering Drum magnetic separation was regarded as a subsidiary separation unit, and the concentrate and tails streams were treated as secondary feed streams to the main circuit, with constant size and liberation spectra. The Scavenger Concentrate stream was also treated as a subsidiary feed stream with constant size and liberation spectra.

The size distributions in the four feed streams were entered in MODSIM as shown in Table 2. The conditional liberation spectra were entered as measured for all available sizes in the feed streams. For the larger size fractions, where the liberation spectra was not measured either because there were not enough particles available for image analysis or because of the 1000 microns top size limitation for the *I.A.* system used, the liberation spectrum measured on the largest size sample was repeated. This assumption is significant only for the Cobber Concentrate stream, which contains approximately 47% of particles larger than 1000 microns.

The primary objectives of the simulation were to match the plant's nominal material balance, as shown in Table 9, and to match the measured size and liberation spectra in each stream. The solids feed rates entered in the simulator were equal to the nominal feed rates obtained from the plant's material balance. Water feed rates were calculated by MODSIM so that the nominal solids content in each feed stream in the circuit were reproduced. The simulation of the secondary grinding circuit requires, besides the liberation model, a comminution model for the ball mill and concentration/classification models for both the rougher wet magnetic drum separator and the hydrocyclone. The models were adjusted and the best set of parameters was obtained by both independent optimization of each unit operation, and manually by repeated simulation of the entire circuit.

Table 9 The nominal flow rates and % solids and the measured grades in the streams of the secondary grinding circuit of the Fairlane Plant. Recoveries are based on the total flow rates from the four feed streams. Stream grades are calculated from image analysis results in each size range and the measured/adjusted size distributions

Stream	Solid Flow, Tons/hour	Water Flow, m^3/hour	solids, %	Recovery of solids, %	Recovery of Chert, %	Grade of Chert, %	Recovery of Magnetite, %	Grade of Magnetite, %
Cob.Conc.	301.26	137.89	68.60	79.11	83.09	43.36	76.32	56.64
Cyc.Feed	618.37	474.35	56.59	162.39	96.52	24.54	208.71	75.46
Cyc.Under	381.77	64.69	85.51	100.26	69.06	28.44	122.19	71.56
Cyc.Over	236.60	679.39	25.83	62.13	29.08	19.32	85.54	80.68
D.D.Conc.	57.48	30.34	65.45	15.09	10.79	29.52	18.12	70.48
D.D.Tails	4.82	59.36	7.51	1.27	2.66	86.83	0.28	13.17
B.M.Disch.	740.51	230.14	76.29	194.47	176.35	37.44	207.20	62.56
Rough.Conc.	618.57	526.93	54.00	162.44	103.95	26.42	203.57	73.58
Rough.Tails	121.94	1913.79	5.99	32.02	63.92	82.41	9.59	17.59
Scav.Conc.	17.23	23.50	42.30	4.52	3.46	31.53	5.28	68.47

Ball Mill Model

There is no information on the particle size distribution in the holdup of the ball mill at the Fairlane Plant. Consequently, classification effects in the mill with respect to particle size cannot be accessed. In fact, the ball mill feed stream was not sampled for particle size distribution measurement. The only direct information available, besides some operational conditions, and the mill's geometry, that is useful for the choice and parameterization of the comminution model, is the size distribution in the product stream. The feed stream to the ball mill could not be sampled due to the plant's physical configuration. A priori, only an approximate size distribution in the feed stream should be sufficient for a preliminary parameterization work. This was obtained by adding the measured size distributions in the Cobber Concentrate, Cyclone Underflow, and Dewatering Drum Concentrate streams, and using the nominal material balance in Table 9. Since the size distribution in the product is not very sensitive to the size distribution in the feed, an approximate distribution should be enough to choose the proper comminution model and to obtain an initial set of parameters by independent optimization.

It was assumed that the transport in the mill can be described by three perfectly mixed regions in series, with the fractional residence times for the solids. This assumption is probably inaccurate, particularly when considering the geometry of the ball mill, which has a diameter to length ratio of approximately 1:2.5. However, this assumption has no impact whatsoever at this stage of the investigation, and the only direct consequence is that the parameters for the model equations corresponding to the selection and breakage functions become even more alienated to the comminution properties of the ore from the phenomenological point of view.

When classification is not considered, the classification coefficients c_i are null for every particle size *i*, and consequently $p_i = p_i^* = p_i^{(3)}$ and $\tau_3' = \tau_3$. The breakage function model chosen for the Taconite ore was Austin's three parameter normalizable function. The selection function for the Taconite ore was modeled by:

$$S_i = S_1 \left(\frac{d_{pi}}{1000} \right)^{\alpha} \qquad \textbf{(1)}$$

It is interesting to point out that the best model for the selection function did not require a description for an abnormal breakage region, perhaps due to the comparatively small particle sizes in the mill's feed. The final parameters for the comminution model of the ball mill are shown in Table 10, including breakage function and selection function parameters, and the residence times in the mill.

Wet Magnetic Drum Separator Model

The model developed for the Rougher separation was empirical, in nature. The classification action in a wet magnetic drum separator is primarily a function of the volumetric abundance of the magnetic phase, here the Magnetite, in the particle. In practice, because the separators are simple drums that produce a constant magnetic field and that rotate at constant speed, the configuration

Table 10 The comminution model parameters for the ball mill used in MODSIM simulation

Selection function parameters	α = 1.28855 S_1 = 1.28076 min^{-1}
Breakage function parameters	Φ = 0.46085 β = 0.44601 γ = 0.98684
Average residence time in perfectly mixed region *n* (minutes)	τ_1 = 0.0548 τ_2 = 0.8492 τ_3 = 3.0960
Total residence time (minutes)	τ = 4.0

of the feed streams and how the particles are exposed to the magnetic field, is of crucial importance. Here, at least at this preliminary modeling stage, it is considerably more important to establish a classification function that can be used to model the classification action, with respect to both particle size and grade, of the magnetic separator.

The classification phenomenon in the unit can be described by:

$$c(g_v, d_p) = \alpha(d_p) + (1 - \alpha(d_p))\, e(g_v) \tag{2}$$

where $c(g_v, d_p)$ represents the fraction of particles that have volumetric grade g_v and representative size d_p that report to the tails stream. The by-pass fraction of particles in the feed that short circuits to the tails stream is represented by $\alpha(d_p)$, which is only a function of particle size. The primary classification function, represented by $e(g_v)$, is exclusively dependent on particle composition.

The by-pass function $\alpha(d_p)$ is based on the principle that smaller particles are more susceptible to the drag produced by the water flow. Approximately 80% of the water in the feed of the Rougher separator reports to the tails stream (Table 9), and some water drag must be expected. The by-pass function was modeled by:

$$\alpha(d_p) = \kappa\, e^{-\varsigma\, d_p} \tag{3}$$

where κ and ς are arbitrary model parameters.

The classification function $e(g_v)$ was modeled with the commonly used Rosin-Rammler functional form:

$$e(g_v) = 1 - e^{-0.693\left(\frac{1-g_v}{1-g_v^{50}}\right)^{\lambda}} \qquad \textbf{(4)}$$

where g_v^{50} represents the volumetric grade of a particle that have equal probability of reporting either to the concentrate or to the tail streams and λ is related to the separation sharpness index *SI*, defined by $SI = \frac{g_v^{25}}{g_v^{75}}$. For the Rosin-Rammler functional form, this is:

$$SI = e^{-\frac{1.5725}{\lambda}} \qquad \textbf{(5)}$$

The following set of parameters were used for the Rougher separation in MODSIM, using the model for a wet magnetic drum separator described above:

- Sharpness Index, *SI* = 0.8926
- Separation volumetric grade, g_v^{50} = 0.090
- By-pass fraction, κ = 0.466
- Exponential factor to reduce by-pass as particle size increases, ς = 56.00 m^{-1}

Finally, the water split factor to the tails stream was set to 0.784, completing the modeling of the Rougher separation unit.

Hydrocyclone Classification Model

The Hydrocyclone is the most common classification operation used in industrial grinding circuits. Consequently, the classification action in hydrocyclones has been the subject of a large number of studies. The most sophisticated hydrocyclone models are based on solutions to the Navier-Stokes transport equations, in two dimensions, and most recently, a considerable effort has been made by Cortes, towards the three dimensional solution. However, these models are rather complex, and at this time, their implementation in a MODSIM like simulator is not yet feasible. The alternatives are first, the use of models based on correlation studies, as for example Lynch's model and Plitt's model, and second, the use of empirical classification models. The correlation models are implemented with advantage, since these models allow some flexibility at simulating the effect of changes in operational conditions of the hydrocyclone, and its geometry. The sampling campaign at the Fairlane Plant produced enough data, with respect to geometry and operational conditions, for the implementation of a correlation based model, and this should be pursued once this study takes on the plant's performance optimization character. At this initial stage, when the liberation characteristics of the Taconite ore and the liberation model are under evaluation, it is more appropriate to select a simpler, fewer parameters empirical classification model.

Here, a standard partition based modeling technique is employed to describe the hydrocyclone operation at the Fairlane Plant. For a general description of empirical models for classification operations the interested reader is referred to the MODSIM manual. The classification action in the hydrocyclone can be described by:

$$c(d_p, g_v) = \alpha + (1 - \alpha)\, e(d_p, g_v) \qquad \textbf{(6)}$$

where $e(d_p, g_v)$ is called the corrected classification function and $c(d_p, g_v)$ is called the actual classification function. The parameter α represents the fraction of particles that by-passes to the underflow stream, and here this is constant with respect to both particle size and composition. The corrected classification function was modeled with the logistic functional form:

$$e(d_p, g_v) = \frac{1}{1 + \left(\dfrac{d_p}{d_p^{50}(g_v)} \right)^{-\lambda}} \qquad \textbf{(7)}$$

where the exponential parameter λ is related to the separation sharpness index *SI* by:

$$SI = e^{-\frac{2.1972}{\lambda}} \qquad \textbf{(8)}$$

and $d_p^{50}(g_v)$ represents the separation size for a particle that has composition g_v. The change in separation size with particle composition was modeled by:

$$d_p^{50}(g_v) = d_{50} \left(\frac{\rho_A}{\rho(g_v)} \right)^{\delta} \qquad \textbf{(9)}$$

In equation 9, the strong concentration action in the hydrocyclone operation due to differential particle density is taken into account, and the value of the parameter *m* is related to the flow regime in the device, with the lower limit of 0.5 corresponding to laminar flow conditions, and higher values for turbulent flow.

Equations 6 through 9 represent a typical empirical model that can be used to describe the classification action, with respect to size and composition, in mineral processing devices, when liberation information is available.

The following set of parameters were used for the hydrocyclone classification in MODSIM, using the empirical model described above:

- Sharpness Index, *SI* = 0.6058
- Separation size, d_{50} = 123.0 microns
- Exponential parameter in separation size function, δ = 0.8

- By-pass fraction, α = 0.0865

Finally, the water split to the underflow stream was assumed to be equal to the by-pass fraction α, completing the preliminary hydrocyclone modeling.

Exercise

Study the impact of replacing the hydrocyclone with a screen with opening equal to the hydrocyclone separation size using MODSIM. Observe any changes in circulation load and in recoveries and grades of magnetite in the product streams. What would be the new flowsheet capacity?