

VERIFICATION OF STEELMAKING SLAG IRON CONTENT

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1.0 INTRODUCTION

The Institute of Materials Processing (IMP) at Michigan Technological University was contracted by the U.S. Department of Energy (Cooperative Agreement DE-FC36-01ID14046) to perform research on the recovery of iron units from steelmaking slag. It is believed that major inroads have been made through the course of this project with regards to slag processing for the separation of iron units and the utilization of processing residues. Due to the lack of funding in the last three years, most of the activities were carried out from the private entities. The principal investigator and the Institute of Materials Processing wish to thank the following parties for their participation in this project.

Sponsor

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Project Team Participants that Contributed Cost Share, Samples, and Guidance

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2.0 PROJECT SUMMARY

2.1 EXECUTIVE SUMMARY

The steel industry in the United States generates about 30 million tons of by-products each year, including 6 million tons of desulfurization and BOF/BOP slag. The recycling of BF (blast furnace) slag has made significant progress in past years with much of the material being utilized as construction aggregate and in cementitious applications. However, the recycling of desulfurization and BOF/BOP slags still faces many technical, economic, and environmental challenges. Previous efforts have focused on in-plant recycling of the by-products, achieving only limited success. As a result, large amounts of by-products of various qualities have been stockpiled at steel mills or disposed into landfills. After more than 50 years of stockpiling and landfilling, available mill site space has diminished and environmental constraints have increased. The prospect of conventionally landfilling of the material is a high cost option, a waste of true national resources, and an eternal material liability issue.

The research effort has demonstrated that major inroads have been made in establishing the viability of recycling and reuse of the steelmaking slags. The research identified key components in the slags, developed technologies to separate the iron units and produce marketable products from the separation processes. Three products are generated from the technology developed in this research, including a high grade iron product containing about 90%Fe, a medium grade iron product containing about 60% Fe, and a low grade iron product containing less than 10% Fe. The high grade iron product contains primarily metallic iron and can be marketed as a replacement of pig iron or DRI (Direct Reduced Iron) for steel mills. The medium grade iron product contains both iron oxide and metallic iron and can be utilized as a substitute for the iron ore in the blast furnace. The low grade iron product is rich in calcium, magnesium and iron oxides and silicates. It has a sufficient lime value and can be utilized for acid mine drainage treatment.

Economic analysis from this research demonstrates that the results are favorable. The strong demand and the increase of price of the DRI and pig iron in recent years are particularly beneficial to the economics.

The favorable economics has brought commercial interests. ICAN Global has obtained license agreement on the technology from Michigan Tech. This right was later transferred to the Westwood Land, Inc. A demonstration pilot plant is under construction to evaluate the technology.

Steel industry will benefit from the new supply of the iron units once the commercial plants are constructed. Environmental benefits to the public and the steel industry will be tremendous. Not only the old piles of the slag will be removed, but also the federal responsible abandoned mines from the old mining activities can be remediated with the favorable product generated from the process. Cost can be reduced and there will be no lime required, which can avoid the release of carbon dioxide from lime production process.

2.2 COMPARISON OF ACTUAL ACCOMPLISHMENTS WITH PROJECT GOALS AND OBJECTIVES

It is believed that the goals and objectives of the project have been met.

The overall goal of the project was to develop a commercially viable technology to recycle and reuse steelmaking slags. The goal was to be accomplished by meeting project objectives, which are briefly described below as:

1. Verification of Iron Content in Steelmaking Slags – determine the iron forms and contents in steelmaking slags.
2. Steelmaking Slag Processing – develop separation processes for optimum recovery of iron units from the slag.
3. Product Market Development - develop utilization of processed residues after iron units recovery for applications in acid mine drainage treatment.
4. Economics – determine the economics of the technology developed in this research.
5. Environmental – evaluate environmental benefits from the technology.
6. Commercialization – generate information and transfer the technology.

Meetings with U.S. Steel, Ispat-Inland (Mittal Steel USA), Wheeling-Pittsburgh, Rouge, and Weirton (Mittal Steel USA – Weirton) personnel have been conducted. Priorities on their slag samples from various processing streams have been established. A total of 27 samples have been studied to verify the iron contents. Among them, 17 samples have metallic iron content exceeding 12%, up to 51%. The total iron content of the 17 samples ranges from 24 to 55%.

Mineralogical characterization of the samples, using SEM and XRD, shows that metallic iron, wustite, magnesium ferrite, dicalcium silicate (a major ingredient of cement), melelite ($\text{Ca}_2\text{MgSi}_2\text{O}_7$), and periclase (MgO) are the major constituents in the slags.

A flowsheet for separation has been developed. This involves various stages of grinding and separations. Lab scale testing shows that three products from each sample can be consistently achieved: A HGI (High Grade Iron) product containing more than 90% Fe total (about 95% of the total Fe in the metallic form), a MGI (Medium Grade Iron) product containing about 60% Fe total, and a LGI (residual material) product with low Fe content.

Furnace model calculations show that the HGI can be a scrap substitute for BOF. 4000 kg HGI has the cooling efficiency equivalent to 3880 kg scrap and increases hot metal by 0.1 MT. The MGI product can be a good feed to the BF.

A one ton per hour bench test facility has been constructed. Continuous separation of the HGI, MGI, and LGI products has been demonstrated. The success of the one ton per hour pilot operation has led to the construction of a 50 ton per hour testing facility, which is near completion.

Briquetting of the HGI product can be achieved with a binder consisting of 6% lime hydrate and 3% molasses. This is comparable with typical dosages for briquetting operations. The binder system for the MGI product is about 9% Portland cement and 3% bentonite.

One important issue of this research is to find a market for the processing fine residues, the LGI product. This material may contribute up to 70% of the original weight. The steel plant will not be able to host this material on its site due its fineness. Stockpiling is not an option. To address this issue, a market which can use large quantities of alkaline material was investigated. This market is acid mine drainage treatment. Lime has been traditionally utilized in this application. However, the country does not have sufficient lime due to the vast quantity required. In addition, lime production gives off large quantities of CO₂ from limestone calcining. The lime substitution depends on the neutralization potential of the LGI product. This study found that the LGI has a neutralization potential about 25% equivalency to lime.

The capital and operation cost for a 50 ton per hour plant has been estimated at \$10.31 per ton. If a ton of steelmaking slag is processed, the potential profit can be in the range of \$20 to \$45 per ton, depending on the slag metallic iron content and the market value of the LGI product.

The favorable economics has attracted commercial interest from private entities. ICAN GLOBAL, Inc has licensed the technology for commercialization. The company invested to build a one ton per hour pilot testing facility. The operation was successful. This attracted the interest of another firm, Westwood Land, Inc. This company acquired all of the rights from ICAN GLOBAL and is constructing a 50 ton per hour testing facility, which is near completion.

2.3 SUMMARY OF PROJECT ACTIVITIES

The hypotheses of the research effort are that there are sufficient iron units left in the steelmaking slag wastes and a commercially viable technology could be created to recover iron units from steelmaking slag wastes and the residuals after the iron unit removal can be utilized in a market. The research, therefore, focused on the following activities:

- Obtain samples from various steel mills and verify iron forms in these samples.
- Develop processes to recover iron units and generate products
- Demonstrate that scale up of the process is possible
- Agglomerate the products for feeding into the steel mill furnaces
- Investigate if the processing residues can be utilized for acid mine drainage treatment
- Generate sufficient information related to the technical, economical and environmental feasibility to attract commercial interest
- Conduct technology transfer to private industry

To achieve this, slag samples from various steel mills were collected and analyzed to verify the iron units. Samples from US Steel, Inland (Mittal Steel USA), and Wheeling Pitt were chosen by the team members for detailed study. Separation technology is designed based on the characterization results of the samples and is carried out primarily by the team from Michigan Tech, and then experimentally tested. Separated fine iron units are evaluated with furnace

models to determine the best approach for their reuse in the steel mill. Dr. Balajee from Inland Steel (Mittal Steel USA) provided major assistance to carry out this task. Dr. Komar Kawatra at Michigan Tech investigated the briquetting and agglomeration of separated iron units. The residual materials are evaluated for their potential applications in acid mine drainage treatment. Dr. Paul Ziemkiewicz, West Virginia University, is responsible for this effort through the National Mined Land Reclamation Center that he directs. A one-ton per hour bench scale circuit has been tested to determine the feasibility to scale up the process. ICAN Global was a major partner in this feasibility study. Information from all team members was analyzed to assess the technical, economical and environmental feasibility. ICAN Global elected to license the technology from Michigan Tech. Activities on technology transfer for commercialization were initiated. The license was later transferred to Westwood Lands, Inc. A demonstration pilot facility is under construction.

2.4 PRODUCTS DEVELOPED UNDER THE AWARD

Two papers were produced through the course of the award:

- 2003 Z. Xu, J.Y. Hwang, R. Greenlund, X. Huang, J. Luo, and S. Anschuetz, "Quantitative Determination of Metallic Iron Content in Steel-Making Slag", *Journal of Minerals and Materials Characterization and Engineering*, V. 2, No. 1, pp. 65-70.
- 2004 Z. Xu, N. Popko, R. Greenlund, J. Hwang, "Recycling of Steel-Making Slag", *JOM* v.56, no.11, p.322.

3.0 STEELMAKING SLAG SAMPLING AND CHARACTERIZATION

3.1 SAMPLING AND PRIORITY

Meetings with personnel from steel companies (U.S. Steel, Ispat Inland (Mittal Steel USA), Wheeling Pittsburgh, Weirton (Mittal Steel USA – Weirton), Rouge, and National (US Steel – Great Lakes)) reached the conclusion that samples from four mills would be representative for this research. The four mills include the USS Gary Works, USS Edgar Thompson, Inland (Mittal Steel USA), and Wheeling Pitt.

Of the four mills participating in the project, two have sintering plants (Mills A and B) and two do not (Mills C and D). In meetings with steel company representatives and contracted slag processors, it was determined that each type of mill has different priorities with regards to steelmaking slags. The mills with a sintering plant have the following priorities with regards to disposal or process need: 1) Desulfurization slag fines; 2) Coarse (1/4" x 6" range) non-magnetic BOF slag; 3) Magnetic BOF slag fines; and 4) Non-magnetic BOF slag fines. The mills without sintering plants listed the following priorities: 1) Magnetic BOF slag fines; 2) Desulfurization slag fines; 3) Non-magnetic BOF slag fines; and 4) Coarse non-magnetic BOF slag.

Sampling from Mills A and B occurred during June, 2001. Fresh samples from on-going processing, as well as, long term stockpile samples were obtained. Mill C samples were obtained during early July 2001, with only fresh material being sampled as all non-reusable slag fractions are currently landfilled. The last set of samples were obtained in October, 2001, with freshly processed fractions being obtained, as well as, a stockpile sample of combined C scrap and desulfurization slag fines.

During the sampling program MTU/IMP personnel that were on-site gathered flowsheet data, production figures, and site specific information from steel mill company representatives and mill site slag processing companies' representatives. Excellent cooperation from the slag processing companies at steel mill sites was provided. Efforts will be made in this report to protect what may be deemed as proprietary information of both the steel companies and the slag processing companies to not put them under any competitive disadvantage.

While obtaining samples and information it became clear that mills with sintering plants have slag problems that are different from those without sintering plants. Tables 1 and 2 list the priority needs of different mills with sintering plants and without sintering plants. As can be seen from Tables 1 and 2, desulfurization slag is the number one priority of mills with sintering plants and the number two priority among mills without sintering plants and is reflective of the undesirable chemical nature of the material for return back through the steelmaking system. The number one slag priority of mills without sintering plants is magnetic BOF fines, whereby the small particle size of the material prevents reuse in their blast furnace. Mills with sintering plants maintain considerably more control over slag reuse. For mills without sintering plants, efforts have been made to return as much material as possible to the blast furnace for reuse.

Table 1. Priorities of Mills with Sintering Plants	
Mill A	Mill B
1. -3/8" Desulfurization slag fines – 118,625 TPY, 80,000 Ton Stockpile – S content and size limit reuse – no markets.	1. -1/4" Desulfurization slag fines – 127,300 TPY, 150,000 Ton Stockpile – sinter plant or stockpile – S content and size limit rate of reuse – no markets.
2. 3/8" x 4" BOF Non-magnetic Slag – 155,125 TPY, 90,000 Ton Stockpile – reuse for acid adjustment in BF, low metallic Fe content presents little recoverable Fe units – Sold when opportunity presented.	2. 1/2" x 4" BOF Non-Magnetic Slag – 261,400 TPY, 1 million ton stockpile – Some used for flux and acid control in BF, use not keeping up with production – no market.
3. -3/8 Non-Magnetic Fines – 146,000 TPY, 20,000 Ton Stockpile – Sinter plant as flux, but little recoverable Fe units – no markets.	3. -1/4" BOF Magnetic Fines – 70,300 TPY, used on varying proportionate basis with -1/4" C Slag in sinter plant for flux and Fe unit value – no market.
4. -3/8 BOF Magnetic Fines – 255,500 TPY, 160,000 T Stockpile – Sinter plant, used for flux and Fe unit recovery – Use in sinter plant has not kept pace with production.	4. -1/4" BOF Non-Magnetic Fines – 416,000 TPY, used on varying proportionate basis with -1/4" C scrap in sinter plant for flux value – no market.

Table 2. Priorities of Mills with No Sintering Plant	
Mill C	Mill D
1. -3/4" BOF Slag – 274,000 TPY – 41,400 TPY to BF for Fe unit recovery. 232,600 TPY mostly destined for landfill, some used for BF acid adjustment – Small market in Agriculture, no significant space for stockpiles on site.	1. BOF Magnetic Fines – 132,000 TPY, 2.7M Ton Stockpiles mostly C scrap – no market.
2. -3/4" Desulf. Slag – 7,150 TPY – 1,980 TPY to BF for Fe unit recovery, the rest landfill – no markets.	2. Desulf. Slag Fines – 48,000 TPY, currently stockpiled – no market.
3. 3/4" x 7" Desulf. Slag Non-mags – 1,300 TPY all to landfill – no markets.	3. BOF Non-Magnetic Fines – 36,000 TPY – 36,000 TPY - 95% Landfill, 5% sold.
4. 3/4" x 7" BOF Slag Non-mags – currently going to BF for acid adjustment – analysis shows some Fe metallics present but would require further processing, but then residual material would be too fine for this application.	4. Coarse BOF Non-Magnetic Slag – 96,000 TPY – used as BF flux.
	5. Coarse Non-Magnetic Desulf. Slag – 14,400 TPY - Fe unit recovery in BF.

3.2 STEELMAKING SLAG PRODUCTION DISTRIBUTION

In order to provide a perspective on how steelmaking slags are utilized, processed, stockpiled, or landfilled slag production data was gathered. Table 3 provides a breakdown of what would be considered the current non-recycled materials, which includes desulfurization slag fines, BOF magnetic fines, BOF non-magnetic fines, and BOF coarse non-magnetics. Also included are stockpile amounts or current alternatives to stockpiling such as landfilling, sinter plant use, or BF fluxing agent.

In looking at the data in Table 3, it can be observed that the amount of desulfurization fines ranges from 22.85-67.80% of the total amount produced, indicating significant differences in processing methodology among the mills sampled. Currently three of the four mills stockpile the desulfurization slag on site, with one company preferring to landfill the material because of lack of space. The BOF magnetic material ranges from 2.52-36.67% of the total BOF slag produced at the mills. The 2.52% figure is indicative of the slag processing strategy to minimize the amount of material going to landfill in that case. If not included, the range would be much lighter, 20.23-36.67%, and more indicative of the industry numbers. The use of a sintering plant in mills A and B relative to a non-sinter plant site of Mill D shows the effect on minimizing stockpile amounts.

Table 3. Steelmaking slag production breakdown.

Mill	Total Desulf. Slag Produced (TPY)	Desulf. Fines (TPY)	Desulf Fines Stockpile Amount (Tons)	Total BOF Slag Produced (TPY)	BOF Mag. Fines (TPY)	Stockpile (Tons)	BOF Non-Mag. Fines (TPY)	Stockpile (Tons)	BOF Non-Mag. Coarse (TPY)	Stockpile (Tons)	Overall Waste % of Total BOF Produced
A	255,600	118,675	80,000	1,262,900	255,500	160,000	146,000	20,000	155,125	90,000	44.07
B	251,400	127,300	150,000	1,411,000	416,000	Sinter Plant	70,300	Sinter Plant	565,000	1,000,000	74.50
C	13,000	2,970	Landfill	444,000	11,200	Landfill	132,800	Uses & Landfill	238,600	BF Flux & Landfill	86.17
D	70,800	48,000	Included with BOF Mag fines stockpile.	360,000	132,000	2.7M	36,000	Landfill	96,000	BF Flux	73.74

The BOF non-magnetic fines range from 4.98%-29.91% of the total BOF slag produced. The mills with sintering plants are able to maintain small stockpiles of this material, while those mills without sintering plants are forced to landfill or find alternative uses for it. The BOF coarse non-magnetic material has a range of 12.28 to 53.74% of the total BOF slag produced. This material, which is similar in composition to the BOF non-magnetic fines, presents more problems for plants with sintering plants as the size of the material (or lack of further size reduction) makes this material less desirable for recirculation in the steelmaking process scheme or for use in the sintering plant. Mills C and D which do not have sintering plants have focused on using the material as flux in the BF to minimize landfill costs.

When the percentages are added up for each mill, 44.07-86.17% of the total BOF slag production reports to the magnetic fines, and the fine and coarse non-magnetic material. If the 44.07% total is removed, the range becomes 73.74-86.17% of the total BOF slag produced. This represents a significant amount of material that needs markets for larger tonnage applications.

3.3. CHARACTERIZATION

3.3.1 Iron Content of Samples

Table 3 displays the iron content derived on head samples taken from the gathered sample barrels. As can be seen in Table 4 there are stockpile and freshly processed samples. All of these analyses were performed at MTU/IMP under the same analytical methods and are relative to each other. The issue of metallic iron analysis will be addressed later in this report under “Issues and Concerns.” As would be expected, more metallic iron, as well as, total iron content are found in the magnetic BOF slag fractions and in the desulfurization slag fines. However, in the non-magnetic BOF slag fractions there is generally 20-30% total iron and the issue of recoverable iron units becomes apparent, particularly if little metallic iron is present. More detail regarding the subject of recoverable iron units will be addressed under “Laboratory Separation Testing.” As can be seen by the slag fractions in Table 4, there are differences on how BOF and Desulfurization Slag are currently processed for iron unit recovery. The biggest differences seems to be in fines, both desulfurization and BOF.

3.3.2 Particle Size and Iron Content by Size of Sample

Tables 5 through 12 illustrate the size distribution of particles in the slags identified in Table 4 and the corresponding iron content found in various size fractions. As would be expected, the metallic iron is most prevalent in the coarser sizes, thus providing a similar effect with regards to total iron content within the size distribution. In the non-magnetic fractions there are some differences in iron content between mills which seem to be attributed to the size of the slag, which is determined by the slag processor’s system. For the most part the non-magnetic fractions were found to be fairly lean with regards to metallic iron content, yet generally contained 20-30% total iron content.

3.2.3 Mineralogy

From XRD analysis, Table 13 illustrates the different compounds that are present in various slags.

The dominant compounds present in BOF slags, minus various percentage of metallic iron present, are di-calcium silicate, tricalcium silicate, calcium iron oxide, di-calcium ferrite. The desulfurization slag should be a similar mineral makeup, but with a noticeable increase in the percentage of unreacted calcite and carbon, as would be expected since the increase in calcite corresponds to the desulfurization process and the metal has yet to see the influx of O₂ with BOF to burn out the carbon.

Table 4. Iron Content of Samples Obtained				
Sample			Analysis	
Source	Sample #	Description	FeM	FeT
Mill A	1A	-3/8" Desulfurization fines: stockpile	21.20	42.71
	1B	-3/8" Desulfurization fines	29.05	47.95
	2B	3/8" x 4" BOF non-mags, slag	2.03	22.03
	3A	-3/8" BOF Non-mags, stockpile	2.38	24.06
	4A	-3/8" BOF Magnetic fines, stockpile	21.25	48.19
	4B	-3/8" BOF Magnetic fines	12.46	39.20
Mill B	1A	-1/4" Desulfurization slag, stockpile	30.22	43.54
	1B	-1/4" Desulfurization Mag fines	34.42	44.58
	1C	Desulfurization Non-Mag fines	7.80	22.23
	2A	1/2" x 4" BOF Non-Mag, stockpile	5.27	22.06
	2B	1/2" x 4" BOF Non-Mag slag	5.37	23.00
	3B	-1/4" BOF Magnetic fines	14.19	32.94
Mill C	4B	-1/4" BOF Non-mag fines	4.30	23.13
	6B	1/4" x 1/2" BOF Mags	42.80	55.35
	1D	3/4" x 6" Non-mag Desulfurization slag	15.91	18.79
	1B	3/4" x 6" Non-mag BOF slag	12.96	23.89
	2D	-3/4" Desulfurization Mag fines	50.94	52.27
	2B	-3/4" BOF Mag fines	49.08	51.22
Mill D	3D	-3/4" Desulfurization Non-mag fines	36.57	40.54
	3B	-3/4" BOF Non-mag fines	23.79	28.77
	4B	-1/4" BOF Mag fines	22.94	29.65
	1B	-3/8" Desulfurization fines	28.09	55.47
	2A	-3/8" BOF Mags & Desulfurization fines, stockpile	4.84	28.03
	2B	-3/8" BOF Mag, fines	37.88	41.88
Mill D	3B	1 1/2" x 4", BOF Non-mag slag	3.03	17.27
	4B	3/8" x 1 1/2", BOF Non-mag slag	3.19	23.89
	5B	-3/8", BOF, Non-mag fines	5.63	22.51

Table 5. Mill A Size Distribution and Iron Content by Size for Sample 1 and 2						
Size	Wt. %	% Fe Met.	% Fe Tot.	Wt. %	% Fe Met.	% Fe Tot.
	Mill A - 1A -3/8" Desulfurization Fines Stockpile			Mill A - 1B -3/8" Desulfurization Fines		
+1/2"	5.68	34.96	54.62	4.75	58.48	76.32
+3 mesh	16.45	36.07	56.81	14.55	33.95	53.69
+8 mesh	33.88	27.15	46.62	28.21	22.29	51.46
+14 mesh	16.84	15.31	45.94	14.59	15.96	44.02
+28 mesh	10.68	12.60	36.22	11.69	7.94	43.59
+65 mesh	9.63	7.71	29.59	14.26	0.46	24.34
+100 mesh	2.98	1.96	19.30	4.16	1.10	20.35
+150 mesh	0.87	4.61	25.64	1.78	1.82	22.10
+200 mesh	1.06	4.24	25.10	2.05	0.69	22.11
-200 mesh	1.93	2.51	23.31	3.96	0.91	18.27
Calc Head	100.00	21.98	44.21	100.00	17.46	43.36
Act Head	100.00	21.20	42.71	100.00	29.05	47.95
	Mill A - 2B 3/8" x 4" BOF Non-Mags					
+2"	3.06	1.46	24.92			
+1"	34.50	1.81	26.81			
+3/4"	17.47	1.77	23.25			
+1/2"	30.58	1.79	20.96			
+3/8"	9.90	1.40	25.25			
-3/8"	4.49	2.13	22.14			
Calc Head	100.00	1.76	24.00			
Act Head	100.00	2.03	22.23			

Table 6. Mill A Size Distribution and Iron Content by Size for Sample 3 and 4						
Size	Wt. %	% Fe Met.	% Fe Tot.	Wt. %	% Fe Met.	% Fe Tot.
	Mill A - 3A -3/8" BOF Non-Mags Stockpile Slag			Mill A - 4A -3/8" BOF Magnetic Fines, Stockpile		
+1/2"	13.62	3.76	25.45	0.00	0.00	0.00
+3 mesh	26.69	1.04	27.00	8.00	22.68	52.73
+8 mesh	27.12	1.73	25.54	26.82	18.26	48.26
+14 mesh	10.96	0.64	28.21	24.08	15.18	40.30
+28 mesh	7.29	0.60	26.93	18.91	10.48	37.90
+65 mesh	8.04	0.69	21.02	13.35	3.74	36.68
+100 mesh	2.48	0.66	20.83	3.27	2.35	22.56
+150 mesh	1.14	0.22	21.55	1.64	0.48	20.52
+200 mesh	1.18	0.50	20.59	1.70	1.36	21.40
-200 mesh	1.48	0.28	17.95	2.23	1.10	28.73
Calc Head	100.00	1.46	25.61	100.00	12.98	41.01
Act Head	100.00	2.38	24.06	100.00	21.25	48.19
	Mill A - 4B -3/8" BOF Magnetic Fines					
+1/2"	2.38	29.94	71.51			
+3 mesh	18.14	20.58	49.27			
+8 mesh	35.73	9.30	37.36			
+14 mesh	14.51	7.60	35.12			
+28 mesh	10.43	3.48	42.81			
+65 mesh	8.83	0.88	30.20			
+100 mesh	2.58	0.87	25.86			
+150 mesh	1.48	1.04	27.19			
+200 mesh	1.98	1.37	26.34			
-200 mesh	3.94	0.57	24.37			
Calc Head	100.00	9.38	38.77			
Act Head	100.00	12.46	39.20			

Table 7. Mill B Size Distribution and Iron Content by Size for Sample 1A, 1B, 4B and 6B						
Size	Wt. %	% Fe Met.	% Fe Tot.	Wt. %	% Fe Met.	% Fe Tot.
	Mill B - 1A -1/4" Desulfurization Slag Stockpile			Mill B - 1B -1/4" Desulfurization Mag Fines		
+1/2"	0.00	0.00	0.00	0.00	0.00	0.00
+3 mesh	17.88	34.28	44.81	17.31	42.29	52.10
+8 mesh	43.28	32.04	43.01	43.02	34.32	45.63
+14 mesh	13.70	39.51	50.05	14.71	42.98	48.38
+28 mesh	9.11	37.60	46.25	10.44	39.13	47.87
+65 mesh	8.13	34.35	39.14	8.40	28.58	36.58
+100 mesh	2.28	14.66	21.51	2.04	8.33	34.79
+150 mesh	1.39	16.15	23.76	1.13	18.71	28.07
+200 mesh	1.60	11.82	18.15	1.23	5.37	23.81
-200 mesh	2.63	10.25	17.75	1.71	7.68	16.15
Calc Head	100.00	32.64	42.46	100.00	35.48	45.44
Act Head	100.00	30.22	43.54	100.00	34.42	44.58
	Mill B - 4B -1/4" BOF Non-Mag Fines			Mill B - 6B 1/4" x 1/2" BOF Mags		
+1/2"	0.00	0.00	0.00	7.18	41.47	54.59
+3 mesh	14.42	3.82	23.56	62.73	42.93	57.70
+8 mesh	54.89	3.85	24.38	25.79	33.64	49.46
+14 mesh	13.89	4.35	24.12	1.27	18.67	37.87
+28 mesh	9.01	5.22	24.43	0.49	6.63	27.51
+65 mesh	4.82	2.13	23.21	0.68	3.18	21.32
+100 mesh	0.88	2.69	20.91	0.41	0.99	18.26
+150 mesh	0.47	1.11	18.33	0.31	2.00	18.64
+200 mesh	0.50	1.46	19.43	0.39	0.75	15.46
-200 mesh	1.12	0.88	16.82	0.75	0.87	15.82
Calc Head	100.00	3.89	24.01	100.00	38.90	53.94
Act Head	100.00	4.30	23.13	100.00	42.80	55.35

Table 8. Mill B Size Distribution and Iron Content by Size for Sample 1C, 2A, 2B and 3C						
Size	Wt. %	% Fe Met.	% Fe Tot.	Wt. %	% Fe Met.	% Fe Tot.
	Mill B - 1C Desulfurization Non-Mag Fines			Mill B - 3B -1/4" BOF Mag Fines		
+1/2"	0.00	0.00	0.00	0.00	0.00	0.00
+3 mesh	12.81	6.40	20.31	1.68	20.91	38.24
+8 mesh	38.69	4.99	23.16	47.35	18.02	31.41
+14 mesh	13.13	9.20	19.24	24.99	17.93	36.84
+28 mesh	11.15	16.85	23.71	13.27	9.43	27.72
+65 mesh	13.16	7.03	19.58	7.81	5.13	23.60
+100 mesh	3.59	9.12	18.39	1.58	1.60	23.78
+150 mesh	1.93	8.84	19.36	0.84	1.37	17.61
+200 mesh	2.10	7.40	20.84	0.81	1.68	17.90
-200 mesh	3.45	6.03	14.21	1.67	1.39	14.57
Calc Head	100.00	7.56	21.27	100.00	15.09	31.16
Act Head	100.00	7.80	22.23	100.00	14.19	32.94
	Mill B - 2A 1/2" x 4" BOF Non-Mags, Stockpile			Mill B - 2B 1/2" x 4" BOF Non-Mags		
+2"	9.48	12.91	28.06	12.82	15.01	30.20
+1"	29.95	8.07	21.71	34.10	5.59	32.98
+3/4"	25.08	5.44	22.62	19.49	6.62	23.18
+1/2"	26.70	4.57	21.42	22.31	5.68	23.88
+3/8"	5.96	5.18	20.65	6.67	4.38	23.58
-3/8"	2.83	5.23	20.35	4.62	3.88	22.32
Calc Head	100.00	6.68	22.36	100.00	6.86	24.38
Act Head	100.00	5.27	22.06	100.00	5.37	23.00

Table 9. Mill C Size Distribution and Iron Content by Size for Sample 1B, 1D, 2B and 2D						
Size	Wt. %	% Fe Met.	% Fe Tot.	Wt. %	% Fe Met.	% Fe Tot.
	Mill C - 1B 3/4 x 6" Non-Mag BOF Slag			Mill B - 1D 3/4 x 6" Non-Mag Desulfurization Slag		
+4"	25.95	5.51	26.98	15.99	3.58	23.06
+2"	36.33	3.16	18.78	10.03	5.80	22.33
+1"	24.90	8.89	20.28	39.57	19.59	20.95
+3/4"	7.44	19.93	21.37	11.92	17.56	14.11
-3/4"	5.38	19.94	20.38			
+1/2"				6.23	19.66	18.86
-1/2"				16.26	3.16	17.96
Calc Head	100.00	7.35	21.56	100.00	12.74	19.99
Act Head	100.00	12.96	23.89	100.00	15.91	18.79
	Mill C - 2B -3/4" BOF Mag Fines			Mill C - 2D -3/4" Desulfurization Mag Fines		
+1/2"	7.19	67.27	77.89	4.31	60.56	74.92
+3 mesh	16.44	57.10	66.09	6.07	70.56	76.84
+8 mesh	34.85	40.40	51.23	31.91	45.55	56.15
+14 mesh	16.23	32.24	46.30	21.75	52.18	54.05
+28 mesh	11.26	32.62	38.26	17.47	44.30	51.75
+65 mesh	8.95	24.72	31.82	13.08	34.61	35.16
+100 mesh	1.83	19.48	23.94	1.91	10.34	21.79
+150 mesh	0.91	10.05	19.20	0.89	9.64	22.93
+200 mesh	0.91	6.60	16.03	0.83	7.01	20.51
-200 mesh	1.43	3.41	12.65	1.78	1.86	11.09
Calc Head	100.00	36.31	49.93	100.00	45.42	52.19
Act Head	100.00	49.08	51.22	100.00	50.94	52.27

Table 10. Mill C Size Distribution and Iron Content by Size for Sample 3B, 3D and 4B						
Size	Wt. %	% Fe Met.	% Fe Tot.	Wt. %	% Fe Met.	% Fe Tot.
	Mill C - 3B -3/4" BOF Non-Mag Fines			Mill C - 3D -3/4" Desulfurization Non-Mags		
+1/2"	11.20	16.33	29.28	17.83	29.75	31.60
+3 mesh	16.20	18.49	26.69	20.49	28.79	34.06
+8 mesh	29.94	23.30	30.92	27.13	38.70	40.95
+14 mesh	15.32	25.04	33.47	13.79	32.87	36.62
+28 mesh	10.56	24.60	29.28	10.00	33.65	33.85
+65 mesh	9.10	17.35	22.47	7.08	31.22	33.15
+100 mesh	2.33	13.10	19.83	1.34	19.18	21.92
+150 mesh	1.36	13.39	18.73	0.69	17.47	26.99
+200 mesh	1.52	4.14	16.07	0.66	14.82	21.49
-200 mesh	2.47	8.13	15.26	0.99	12.16	13.66
Calc Head	100.00	20.56	28.46	100.00	32.41	35.26
Act Head	100.00	23.79	28.77	100.00	36.57	40.54
	Mill C - 4B -1/4" BOF Mag Fines					
+1/2"	0.00	0.00	0.00			
+3 mesh	10.70	23.00	27.91			
+8 mesh	54.73	25.49	32.07			
+14 mesh	15.11	24.82	31.41			
+28 mesh	8.00	16.79	27.37			
+65 mesh	5.54	19.76	22.10			
+100 mesh	1.76	12.84	18.40			
+150 mesh	1.18	13.72	20.43			
+200 mesh	1.36	12.18	20.90			
-200 mesh	1.62	10.55	19.44			
Calc Head	100.00	23.32	29.86			
Act Head	100.00	22.94	29.65			

Table 11. Mill D Size Distribution and Iron Content by Size for Sample 1B, 2A, 2B, 5B						
Size	Wt. %	% Fe Met.	% Fe Tot.	Wt. %	% Fe Met.	% Fe Tot.
	Mill D - 1B -3/8" Desulfurization Fines			Mill D - 2A -3/8" BOF Mags & Desulfurization Fines Stockpile		
+1/2"	0.00	0.00	0.00	0.00	0.00	0.00
+3 mesh	6.60	68.07	77.94	15.46	5.97	29.50
+8 mesh	23.07	39.07	69.25	37.60	7.07	28.91
+14 mesh	16.85	33.01	54.71	15.08	4.99	29.28
+28 mesh	13.73	30.73	52.74	11.91	4.56	24.89
+65 mesh	18.87	14.46	56.41	12.56	2.75	23.91
+100 mesh	7.24	5.80	59.34	2.85	1.48	21.12
+150 mesh	4.04	5.79	59.37	1.38	1.77	20.29
+200 mesh	4.13	4.96	57.22	1.22	1.58	19.77
-200 mesh	54.70	5.40	45.63	1.95	0.48	17.12
Calc Head	100.00	27.18	59.78	100.00	5.32	27.27
Act Head	100.00	28.09	55.47	100.00	4.84	28.03
	Mill D - 2B -3/8" BOF Mag Fines			Mill D - 5B -3/8" BOF Non-Mag Fines		
+1/2"	0.00	0.00	0.00	0.00	0.00	0.00
+3 mesh	1.72	43.47	52.27	14.33	6.12	21.05
+8 mesh	39.06	39.20	48.86	33.47	5.40	29.32
+14 mesh	18.33	33.96	37.01	14.09	7.85	20.25
+28 mesh	14.65	37.93	44.04	9.44	10.58	21.32
+65 mesh	14.52	23.74	34.34	10.92	6.54	20.03
+100 mesh	4.15	15.25	19.57	4.33	2.51	17.52
+150 mesh	2.58	11.65	20.69	3.06	4.30	15.41
+200 mesh	2.41	12.70	17.66	3.71	2.47	16.73
-200 mesh	2.58	7.73	16.28	6.63	0.69	16.54
Calc Head	100.00	32.73	40.40	100.00	5.88	22.84
Act Head	100.00	37.88	41.88	100.00	5.63	22.51

Table 12. Mill D Size Distribution and Iron Content by Size for Sample 1B and 4B						
Size	Wt. %	% Fe Met.	% Fe Tot.	Wt. %	% Fe Met.	% Fe Tot.
	Mill D - 1B -3/8" Desulfurization Fines					
+2"	47.15	2.17	13.59			
+1"	44.73	3.65	19.10			
+3/4"	4.47	3.01	19.94			
-3/4"	3.65	4.68	20.97			
Calc Head	100.00	2.96	16.61			
Act Head	100.00	3.03	17.27			
	Mill D - 4B 3/8" x 1-1/2" BOF Non-Mags					
+1"	2.86	1.35	21.93			
+3/4"	18.54	3.14	21.82			
+1/2"	32.64	2.41	19.84			
+3/8"	29.00	3.16	22.14			
-3/8"	16.96	2.79	20.51			
Calc Head	100.00	2.80	21.05			
Act Head	100.00	3.19	23.89			

Table 13. XRD Analysis of Compounds Found to Exist in Slags Tested			
Di-Calcium Silicate	Ca_2SiO_4	Akermanite/Gelhenite	$\text{Ca}_2(\text{Al, Mg, Si})_3\text{O}_7$
Tri-Calcium Silicate	Ca_3SiO_5	Fe-Monticellite / Kirschsteinite	CaFeSiO_4
Calcium Iron Oxide	$\text{Ca}_2\text{Fe}_7\text{O}_{11}$ CaFeO_2	Rankinite	$\text{Ca}_3\text{Si}_2\text{O}_7$
Di-Calcium Ferrite	$\text{Ca}_2\text{Fe}_2\text{O}_5$	Merwinite	$\text{Ca}_3\text{MgSi}_2\text{O}_8$
Magnetite/Magnesio-ferrite	$\text{Fe}_3\text{O}_4/\text{MgFe}_2\text{O}_4$	Glaucochroite	CaMnSiO_4
Wustite	FeO	Calcite	CaCO_3
Periclase	MgO	Iron Metal	Fe
Corundum	Al_2O_3	Graphite	C

4.0 LABORATORY SEPARATION TESTS

4.1 PERFORMANCE SUMMARY

Slags from each mill were processed to obtain a +90% FeT product, a +60% FeT product, and a residual fraction. From each mill the desulfurization slag fines, magnetic BOF slag fines, and the non-magnetic slag fines were used for separation testing. Since the assays of the coarse non-magnetic slag fractions were very similar to the fines, it was felt that the separations for the material would be similar to the fines if ground sufficiently, thus, the coarse non-magnetic fractions were not separated.

The processing pattern required for the separation tests is depicted in Figure 1. The principles employed were to develop a representative amount of as-received material, size reduction for liberation, develop performance curves for identifying air classification settings, perform the air classification separation at identified settings, and determine quality, yield, and recovery of the product streams.

Tables 14-17 show the results from the laboratory separation tests. For the desulfurization slag fines the yield to the high-grade fraction ranged from 11.58-25.46%, which represents a metallic iron recovery range of 49.44-64.08% and a total iron recovery range of 18.85-53.48%. With regards to the mid-grade product for the desulfurization slag fines, yields ranged from 4.67% to 13.32%. This corresponds to a metallic iron recovery range of 8.14-25.63 and a total iron recovery range of 7.13-22.06%. Products from the desulfurization slag fines had a combined metallic iron recovery range of 69.23-87.12% and a total iron recovery range of 29.33-75.54%. In general the process performed fairly effectively on recovery of iron units. The residual fraction accounted for a large yield, ranging from 61.22 to 81.04% of the feed weight. The metallic iron content in the residuals ranged from 6.55 to 12.40%, with total iron content ranging from 17.39 to 50.52%. Comparing mills' desulfurization fines, Mills A, B, and C look to be quite similar in quality and separation performance. The quality for the desulfurization slag of Mill D was somewhat different in that it is lower in metallic iron content, yet higher in total iron content than the other mills, which seemed to produce less total iron recoveries to the products.

For the BOF magnetic fines the yield of the high grade fraction ranged from 8.48 to 30.04%, which represents a metallic iron recovery range of 37.32-75.73%, and a total iron recovery range of 20.17-64.05%. The mid-grade product for the BOF magnetic fines resulted in yields ranging from 5.76 to 10.92%, which corresponds to a metallic iron recovery range of 13.73-25.74% and a total iron recovery range of 11.89-19.22%. When combined the high and mid grade products represent a yield range of 15.26-38.72%, a metallic iron recovery range of 57.10-89.46%, and a total iron recovery range of 32.73-76.65%. The results are quite similar to that of the desulfurization slag tests. The residual fraction of BOF magnetic fines accounted for a yield range of 61.28-84.74% of the feed weight. The metallic iron content in the residuals ranged from 6.00 to 10.12%, with total iron content ranging from 16.52 to 29.92%. Comparing BOF magnetic fines between mills, Mills C and D, which are mills without a sintering plant, have a higher percentage of metallic iron in them than material from Mills A and B. Some of these are

attributable to making a coarser bottom size slag cut for Mill C, but Mills A and D both have a 3/8" size cut whereby there are still some differences.

Figure 1. IMP Process Pattern for Laboratory Separation Tests

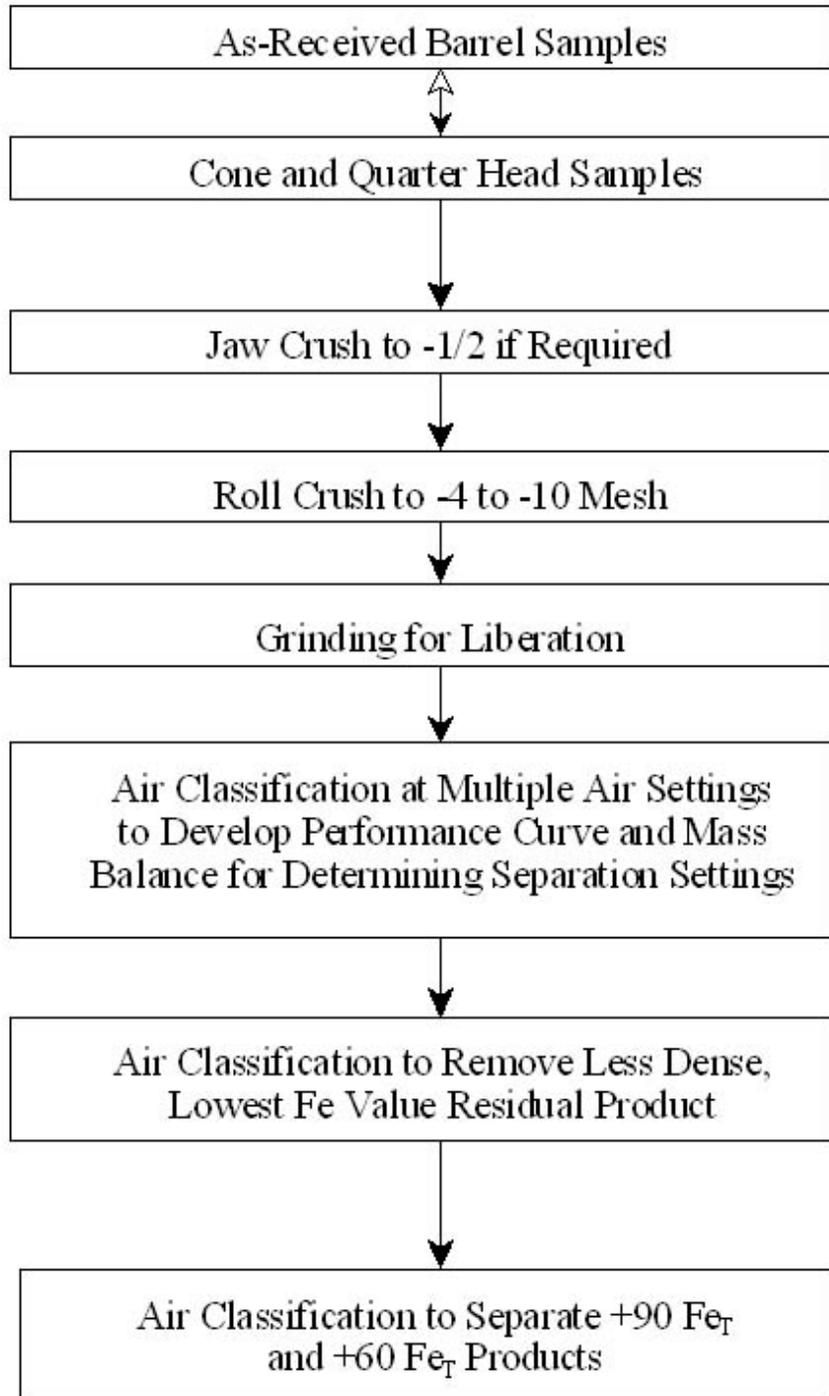


Table 14. Mill A Separation Performance					
Air Setting (in W.C.)	Wt. %	% Fe Met	FeM Rec.	% Fe Tot.	FeT Rec.
MA 1B – -3/8" Desulfurization Fines					
0.75 Sink	17.41	89.41	52.86	91.62	39.08
0.75 Liftings	9.52	50.63	16.37	59.27	13.82
0.17 Liftings	73.07	12.40	30.77	26.31	47.10
Calc Head	100.00	29.45		40.82	
MA 4A – -3/8" BOF Magnetic Fines, Stockpile					
2.10 Sink	8.48	86.93	37.32	88.62	20.17
2.10 Liftings	7.79	50.17	19.79	60.02	12.56
0.75 Liftings	83.73	10.12	42.90	29.92	67.27
Calc Head	100.00	19.75		37.24	
MA 3A – -3/8" BOF Non-Mags, Stockpile					
2.0 Sink	0.90	70.54	13.62	81.34	3.31
2.0 Liftings	1.20	65.20	16.79	70.05	3.80
0.50 Liftings	97.90	3.32	69.59	20.96	92.89
Calc Head	100.00	4.66		22.09	

Table 15. Mill B Separation Performance					
Air Setting (in W.C.)	Wt. %	% Fe Met	FeM Rec.	% Fe Tot.	FeT Rec.
MB 1A – Desulfurization Slag, Stockpile					
0.8 Sink	22.62	89.15	64.08	90.36	47.64
0.8 Liftings	4.67	54.87	8.14	65.47	7.13
0.50 Liftings	72.71	12.02	27.78	26.68	45.23
Calc Head	100.00	31.47		42.90	
MB 3B – -1/4" BOF Magnetic Fines					
2.0 Sink	9.50	89.10	51.83	89.64	26.47
2.0 Liftings	5.76	44.41	15.66	66.38	11.89
0.75 Liftings	84.74	6.26	32.51	23.40	61.64
Calc Head	100.00	16.33		32.17	
MB 4B – -1/4" BOF Non-Mag Fines					
2.0 Sink	1.30	88.80	26.54	90.55	5.41
2.0 Liftings	1.60	51.80	19.05	61.39	4.52
0.75 Liftings	97.10	2.44	54.41	20.17	90.07
Calc Head	100.00	4.35		21.74	

Table 16. Mill C Separation Performance					
Air Setting (in W.C.)	Wt. %	% Fe Met	FeM Rec.	% Fe Tot.	FeT Rec.
MC 2D – -3/4" Desulfurization Mag Fines					
1.40 Sink	25.46	86.55	62.25	91.45	53.48
1.40 Liftings	13.32	66.12	24.87	72.12	22.06
0.17 Liftings	61.22	7.45	12.88	17.39	24.46
Calc Head	100.00	35.40		43.54	
MC 2B – -3/4" BOF Magnetic Fines					
1.10 Sink	30.04	87.99	75.73	92.46	64.05
1.10 Liftings	8.68	55.24	13.73	62.96	12.60
0.17 Liftings	61.28	6.00	10.54	16.52	23.35
Calc Head	100.00	34.90		43.36	
MC 3B – -3/4" BOF Non-Mag Fines					
1.10 Sink	8.20	86.48	80.03	81.51	32.96
1.10 Liftings	20.84	4.48	10.53	20.38	18.66
0.17 Liftings	70.96	1.18	9.44	15.52	48.38
Calc Head	100.00	8.86		22.76	

Table 17. Mill D Separation Performance					
Air Setting (in W.C.)	Wt. %	% Fe Met	FeM Rec.	% Fe Tot.	FeT Rec.
MD 1B – 3/8" Desulfurization Fines					
1.10 Sink	11.58	90.94	49.44	94.30	18.85
1.10 Liftings	7.38	73.97	25.63	82.24	10.48
0.17 Liftings	81.04	6.55	24.93	50.52	70.67
Calc Head	100.00	21.30		57.93	
MD 2B – -3/8" BOF Magnetic Fines					
1.40 Sink	14.48	89.22	48.15	92.88	34.45
1.40 Liftings	10.92	63.24	24.74	68.72	19.22
0.50 Liftings	74.60	9.39	26.11	24.24	46.33
Calc Head	100.00	26.83		39.03	
MD 5 – -3/8" BOF Non-Mag Fines					
1.40 Sink	3.35	71.19	47.97	78.43	11.38
1.40 Liftings	7.90	13.87	22.03	34.78	11.90
0.50 Liftings	88.75	1.68	30.00	19.97	76.72
Calc Head	100.00	4.97		23.10	

For the low-in-iron units BOF non-magnetic fines, the separation process proved that high and mid-grade products could be obtained, however, the resultant yields are low. The yield of the high grade fraction ranged from 1.3 to 8.2%, which represents a metallic iron recovery range of 26.54 to 80.03% and a total iron recovery range of 5.41 to 32.96%. Only material from Mills B and C were able to obtain high-grade products of ~90% FeT in content. The mid-grade product (+60% FeT) was obtained in three of the four BOF non-magnetic fines materials, with yields ranging from 1.60 to 3.35%. The metallic iron recovery ranged from 19.05-47.97% and

the total iron recovery range was 4.52-11.38%. When combined the high and mid-grade products represent a yield range of 2.10 to 8.20% of the feed weight. The corresponding yields in the residuals fraction of the BOF non-magnetic fines therefore, range from 91.80-97.90%. The metallic iron content in the residual fraction is quite low, ranging from 1.93 to 3.32%. The total iron content of the residual fraction ranges from 16.62 to 21.18%. Overall, the head assays for Fe metallic and Fe total were close for the BOF non-magnetic fines samples from all mills tested, yet somewhat different performance in each mills case.

4.2 PRODUCT SIZE DISTRIBUTIONS

To further understand the products produced in the laboratory air classification separation tests, one should look at the size distribution of the products produced. Figure 2 compares the size distribution between mills for the high grade products produced from desulfurization slag fines. From Figure 2, it can be seen that this product is relatively coarse with almost all the material being coarser than 35 mesh. Between mills, Mill D tended to be coarser in composition than the other mills.

Figure 3 compares the size distribution between mills for the mid-grade products produced from desulfurization slag fines. For this product which is composed of metallics and oxides, one may expect some difference in size distribution because of the differences in densities between the oxides and metallics. Generally, this product showed a relatively tight size distribution where most of the material is coarser than 65 mesh. The spaced parallel nature of the curves indicates similarities and differences. The similar slope of the curves indicates that common cumulative distribution can be expected for this product, with the space difference between the curves being dictated by the relationship of density and particle size. Mill D, for example has the finest size distribution which may indicate the presence of more metallic iron. This seems to be the case if one compares metallic iron values for this fraction in Tables 13-16.

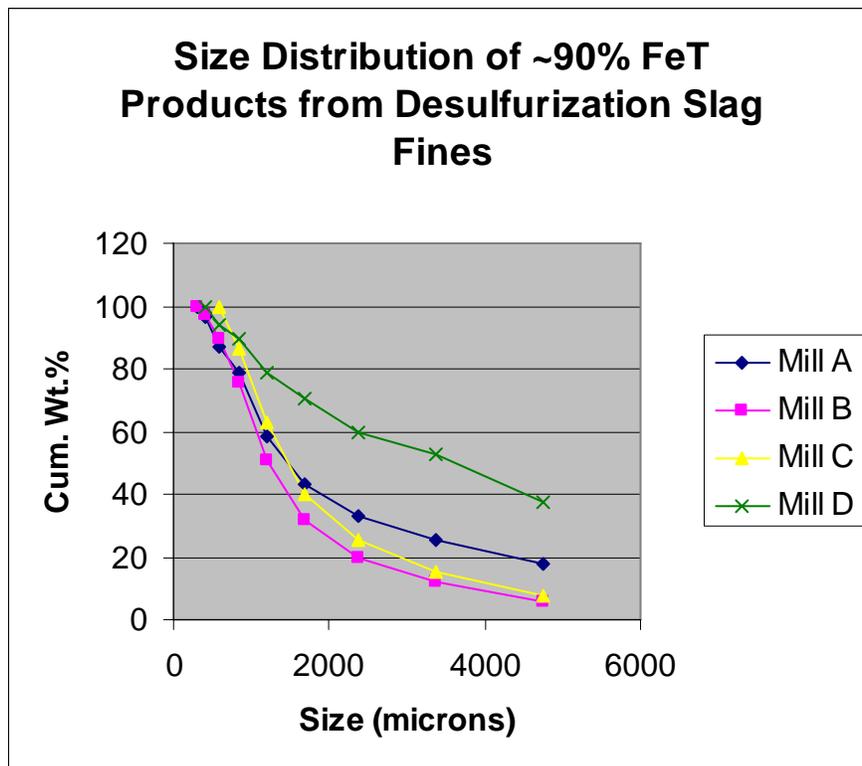
Figure 4 compares the size distribution between mills for the high grade product produced from BOF magnetic fines. Overall, this product is generally coarser than 28 mesh, slightly coarser than the high grade product distribution from desulfurization slag fines discussed previously. When compared to Figure 2 there exists a tighter packing of curves in Figure 4, indicating a more consistently sized high grade product can be expected from BOF magnetic fines. Mill D has the finest size distribution. Based on logic discussed above it would be expected therefore, to have the highest metallic iron content. Again, referencing Tables 13-16 that assumption seems to hold true.

Figure 5 compares the size distribution between mills for the mid-grade product produced from BOF magnetic fines. The mid-grade product derived from BOF magnetic fines is very similar to that of the mid-grade product produced from desulfurization slag fines, with almost all material being coarser than 65 mesh. Based on previous results, the Mill C curve should indicate more metallics as it possesses a finer size distribution. Referencing Tables 13-16 it can be seen that actually Mill D has a higher metallic iron content, thereby nullifying a relationship that has held true until now.

Because of very low yields of high and mid-grade products from BOF non-magnetic fines, it was elected to not pursue screen analysis quantities for those fractions.

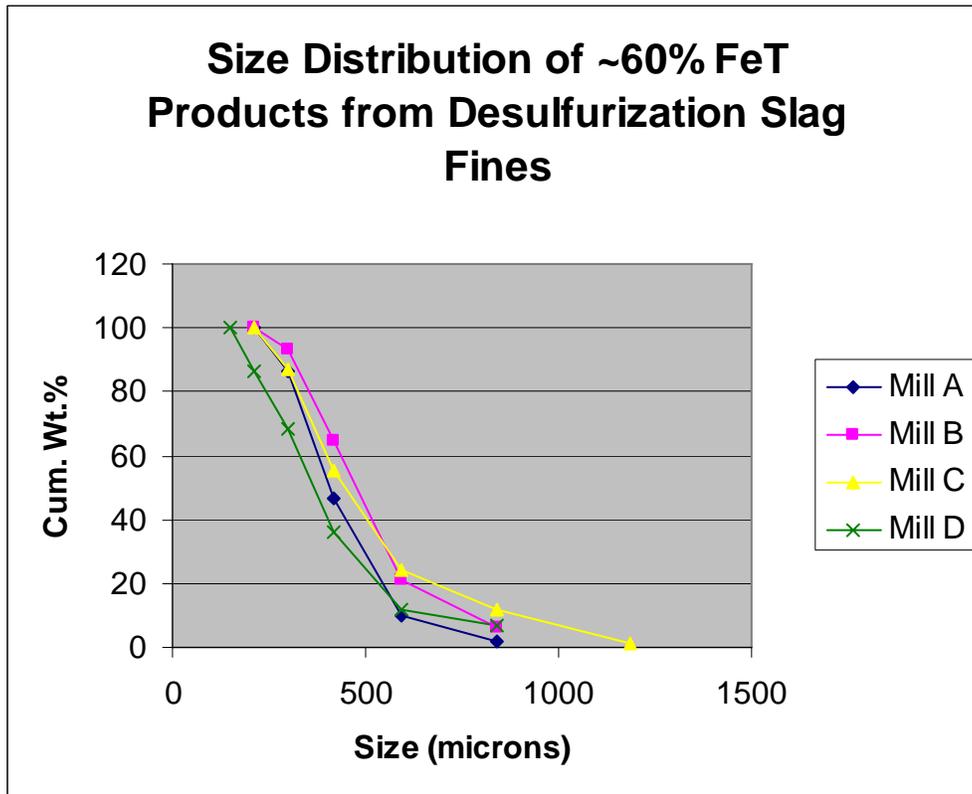
**Figure 2. Size Distribution of ~90% FeT Products from Desulfurization Slag Fines
Cumulative Weight % by Size**

Size (mesh)	Size (microns)	Mill A	Mill B	Mill C	Mill D
+4mesh	4760	17.92	5.41	7.34	37.59
+6mesh	3360	25.23	12.17	15.29	52.48
+8mesh	2380	32.79	19.60	25.16	59.93
+10mesh	1682	43.45	31.81	40.18	70.21
+14mesh	1188	58.41	50.57	63.06	78.72
+20mesh	841	78.43	75.26	86.46	89.36
+28mesh	594	87.14	89.24	100.00	93.97
+35mesh	420	96.50	97.19		100.00
-35mesh	297	100.00	100.00		



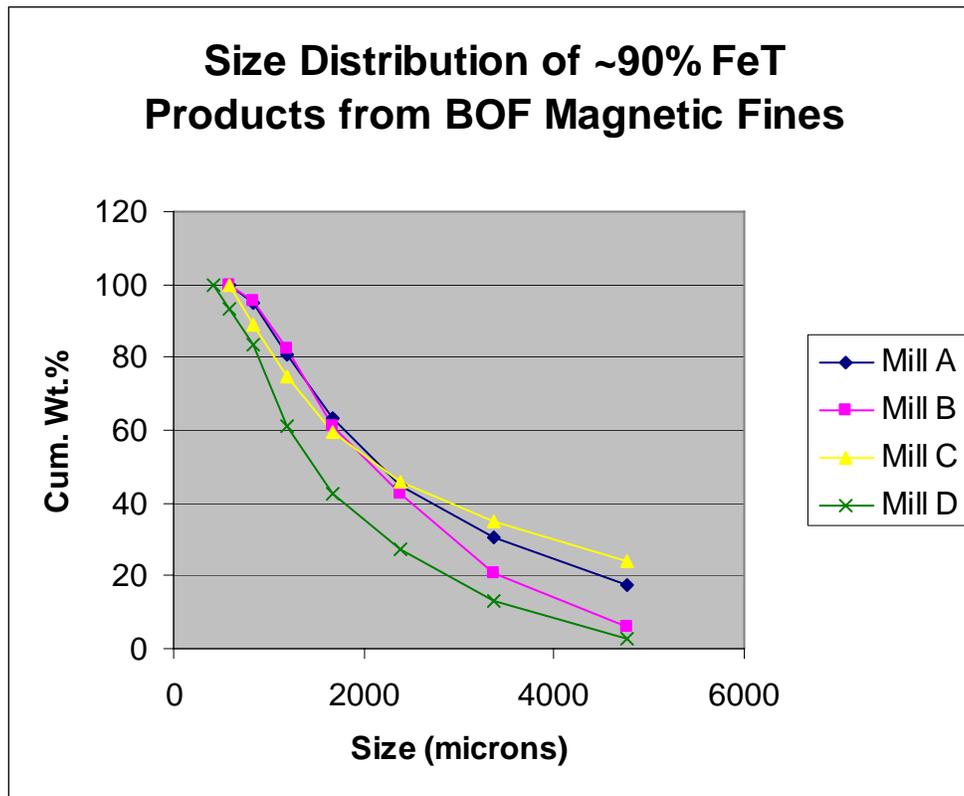
**Figure 3. Size Distribution of ~60% FeT Products from
Desulfurization Slag Fines
Cumulative Weight % by Size**

Size (mesh)	Size (microns)	Mill A	Mill B	Mill C	Mill D
+14mesh	1188			1.35	
+20mesh	841	2.06	6.47	11.94	6.87
+28mesh	594	9.74	21.14	24.21	11.83
+35mesh	420	46.82	64.92	55.13	36.26
+48mesh	297	86.52	93.53	87.23	68.32
+65mesh	210	100.00	100.00	100.00	86.26
-65mesh	149				100.00



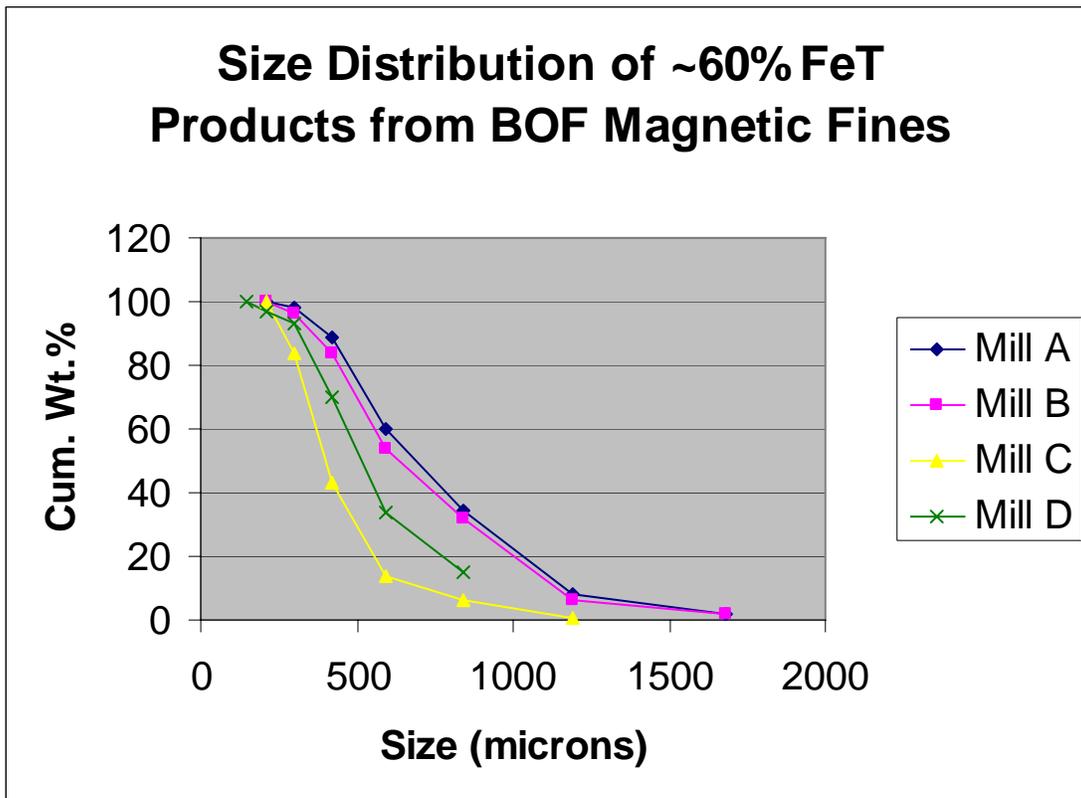
**Figure 4. Size Distribution of ~90% FeT Products from BOF
Magnetic Fines
Cumulative Weight % by Size**

Size (mesh)	Size (microns)	Mill A	Mill B	Mill C	Mill D
+4mesh	4760	17.68	6.21	24.00	2.53
+6mesh	3360	30.43	20.76	34.66	13.06
+8mesh	2380	44.63	42.37	45.70	27.10
+10mesh	1682	63.47	61.16	59.48	42.50
+14mesh	1188	80.87	82.49	74.74	61.02
+20mesh	841	95.07	95.20	88.96	83.63
+28mesh	594	100.00	100.00	100.00	93.18
-28mesh	420				100.00



**Figure 5. Size Distribution of ~60% FeT Products from BOF
Magnetic Fines
Cumulative Weight % by Size**

Size (mesh)	Size (microns)	Mill A	Mill B	Mill C	Mill D
+10mesh	1682	2.14	1.92		
+14mesh	1188	7.91	6.55	0.77	
+20mesh	841	34.62	31.95	6.18	14.69
+28mesh	594	60.26	54.00	13.66	33.76
+35mesh	420	88.89	83.55	43.30	70.10
+48mesh	297	98.29	96.49	84.02	93.04
+65mesh	210	100.00	100.00	100.00	96.65
-65mesh	149				100.00



The residual fractions compose a high weight percentage of the separations. Ultimately a large volume application will have to be recognized or developed for this material, such as AMD treatment technology. A discussion concerning size distribution of this material is included in this report to provide preliminary insight regarding this material. Figures 6 through 9 provide clear indication that the residuals from processing either desulfurization fines, BOF magnetic fines, or BOF non-magnetic fines at particular mill sites can be expected to have very similar size distributions. Figures 10 through 12 show the similar nature of the residual size distribution between mills for BOF magnetic fines, desulfurization slag fines, and BOF non-magnetic fines. Overall, given a consistent grinding scheme, one can expect the residual product to be quite homogeneous, as supported with 76.95-81.08% of the material being coarser than 270 mesh for the materials tested.

4.3 CHEMICAL ANALYSIS OF HGI AND MGI PRODUCTS

The high-grade and medium grade iron (~90% FeT, ~60% FeT) products from the separation were sent out to each companies' lab for complete chemical analysis. The companies were instructed to perform the analysis as needed to run their steelmaking models or to comply with how they evaluate a material for charging into their systems. The analyses that were performed are provided in Tables 18 through 21. As seen from these analyses, the verification of total iron content present in the products is fairly close to the targeted qualities. With regards to impurities, the primary ones of concern among participating steel companies were phosphorus and sulfur, as this to a large extent would limit how much material could be effectively charged without ruining metal quality of their respective operations.

Taking a closer look at the analysis, the following observations can be made. The results verify that the ~90%FeT products were obtainable for all mills from both desulfurization fines and BOF magnetic fines. The BOF magnetic fines high-grade products all contain reasonably low amounts of P and S. For the desulfurization fines high-grade, Mill B showed a larger amount of P and S than the other mills.

For the ~60% FeT medium grade products, the results obtained from Mill B were somewhat lower than expected, while the results from all the other mills were in line with what would be expected. The ~60% FeT products from desulfurization fines, as would be somewhat expected, contained considerable amounts of sulfur and in two out of four case phosphorous as well, which could limit the amount that could be charged to the BF. The medium-grade product from BOF magnetic fines in two out of four cases surprisingly showed considerable sulfur present, and in the case of Mill B substantially more phosphorous than experienced in other mills.

Analysis (%)	Desulf. Slag Products		BOF Slag Products	
	~ 90 FeT	~ 60 FeT	~ 90 FeT	~ 60 FeT
FeT	92.29	60.12	94.33	70.13
S	0.05	0.20	0.02	0.07
P	0.04	0.16	0.04	0.11
Pb	<0.01	<0.01	N/A	<0.01
Zn	0.00	0.02	N/A	0.01
Al ₂ O ₃	0.32	3.08	0.15	1.15
CaO	1.36	2.45	0.89	10.39
K ₂ O	0.00	0.00	0.00	0.00
MgO	0.45	6.32	0.25	3.48
MnO	0.23	3.24	0.14	1.86
Na ₂ O	0.65	0.02	0.01	0.07
SiO ₂	0.78	9.65	0.44	3.84
Sr	<0.01	<0.01	<0.01	0.01
TiO ₂	0.05	0.51	0.03	0.41
ZrO ₂	0.00	0.02	0.00	0.01
Cr ₂ O ₃	0.03	0.30	0.01	0.17
FeO	12.10	41.74	N/A	28.25
C	0.64	1.38	0.15	0.55

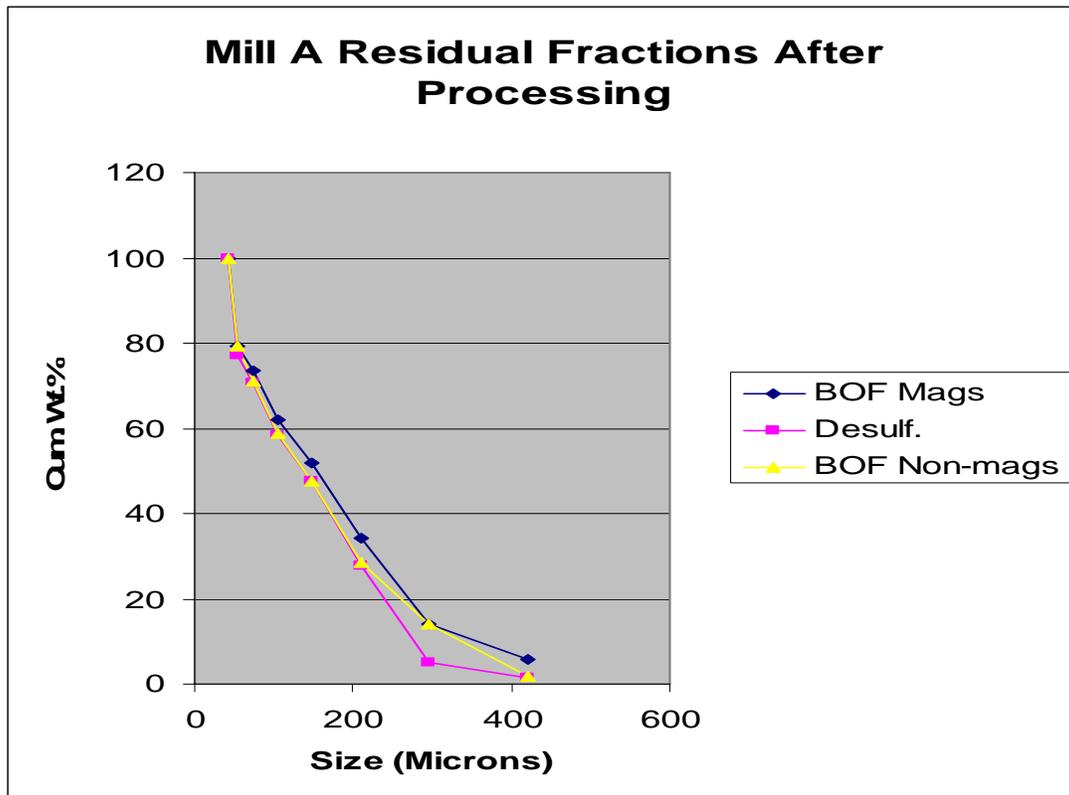
Analysis (%)	Desulf. Slag Products		BOF Slag Products	
	~ 90 FeT	~ 60 FeT	~ 90 FeT	~ 60 FeT
FeT	88.95	50.91	88.76	48.83
S	0.14	0.46	0.02	0.05
P	0.33	0.22	0.02	0.33
Pb	<0.002	<0.002	<0.002	<0.002
Zn	0.00	0.01	0.00	0.01
Al ₂ O ₃	0.24	3.10	0.18	2.36
CaO	1.73	20.50	1.46	21.67
K ₂ O	<0.005	0.01	<0.005	<0.005
MgO	0.51	5.16	0.36	5.16
MnO	0.20	2.37	0.19	2.57
Na ₂ O	0.02	0.01	<0.005	0.01
SiO ₂	0.59	6.98	0.44	6.07
Fe ₂ O ₃	0.90	0.90	0.94	10.92
Cr ₂ O ₃	0.02	0.18	0.02	0.22
FeO	0.81	8.49	1.85	12.16
C	2.81	1.47	0.26	0.27
Fe Met	87.69	38.86	86.67	31.77

Analysis (%)	Desulf. Slag Products		BOF Slag Products	
	~ 90 FeT	~ 60 FeT	~ 90 FeT	~ 60 FeT
FeT	92.90	79.38	92.99	72.31
S	0.06	0.25	0.04	0.20
P	0.00	0.05	0.00	0.08
Pb	<0.002	<0.002	<0.002	<0.002
Zn	0.00	0.01	<0.002	0.01
Al ₂ O ₃	0.02	0.96	0.03	1.64
CaO	0.24	5.66	0.21	9.24
K ₂ O	<0.005	0.01	<0.005	0.01
MgO	0.06	1.51	0.06	2.56
MnO	0.05	0.98	0.05	1.72
Na ₂ O	<0.005	0.02	0.02	0.02
SiO ₂	0.14	2.62	0.13	4.34
Fe ₂ O ₃	0.64	2.99	0.60	6.23
Cr ₂ O ₃	0.01	0.11	0.01	0.21
FeO	<0.50	3.02	<0.50	6.26
C	1.90	2.63	2.41	2.17
Fe Met	92.45	74.95	92.57	63.10

Analysis (%)	Desulf. Slag Products		BOF Slag Products	
	~ 90 FeT	~ 60 FeT	~ 90 FeT	~ 60 FeT
FeT	91.49	68.95	91.30	58.59
S	0.09	0.27	0.11	0.38
P	0.04	0.02	0.03	0.09
Al ₂ O ₃	0.08	0.56	0.14	1.70
CaO	2.09	3.27	3.65	14.22
K ₂ O	0.00	0.02	0.00	0.03
MgO	0.21	2.14	0.52	3.94
MnO	0.39	0.36	0.28	1.21
Na ₂ O	0.01	0.05	0.01	0.04
SiO ₂	1.81	1.87	1.31	5.14
TiO ₂	0.05	0.08	0.08	0.34
Sn	0.00	0.00	0.00	0.00
Cu	0.00	0.00	0.01	0.00
Ni	0.00	0.00	0.00	0.00
Mo	0.00	0.00	0.00	0.00
Co	0.00	0.00	0.00	0.00
As	0.00	0.00	0.00	0.00
V	0.01	0.00	0.01	0.01
LOI	35.55	26.98	34.86	22.95

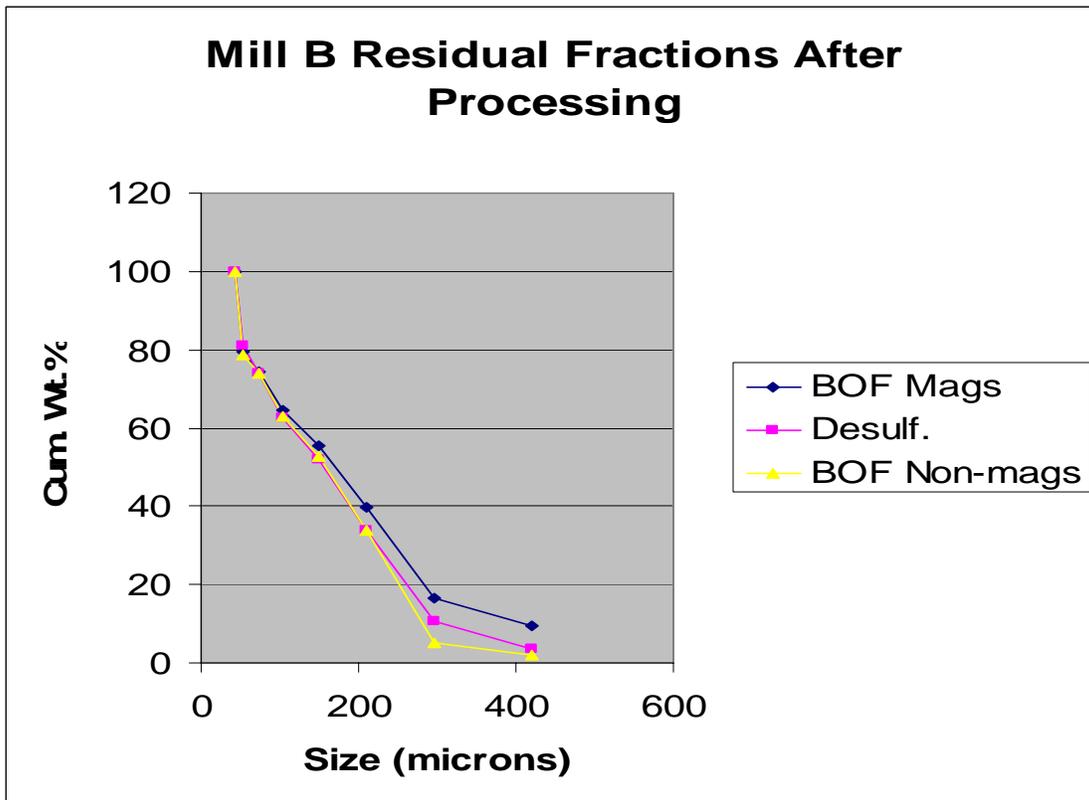
**Figure 6. Mill A Residual Fractions After Processing
Cumulative Weight % by Size**

Size (mesh)	Size (microns)	BOF Mags	Desulf.	BOF Non-mags
+35mesh	420	5.72	1.40	1.68
+48mesh	297	14.08	5.08	14.20
+ 65mesh	210	34.31	27.87	28.41
+100mesh	149	51.91	47.50	47.66
+150mesh	105	62.02	58.37	58.69
+200mesh	74	73.61	70.64	71.03
+270mesh	53	79.18	76.95	79.25
-270mesh	44	100.00	100.00	100.00



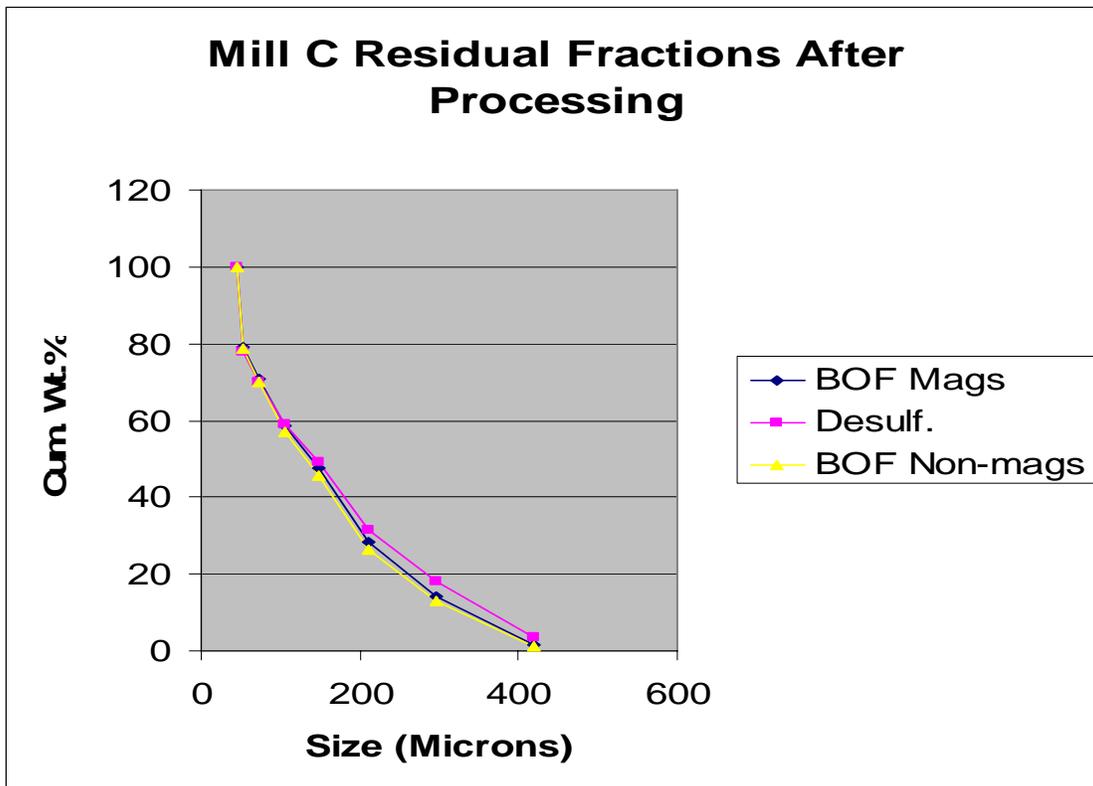
**Figure 7. Mill B Residual Fractions After Processing
Cumulative Weight % by Size**

Size (mesh)	Size (microns)	BOF Mags	Desulf.	BOF Non-mags
+35mesh	420	9.59	3.62	1.85
+48mesh	297	16.44	10.46	4.94
+ 65mesh	210	39.73	33.80	33.95
+100mesh	149	55.62	52.11	52.88
+150mesh	105	64.38	62.37	62.96
+200mesh	74	74.25	74.04	74.07
+270mesh	53	79.45	81.08	78.81
-270mesh	44	100.00	100.00	100.00



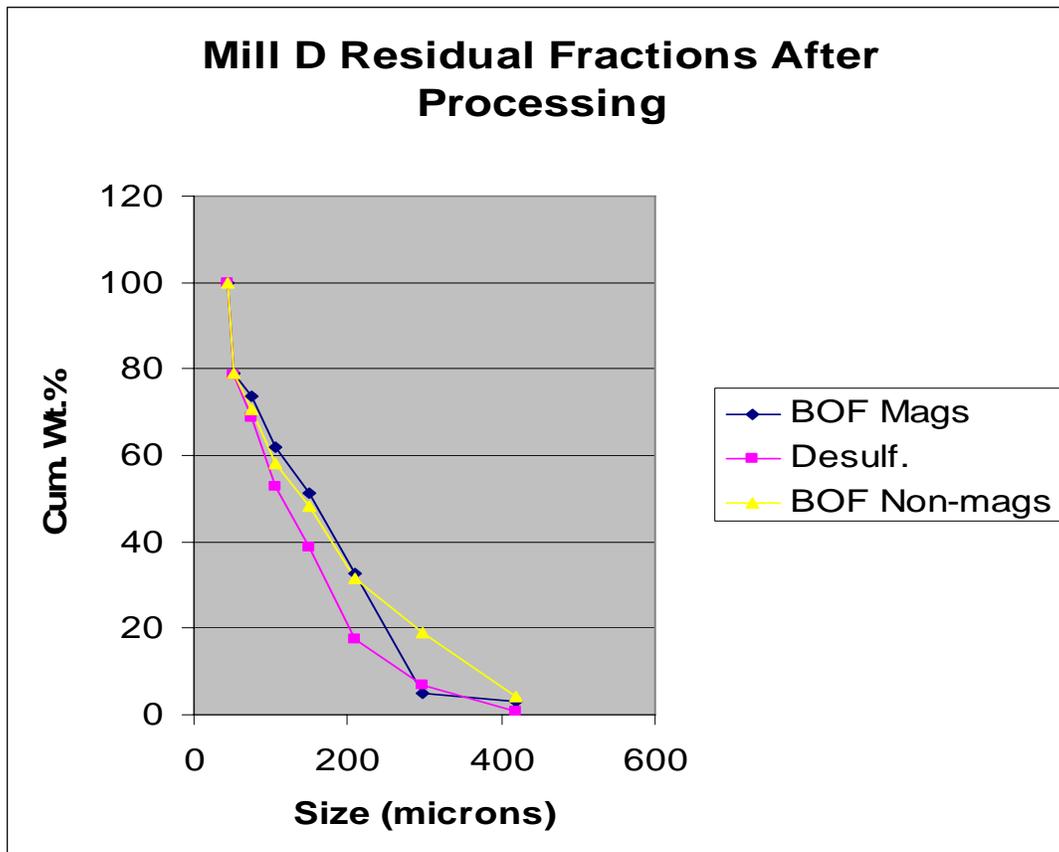
**Figure 8. Mill C Residual Fractions After Processing
Cumulative Weight % by Size**

Size (mesh)	Size (microns)	BOF Mags	Desulf.	BOF Non-mags
+35mesh	420	1.72	3.42	1.20
+48mesh	297	14.32	17.95	13.02
+ 65mesh	210	28.36	31.63	26.55
+100mesh	149	47.56	49.15	45.56
+150mesh	105	58.45	58.98	56.86
+200mesh	74	70.77	70.09	69.87
+270mesh	53	79.08	77.78	78.60
-270mesh	44	100.00	100.00	100.00



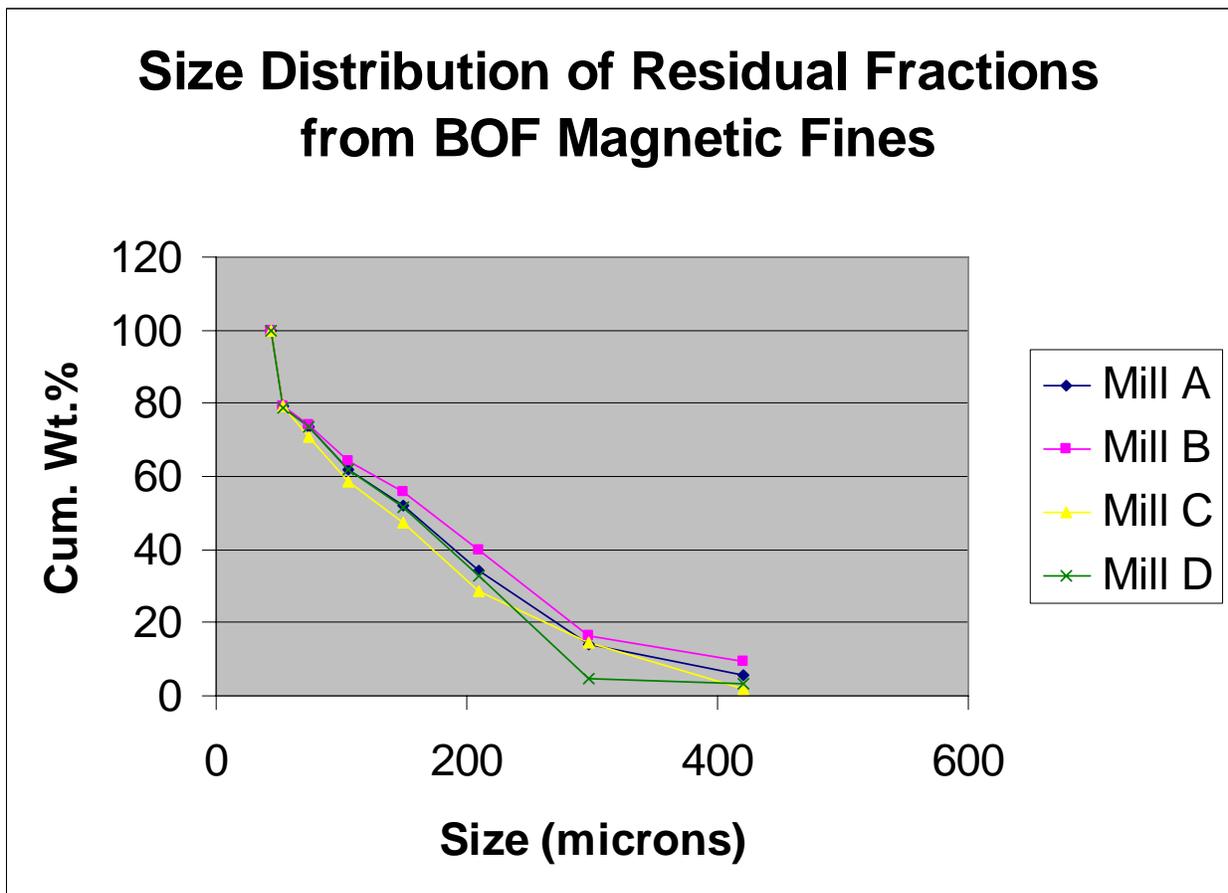
**Figure 9. Mill D Residual Fractions After Processing
Cumulative Weight % by Size**

Size (mesh)	Size (microns)	BOF Mags	Desulf.	BOF Non-mags
+35mesh	420	3.11	0.65	4.22
+48mesh	297	4.81	6.86	18.88
+ 65mesh	210	32.78	17.64	31.33
+100mesh	149	51.42	38.88	48.20
+150mesh	105	61.87	52.61	58.24
+200mesh	74	73.73	68.62	70.49
+270mesh	53	78.81	78.43	79.12
-270mesh	44	100.00	100.00	100.00



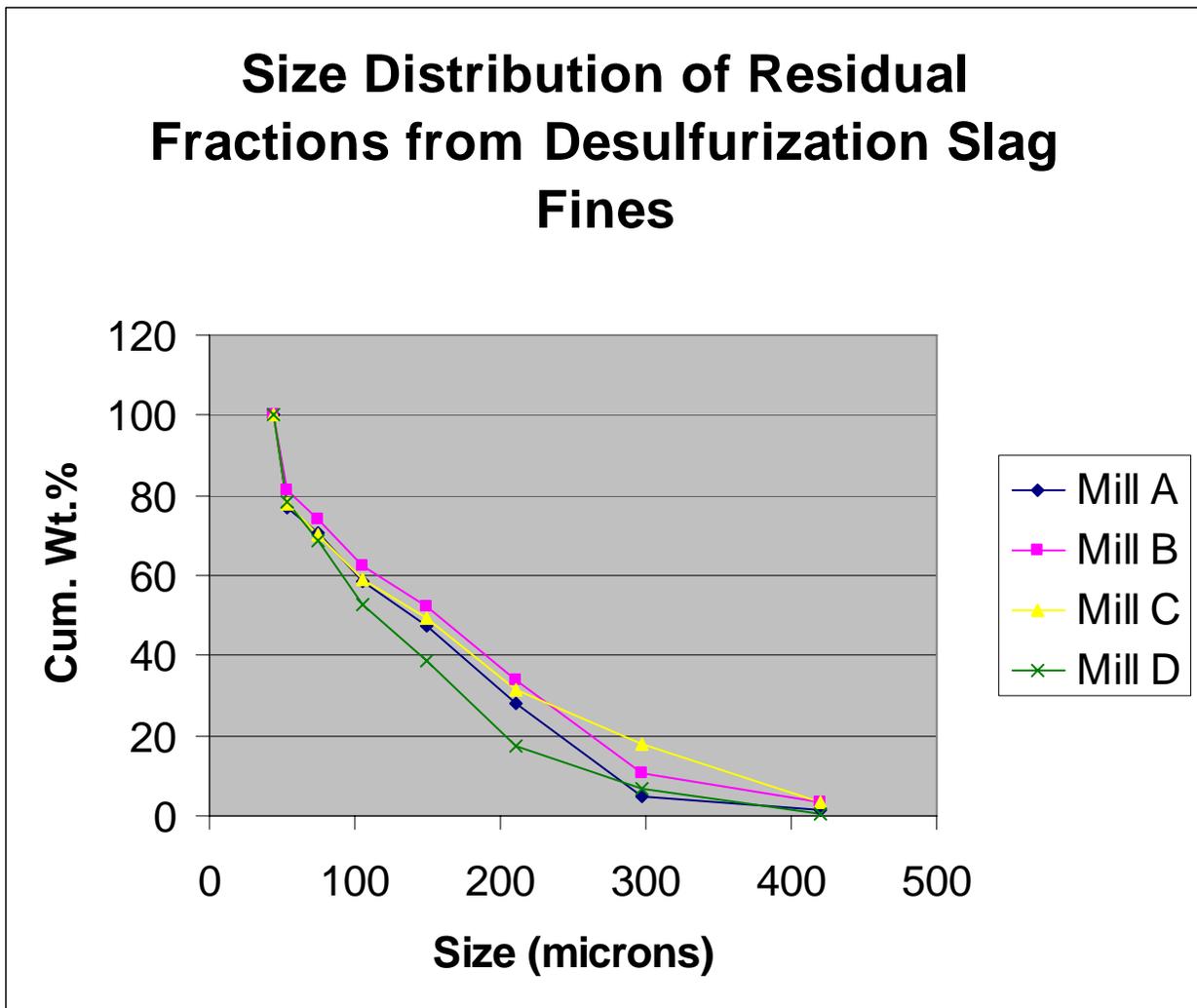
**Figure 10. Size Distribution of Residual Fractions from BOF Magnetic Fines
Cumulative Weight % by Size**

Size (mesh)	Size (microns)	Mill A	Mill B	Mill C	Mill D
+35mesh	420	5.72	9.59	1.72	3.11
+48mesh	297	14.08	16.44	14.32	4.81
+ 65mesh	210	34.31	39.73	28.36	32.78
+100mesh	149	51.91	55.62	47.56	51.42
+150mesh	105	62.02	64.38	58.45	61.87
+200mesh	74	73.61	74.25	70.77	73.73
+270mesh	53	79.18	79.45	79.08	78.81
-270mesh	44	100.00	100.00	100.00	100.00



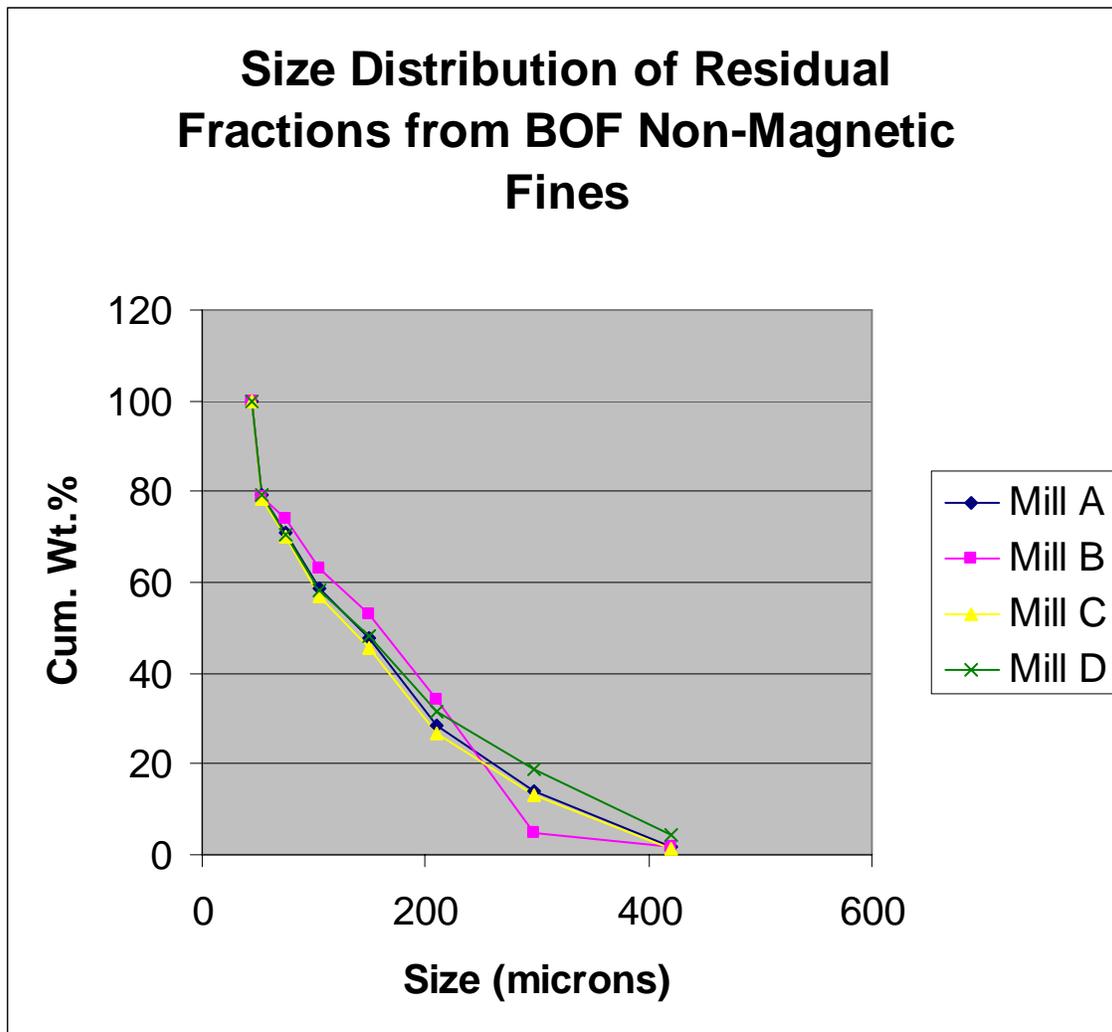
**Figure 11. Size Distribution of Residual Fractions from Desulfurization Slag Fines
Cumulative Weight % by Size**

Size (mesh)	Size (microns)	Mill A	Mill B	Mill C	Mill D
+35mesh	420	1.40	3.62	3.42	0.65
+48mesh	297	5.08	10.46	17.95	6.86
+ 65mesh	210	27.87	33.80	31.63	17.64
+100mesh	149	47.50	52.11	49.15	38.88
+150mesh	105	58.37	62.37	58.98	52.61
+200mesh	74	70.64	74.04	70.09	68.62
+270mesh	53	76.95	81.08	77.78	78.43
-270mesh	44	100.00	100.00	100.00	100.00



**Figure 12. Size Distribution of Residual Fractions from BOF Non-Magnetic Fines
Cumulative Weight % by Size**

Size (mesh)	Size (microns)	Mill A	Mill B	Mill C	Mill D
+35mesh	420	1.68	1.85	1.20	4.22
+48mesh	297	14.20	4.94	13.02	18.88
+ 65mesh	210	28.41	33.95	26.55	31.33
+100mesh	149	47.66	52.88	45.56	48.20
+150mesh	105	58.69	62.96	56.86	58.24
+200mesh	74	71.03	74.07	69.87	70.49
+270mesh	53	79.25	78.81	78.60	79.12
-270mesh	44	100.00	100.00	100.00	100.00



4.4 LGI PRODUCT EVALUATION

In Section 3.3 the compounds composing the slags are identified and in Section 4.1 and 4.3, we have shown that the high grade product is composed primarily of metallic iron, with the mid-grade composed of a high percentage of metallic iron and iron oxide. To explore the possibility of iron unit enhanced recovery, and to understand in more detail the composition of the residues, a detailed look at the residual fraction was performed.

The residual fractions from desulfurization slag fines, BOF magnetic fines, and BOF non-magnetic fines from Mill B were examined in greater detail to understand quantities of compounds present and how they are related to potential enhanced iron unit recovery.

The dominant phases, compounds, or minerals present are depicted in Table 22 along with a quantitative determination.

Compound	Desulfurization Fines (Vol. %)	BOF Mag. Fines (Vol. %)	BOF Non-Mag Fines (Vol. %)
Aluminum Silicate	1.8	0.8	0.5
Dicalcium Silicate	20.9	27.2	33.1
Melelite Group	8.0	4.3	5.3
Metallic Iron	22.6	3.2	2.3
Magnesium Ferrite	31.1	43.9	49.1
Wustite	6.9	15.0	6.0
Periclase	3.8	3.5	2.3
Other Oxides	4.9	2.1	1.4
Total	100.0	100.0	100.0

Where:

Aluminum Silicates: a glassy component containing only these elements in various proportions.

Dicalcium Silicate: Lime Olivine $2\text{CaO}\cdot\text{SiO}_2$

Melilite Group: $\text{Ca}_2\text{MgSi}_2\text{O}_7$

Metallic Iron: Fe

Magnesium Ferrite: Partially reduced forms of MgFe_2O_4

Wustite: FeO

Periclase: MgO

Other oxides: finely textured mixture of other components that could not be distinguished further (1-5% of these samples)

Table 23 provides an estimate on how the total iron quantity present is proportioned into various compounds. Because of the small sample quantities used, these numbers should be viewed from a relative basis rather than on an absolute basis for information provided in Tables 14 and 15.

Compound	Desulfurization Fines (Vol. %)	BOF Mag. Fines (Vol. %)	BOF Non-Mag. Fines (Vol. %)
Metallic Iron	54.1	9.5	8.4
Magnesium Ferrite	31.3	54.9	74.2
Wustite	12.9	34.6	16.7
Other Oxides	1.7	1.0	0.7
Total	100.0	100.0	100.0

From Tables 22 and 23 it can be seen that there remains considerable metallic iron in the residual fraction of the desulfurization fines, and magnesium ferrite compounds account for a significant amount of the total iron in all the samples.

SEM image analyses were performed on the residuals from processing of the various slags. The results are portrayed in Figure 13. Images 1, 2, and 4 address the residual material produced from desulfurization slags. Image 1 identifies that there are some liberated metallic iron particles in the residuals which are of particle size just slightly smaller than 65 mesh in one dimension. From this information the first inclination is to state that the separation process employed was not optimized, and needs fine tuning. Images 2 and 3 illustrate that there are slightly smaller than 65 mesh particles that are a true middling. In Image 2 the metallic iron content looks to be approximately 40-50% by cross-sectioned area, and is locked in a wustite matrix. In Image 4, the metallic iron content looks to be roughly 60% by cross-sectioned area, and in this case is locked within a periclase matrix. The particles in images 2 and 4, thus, would address the need for further liberation in future work, realizing that true middling particles of this nature have an overall density that is lighter and makes it non-recoverable by air classification at some point. Addressing these issues in future work has the potential to further increase iron unit recovery.

Image 3 addresses the residual material product from the BOF magnetic fines. Here we find sparse metallic iron in the cross-sectioned area, a true mixture of many compounds, and a crossing influence of primarily dicalcium silicate and magnesium ferrite into one another. The metallic iron has a definite association with magnesium ferrite and not with other compounds present. Because of the crossing over nature of the magnesium ferrite and dicalcium silicate, effective liberation through further grinding would be difficult. Iron unit losses therefore, could be expected to still exist, particularly those iron units associated with magnesium ferrite and any metallics encapsulated by it. If Image 4 is a true indicator of iron unit distribution in the residuals of the BOF magnetic fines, further processing may not be worth the time and dollars needed to do this, thus defining these iron units as potentially non-recoverable.

The next phase of this project will have to more closely evaluate liberation and determine at what particle size other novel separating techniques may be effective, yet realizing also that just as importantly, the economics of further processing.

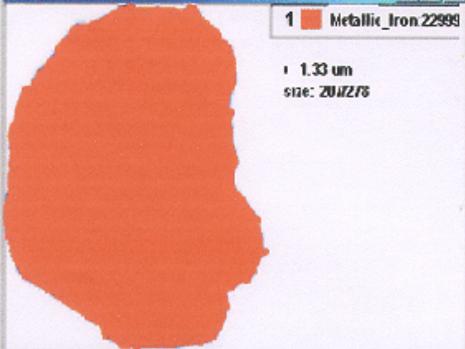
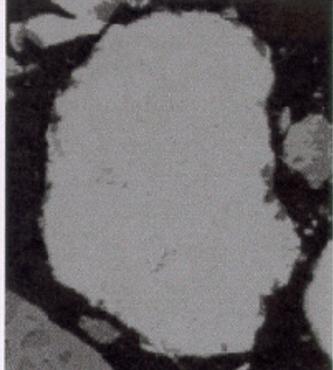
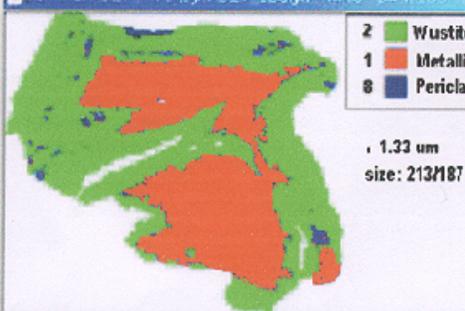
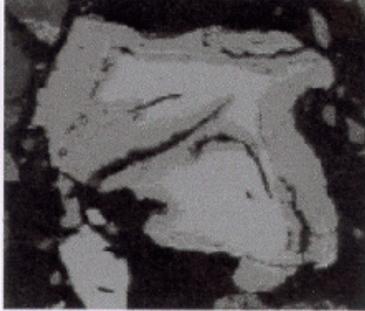
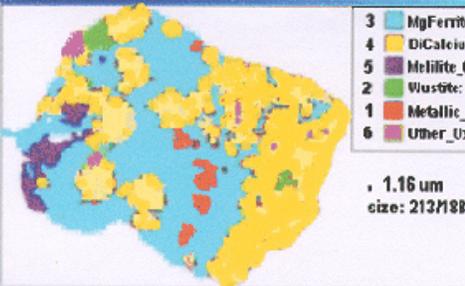
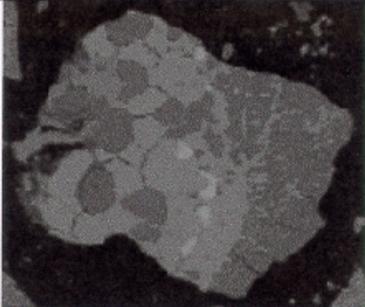
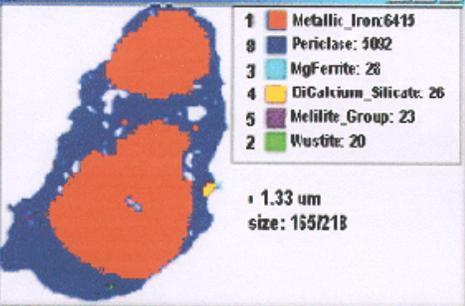
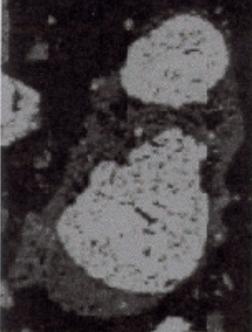
No	Processed MLA Image of Particle	Original SEM Image
1	 <p>1 Metallic_Iron:22598 1.33 um size: 204278</p>	
2	 <p>2 Wustite: 8480 1 Metallic_Iron:5733 8 Periclase: 67 1.33 um size: 213187</p>	
3	 <p>3 MgFerrite: 9213 4 DiCalcium_Silicate: 8730 5 Melilite_Group: 647 2 Wustite: 540 1 Metallic_Iron:368 6 Other_Oxides: 198 1.16 um size: 213188</p>	
4	 <p>1 Metallic_Iron:6415 8 Periclase: 5082 3 MgFerrite: 26 4 DiCalcium_Silicate: 26 5 Melilite_Group: 23 2 Wustite: 20 1.33 um size: 155218</p>	

Figure 13. SEM images of residual material from desulfurization slags (Images 1, 2, 4) and BOF magnetic fines (Image 3).

5.0 BINDER EVALUATION

5.1 BINDER TYPES

Pelletization of iron units recovered from slag requires binders that act quickly, and that have good ability to hold pellets together while they are being heated. The best available candidates are bentonite, and fly ash/calcium hydroxide mixtures. Other possible low-cost binders also exist, such as cement-bentonite mixtures, and these should also be investigated. This type of binder is added to briquettes at a dosage of approximately 10 percent by weight of the oxides. The binder is 75-85 percent by weight of a cement component (Portland cement, granulated blast furnace slag cement, or mixtures of these or other materials) and 15 percent to 25 percent by weight bentonite. The bentonite is claimed to improve the cold and hot strength of briquettes compared to using cement alone as a binder. A somewhat more extreme version of this has also been attempted, where the waste oxides are combined with Portland cement and water to make a flowable mixture, poured into a slab to harden, and then crushed to produce coarse lumps that can be charged back to the furnace.

The compositions, properties, and expected dosages of bentonite binders and fly ash-based binders follow.

5.1.1 Bentonite Binder

Twelve bentonite samples were analyzed to determine water absorption capacity, nature of exchangeable cations, and chemical composition. The analytical results were as shown in Table 24 below. The water absorption values have been considered in the past to be a measure of the effectiveness of a given bentonite as a binder, but our studies have shown that all of the listed bentonites have approximately equal binding capability.

5.1.2 Fly Ash Binder

The compositions of a number of representative fly ashes are given in Table 25. These ashes vary in composition depending on the coal source, with the variation of their calcium content being of most interest because this determines their binding properties. Class “F” and Class “C” fly ashes are produced by standard coal burners, and are the most common types. Fluid-Bed Combustor ashes have artificially elevated levels of calcium oxides and sulfur, because the fluid-bed combustors combine the burning coal with limestone to trap sulfur oxides in the solid phase and reduce emissions.

Class “F” and “C” fly ashes are broadly similar in composition to bentonite, as can be seen in Table 26. For the fluid-bed combustor ashes, the main concern would be their very high sulfate concentration, which would probably make them unsuitable for use in recycling iron units to iron or steelmaking operations.

In order to be used as binders, Class F ashes require approximately their own weight in additional calcium hydroxide, which would need to be figured in to the flux calculations when the agglomerated iron units are recycled. Experimentation has also shown that the effectiveness

of both Class C and Class F ashes as binders is greatly increased if calcium chloride is added as an accelerator at a rate of approximately 20% of the fly ash weight. If this accelerator is used, the chlorine that it contributes to the agglomerate could be a concern during later processing.

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
% Water Absorp.	672	574	540	582	704	760	738	765	806	862	857	670
Na ₂ O	2.29	2.66	2.28	2.15	2.61	2.85	3.17	2.34	2.48	2.52	2.32	2.20
MgO	4.14	1.77	2.03	1.37	2.03	1.99	2.41	1.53	2.62	2.52	2.58	2.45
Al ₂ O ₃	22.4	17.4	17.2	13.9	18.9	19.9	19.3	16.5	23.2	22.1	21.8	21.8
SiO ₂	60.3	69.7	70.6	77.9	67.9	67.2	67.1	73.4	63.4	64.6	65.2	65.7
P ₂ O ₅	0.05	0.03	0.08	0.02	0.05	0.05	0.05	0.03	0.05	0.03	0.03	0.03
SO ₃	0.61	0.45	0.97	0.32	0.61	0.68	0.82	0.31	1.02	0.70	0.64	0.92
K ₂ O	0.34	0.36	0.44	0.22	0.29	0.36	0.31	0.24	0.29	0.26	0.27	0.29
CaO	3.22	1.42	1.29	0.57	1.20	0.79	1.10	0.56	0.97	0.92	0.97	0.84
TiO ₂	0.10	0.07	0.10	0.05	0.09	0.09	0.10	0.07	0.08	0.08	0.07	0.08
MnO	0.03	0.03	0.03	0.02	0.04	0.03	0.03	0.02	0.02	0.03	0.03	0.02
Fe ₂ O ₃	6.53	6.15	5.01	3.38	6.23	6.01	5.57	5.01	5.92	6.18	6.13	5.73

	Class "F" Ashes			Class "C" Ashes		Fluid-Bed Combustor Ashes	
	#1	#2	#3	#4	#5	#6	#7
SiO ₂	50.16	50.07	48.00	38.87	34.23	19.62	19.57
Al ₂ O ₃	27.69	24.41	23.87	22.92	19.53	6.60	6.77
Fe ₂ O ₃	8.33	9.51	9.34	6.09	6.53	5.04	4.93
SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃	86.18	83.99	81.21	67.88	60.29	31.26	31.27
CaO	1.66	2.72	2.63	15.11	25.91	46.19	44.95
MgO	0.63	0.85	0.84	3.56	5.00	3.33	3.19
Na ₂ O	0.24	0.61	0.55	1.71	2.36	0.69	0.58
K ₂ O	1.92	2.68	2.61	0.94	0.38	0.81	0.56
TiO ₂	1.52	1.22	1.25	1.18	1.29	0.43	0.37
MnO ₂	0.01	0.05	0.05	0.05	0.05	0.13	0.14
P ₂ O ₅	0.47	0.09	0.12	0.91	1.05	0.72	0.63
SrO	0.15	0.15	0.14	0.20	0.30	0.08	0.09
BaO	0.17	0.16	0.16	0.48	0.50	0.05	0.06
SO ₃	0.25	0.61	0.54	1.20	2.41	12.53	12.81
LOI	6.79	6.90	11.11	6.78	0.46	3.80	5.37

- The Class "F" fly ashes are relatively low in calcium oxide and require the addition of lime in order to act as binders.
- The Class "C" ashes contain a sufficient amount of calcium oxide to act as binders with no additives.
- The Fluid-Bed Combustor ashes have strong binding properties, but also contain a great deal of sulfur which could make them unsuitable for use in iron and steelmaking feedstocks.

Table 26. Compositions Ranges of 5 Typical Fly Ashes from Conventional Burners (Not Fluidized-Bed Combustors) and 17 Typical Western Bentonites		
Analyte (%)	Typical Fly Ashes Low-High	Typical Western Bentonites Low-High
SiO ₂	34.23 - 50.16	44.35 - 63.60
Al ₂ O ₃	19.53 - 27.69	18.37 - 20.59
Fe ₂ O ₃	6.09 - 9.51	4.0 - 5.0
SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃	60.29 - 86.18	66.85 - 89.35
CaO	1.66 - 25.91	1.34 - 4.35
MgO	0.63 - 5.00	1.75 - 3.80
Na ₂ O	0.24 - 2.36	1.32 - 3.00
K ₂ O	0.38 - 2.68	0.28 - 0.96
TiO ₂	1.18 - 1.52	0.13 - 0.16
MnO ₂	0.01 - 0.05	0.004-0.02
P ₂ O ₅	0.09 - 1.05	0.14 - 0.19
SrO	0.14 - 0.30	~0.00
BaO	0.16 - 0.50	~0.01
SO ₃	0.25 - 2.41	0.47 - 1.00
LOI	0.46 - 11.11	5.59 - 13.24

5.2 DOSAGE AND PROPERTIES OF BINDERS

The necessary binder dosage needed to reach a target pellet strength is strongly dependent on the particle size distribution of the material being pelletized. This can be seen by comparing the size distributions of a ferrous concentrate as a function of grinding (Figure 14), with the corresponding pellet strengths (Table 27). As the concentrate was ground to progressively finer sizes, the strengths of the pellets produced from it improved markedly without any change in the binder dosages.

Bentonites are typically added at dosages of roughly 0.3-1% of the concentrate weight in iron ore pelletization operations. They contribute a non-trivial amount of silica and alumina to the pelletized concentrate, along with small amounts of sodium and calcium. Since standard iron ore concentrate pellets primarily use bentonite as binder, existing blast furnace operations are well accustomed to dealing with the elements contributed by bentonite.

The dosage for the fly ash-based binder in these experiments was chosen to give a level of fly ash of 1% of the concentrate weight. This was selected so that the silica levels contributed by the binder would be comparable to those resulting from a bentonite dosage of 1% of the concentrate weight. Since the fly ash-based binder (FBB) also includes calcium hydroxide activator and calcium chloride accelerator, this resulted in a total FBB dosage of 2.2% of the concentrate weight, with most of the extra weight consisting of material that would reduce the overall flux requirements in the furnace burden. At these dosage levels, the dry strengths for the FBB were significantly higher than the dry strengths using bentonite.

Figure 14. Cumulative size distributions of steelmaking slag concentrate before and after grinding with a rod mill, determined by Microtrac laser diffraction. A typical magnetite pelletizing concentrate is shown for comparison.

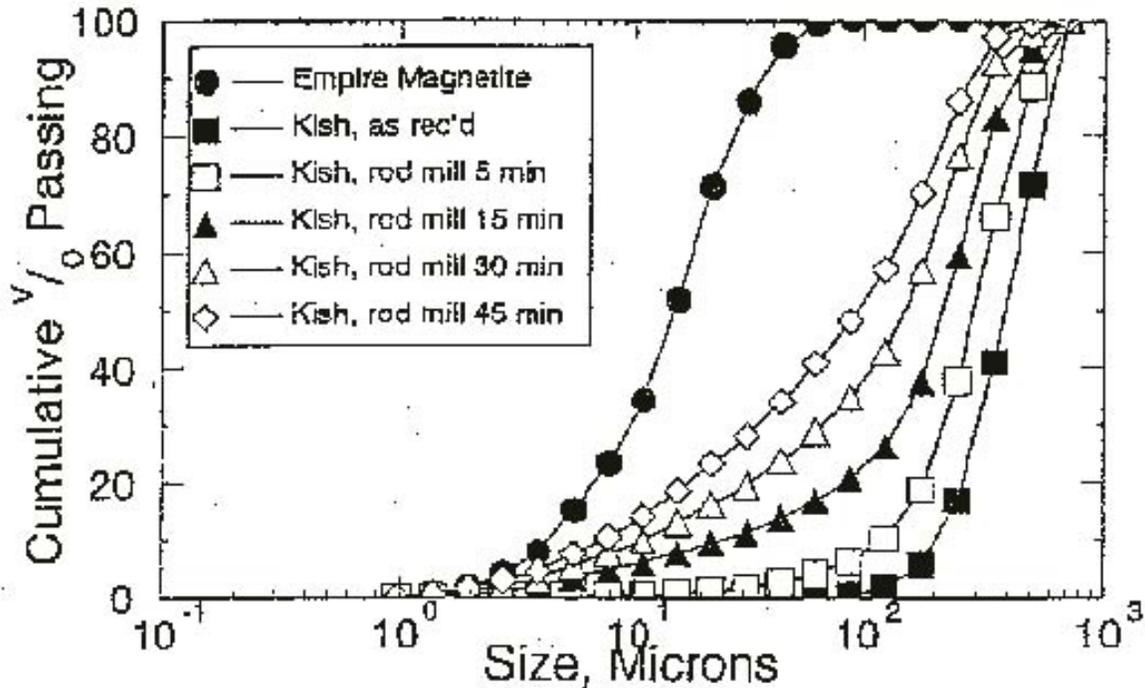


Table 27. Mechanical Properties of Slag Concentrate Pellets

Binder	Rod Milling Time, minutes	Wet knock, number of drops	Wet crush, Newtons (lbf)	Dry crush, Newtons (lbf)	Sintered crush, Newtons (lbf)
Bentonite	5	not determined	not determined	10.7+/-0.9 (2.4+/-0.2)	1041+/-334 (234+/-75)
Bentonite	15	4.6+/-0.5	6.7+/-1.3 (1.5+/-0.3)	12.0+/-0.9 (2.7+/-0.2)	1072+/-356 (241+/-80)
Bentonite	30	13.9+/-1.1	11.1+/-1.8 (2.5+/-0.4)	22.7+/-1.8 (5.1+/-0.4)	1806+/-444 (406+/-100)
Bentonite	45	7.4+/-0.3	13.8+/-1.8 (3.1+/-0.4)	27.6+/-2.7 (6.2+/-0.6)	1832+/-374 (412+/-33)
FBB	45	7.4+/-0.8	22.2+/-1.3 (5.0+/-0.3)	53.4+/-1.8 (12+/-0.4)	1378+/-222 (310+/-50)

- Strengths given are the force needed to fracture pellets 0.5 inches in diameter.
- Bentonite dosage was 1% of the slag weight.
- The fly ash based binder (FBB) was 5 parts by weight fly ash, 5 parts calcium hydroxide, and one part calcium chloride, and was added at a rate of 2.2% of the slag weight.

5.3 OTHER BINDERS

5.3.1 Cement

The most obvious cementitious binder is ordinary Portland cement, which reacts with water to form a hard, cementing phase that binds the particles together.

The typical composition of ordinary Type 1 Portland cement is approximately 67% CaO, 22% SiO₂, 5% Al₂O₃, 3% Fe₂O₃, and 3% other components of various types, depending on the purpose of the cement. As much as 2% may be gypsum, which is added to control the hardening rate. Most of this material is in four major phases: alite (Ca₃SiO₅), belite (Ca₂SiO₄), and ferrite (Ca₂AlFeO₅), with minor amounts of other phases such as alkali sulfates and calcium oxide. From this, it is evident that large dosages of cement as binder will tend to contribute a significant amount of silica.

In addition to typical Portland cements, there are also calcium aluminate cements that may be of interest. These cements can be made containing less than 0.4% SiO₂, and their use would, therefore, minimize the amount of silica contributed to the pellet by the binder. Calcium aluminate cements can be made that harden to a useful strength in only a few hours, and that harden as much in 24 hours as Portland cement does in 28 days. They can also be made to harden even more rapidly by addition of hydrated lime. Some very preliminary work was done with calcium aluminate cement binders; it was found that a high water content was needed for the concentrate to ball properly, and that while it was an effective binder for small pellets, the properties deteriorated as the pellets were enlarged.

When used as a binder, cement must be added at a fairly high dosage. Cement additions of 5-10% of the weight of the material being bonded is fairly typical.

5.3.2 Organic Binders

5.3.2.1 Molasses/Lime

There are a few types of binder which consist of a combination of inorganic and organic materials, which react with each other to harden. The most common example of this is the combination of lime and molasses, which is a reliable binder for agglomerating many ores. The ratio of molasses to lime is typically between 2:1 and 4:1, with the exact ratio for a given application determined by experiment. The reaction which hardens the binder is the production of calcium socrate, which is slowed at high temperatures, and so the curing of the pellets should take place at ambient temperatures. Pellets produced using this binder are quite weak initially, but cure to their full strength in approximately one hour.

The composition range for typical “blackstrap” molasses is as shown in Table 28. This composition varies a great deal, depending on the growing conditions of the plants that it was made from. The “ash” component consists of highly variable levels of calcium, sodium, potassium, magnesium, chlorine, and sulfur. When used as a binder, it would be combined with

lime to make a binder that contains 20-33% CaO. The dosage of this binder would be similar to that of cement (approximately 5-10% of the weight of the material being bonded).

Total solids	78 - 80.5
Moisture (%)	20 - 25
Total sugars (%)	55 - 65
Invert Sugars (%)	9 - 19
Sucrose (%)	41.5 - 51.5
Ash (%) (sulfated)	6 - 11
pH 1:1 dilution	4.5 - 6.0

5.3.2.2 Synthetic Organic Binders

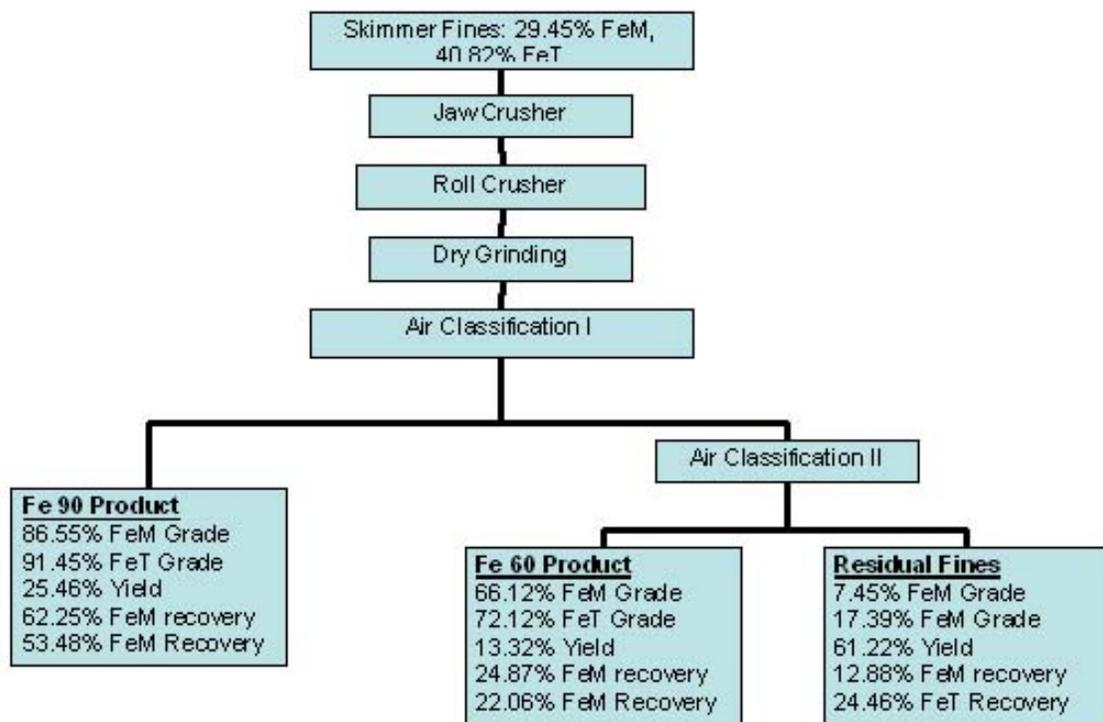
A number of binders are available that are synthetic polymers. While the exact compositions of these binders are proprietary, they are primarily organic polymers that burn away essentially completely when pellets or briquettes are sintered. Examples are Peridur (a derivative of carboxymethyl cellulose) manufactured by Akzo Nobel, and the Alcotac series (copolymers of acrylamide and sodium acrylate, combined with varying amounts of sodium carbonate) manufactured by Ciba Specialty Chemicals. The main element of concern with these binders is sodium, which they frequently contain in substantial quantities as part of their active side groups.

These binders are effective at extremely low dosages (0.03-0.07% is a typical range for Peridur). Because of the low dosages used, and the minimal ash levels in these binders, it is generally accepted that, aside from contributing a certain amount of sodium, synthetic organic binders have no significant effect on finished agglomerate composition.

6.0 PILOT SCALE TESTING

The scale up of the technology was first investigated at MTU. Following the flowsheet developed in the bench testing, as shown in Figure 15, a one ton per hour experiment was examined in batch. The process included using a jaw crusher and followed with a roll crusher to crush down the materials to approximately 10 mesh. Then a dry grinding circuit is introduced. The ground product was fed into an air classification unit to separate the material into various products by gravitational force. Figure 16 shows a photo of the grinding circuit and Figure 17 shows a photo of the air classification circuit.

Figure 15. The flowsheet for the pilot scale operation.



The chemical analysis of the pilot run products on Sample 1B are shown in Table 29. The HGI product has a metallic Fe content of 88.55% and a total Fe content of 91.45%. The yield of the product is 25.46%. The recovery of the metallic iron into the HGI product is 62.25%. The MGI product has a metallic Fe content of 50.63% and a total Fe content of 59.27%. About 13.32% of the total weight reports to this product. The distribution of metallic iron into this product is 24.87%. The residuals, which is the LGI product, has a metallic Fe content at 12.40% and a total Fe content at 26.31%. About 12.88% of the total metallic iron is lost into the LGI product. Majority of the weight of the original material, at 61.22%, belongs to this product. The goal to produce a high grade product at about 90% Fe and a medium grade product at 60% Fe was achieved.

Figure 16. Photo of the pilot grinding circuit.



Figure 17. Photo of the pilot air classification unit.



Table 29. Chemical compositions of the pilot run products from Sample 1B.

Elements	Head	HGI Product	MGI Product	LGI Product
Fe Total	40.82	91.45	59.27	26.31
Fe Metallic	29.45	88.55	50.63	12.40
C	2.61	1.16	1.35	2.89
S	0.46	0.07	0.21	0.56
P	0.12	0.01	0.15	0.15
SiO ₂	13.99	1.39	9.82	18.16
TiO ₂	0.52	0.07	0.50	0.70
Al ₂ O ₃	3.54	0.37	3.13	4.55
Cr ₂ O ₃	0.24	0.04	0.30	0.22
CaO	19.96	2.39	19.58	24.84
MgO	6.55	0.77	6.42	8.10
MnO	2.69	0.41	3.28	3.20
Na ₂ O	0.03	0.04	0.02	0.16
K ₂ O	0.07	0.00	0.00	0.11
ZrO ₂	0.06	0.01	0.03	0.05
Sr	0.01	0.01	0.02	0.02
Zn	0.05	0.01	0.02	0.05

Pilot experiment was also carried out for Sample 4A. The analysis of the three products are shown in Table 30. The HGI product has a metallic Fe content of 86.93% and a total Fe content of 88.62%. The MGI product has a metallic Fe content of 50.17% and a total Fe content of 60.02%. The residuals, which is the LGI product, has a metallic Fe content at 10.12% and a total Fe content at 29.92%. This shows that consistent HGI, MGI and LGI products can be obtained from different samples using the process.

With the encouragement from the success of the batch pilot runs, ICAN GLOBAL, Inc., built a pilot facility at a one ton per hour capacity in Ishpeming, Michigan. To feed the operation of this pilot facility, a total of 500 tons samples were shipped from US Steel. Representative from US Steel, Mr. Mark Conedera, was on site to observe the operation. The operation proved the feasibility of the technology developed in this study. Figure 18 shows a photo of the excavation of the stockpiled sample. Figure 19 is a photo showing the loading and shipping of the material to the test site. Figure 20 shows a photo of the pilot operation. The products generated are also shown in the photo in Figure 21.

Table 30. Chemical compositions of the pilot run products from Sample 4C.

Elements	Head	HGI Product	MGI Product	LGI Product
Fe Total	37.24	88.62	60.02	29.92
Fe Metallic	19.75	86.93	50.17	10.12
C	5.94	1.22	0.59	6.03
S	0.16	0.02	0.07	0.16
P	0.17	0.01	0.10	0.20
SiO ₂	8.80	1.68	4.05	9.60
TiO ₂	0.93	0.08	0.43	0.97
Al ₂ O ₃	2.59	0.57	1.48	2.91
Cr ₂ O ₃	0.38	0.04	0.20	0.33
CaO	22.81	2.52	10.81	24.96
MgO	7.20	0.83	3.63	7.88
MnO	3.76	0.46	1.93	4.12
Na ₂ O	0.08	0.03	0.08	0.11
K ₂ O	0.00	0.00	0.00	0.00
ZrO ₂	0.02	0.01	0.01	0.01
Sr	0.01	0.01	0.01	0.01
Zn	0.07	0.01	0.01	0.08

Figure 18. The excavation of the steel slag stockpile to provide materials for pilot testing.



Figure 19. The loading and shipping of pilot testing material to Michigan operation site.



Figure 20. Photos of the pilot operation in Ishpeming, Michigan.

One Ton Per Hour Bench Testing



Figure 21. A photo showing the three products generated from the pilot operations.

1 T/Hr Testing Product



With the success of the one ton per hour pilot testing, Westwood Land Incorporated acquired the licensing right of the technology from the ICAN GLOBAL, Inc. Westwood is putting together a 50 ton per hour testing facility in Michigan before it goes for a full scale commercial plant. Figure 22 shows the construction activities. Figure 23 is a photo showing the facility is near completion.

Figure 22. Equipment acquisition for the 50 TPH testing facility.



Figure 23. Construction of the 50 TPH testing facility.



7.0 FURNACE MODEL

Based on the analytical numbers above steel company participants were to employ steelmaking models, or whatever methodology they choose to use to evaluate the suitability of the ~90% FeT and ~60% FeT products for reuse back into either the BF or BOF. An example of this exercise is provided in Table 31 from Mill A with Sample 1B. A range of operation was created whereby an established baseline of all scrap was compared to the performance of 4000 kg of standardized waste oxide briquettes. Then 4000 kg of BOF magnetic fines ~60% FeT product and 4000 kg of desulfurization fines ~90% FeT product were used for substitution purposes. The cooling efficiency outcome was that 4000 kg of BOF magnetic fines ~60% FeT product is equivalent to 4300 kg of scrap, and 4000 kg of desulfurization fines ~90% FeT product is equivalent to 388 kg of scrap. The hot metal penalty associated with the 4000 kg of BOF magnetic fines ~60% FeT product is 1.9 MT, and for 4000 kg of desulfurization fines ~90% FeT product 0.1 MT.

Table 31. Mill A Preliminary Charge Calculation Model Results								
Target Temperature 1675°C								
Hot Metal Temperature 1244°C								
Target % Carbon 0.06								
Waste Oxide Briquettes Composition:				Hot Metal Composition				
Fe T% 55.0				Si% 0.32				
FeO% 40.0				Mn% 0.43				
Fe ₂ O ₃ % 35.0				P% 0.038				
FeM% 1.0				S% 0.0038				
Material	Wt. (Kg)	Hot Metal MT/Ht.	Scrap (MT)	Oxygen M³/10 min.	Coke (kg)	FeSi (kg)	Bnt. Lime (kg)	Dol. Lime (kg)
Base	0	208.9	50.2	1382	2250	190	2810	3860
WOBS	4000	215.8	41.0	1383	2250	190	2810	3890
BOF magnetic Fines ~60	4000	210.8	45.9	1390	2250	190	2250	3830
Desulf. Fines ~90	4000	209.0	46.4	1387	2250	190	2810	3850
Cooling Efficiency: 4000 kg of Desulf. Fines ~ 90% FeT Product = 3800 kg Scrap 4800 kg of BOF Magnetic Fines ~60% FeT Product = 4300 kg Scrap								
Hot Metal Penalty: 4000 kg of Desulf. Fines increases Hot Metal 0.1 MT 4000 kg of BOF Magnetic Fines increases Hot Metal 1.9 MT								

8.0 ACID MINE DRAINAGE TREATMENT

8.1 TREATMENT EFFICIENCY

8.1.1 Objectives & Strategy

The LGI Product was tested in parallel with hydrated lime to compare its treatment efficiency with the product that currently dominates the AMD treatment market. This work was conducted at the National Mined land Reclamation Center at West Virginia University.

Treatment efficiency is the mass of chemical needed to neutralize a given volume of AMD within a fixed time period. As the iron recovery process is refined, it is anticipated that varying particle size distributions of the by-product will be developed. These will be tested to determine the effect of particle size on AMD treatment efficiency. This information will be put into the economic analysis for the entire process.

8.1.2 Experimental Method

Michigan Tech provided samples of processed steel slag LGI product to be used in the WVU research evaluating the potential use for treating acid mine drainage (AMD). The processed slag was analyzed for parameters of concern for neutralization of AMD. The laboratory analyses evaluating the efficiency of the processed steel slag for treating AMD utilized the acid water being discharged from the T&T underground coal mine in Preston County, West Virginia. The AMD from the T&T mine was analyzed for parameters of concern at a certified laboratory. The AMD neutralization research analysis was a multi-step process which is outlined in Figure 24. In the first step, two liters of AMD are oxidized with 20 ml of 20% reagent grade hydrogen peroxide then filtered through a 0.45um filter. The filtrate is placed in a beaker and stirred constantly at a low velocity. The alkaline materials (processed steel slag or hydrated lime) are added to the water at specific times and masses until the water reaches and maintains a pH of 8.3. Following neutralization, the titrate water is filtered through a 0.45um filter. The filtrate is analyzed for parameters of concern. The solids on the filters from the initial oxidation step and from the neutralization step are each dried and weighed.

8.1.3 Parameters of Interest

In Processed Steel Slag

Neutralization Potential (NP)

Metals

Fe, Al, Mn, Sb, As, Ba, Be, Cd, Cr, Pb, Hg, Se, Ag, Cu, Ni, Tl, V, Zn

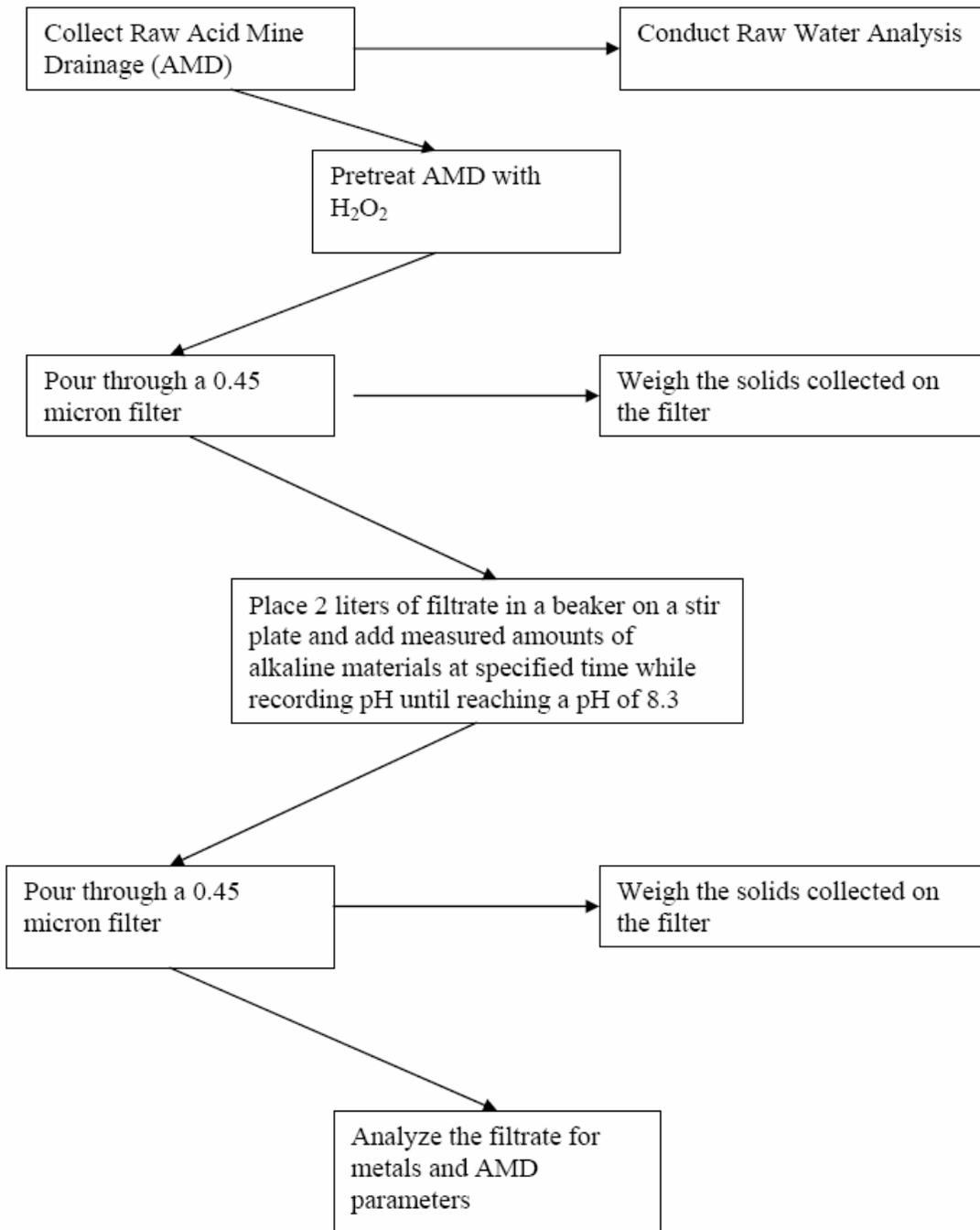
In Water

pH, acidity, estimated acidity, alkalinity, acidity/alkalinity, sulfate, conductivity

Metals

Mg, Ca, Fe, Al, Mn, Sb, As, B, Ba, Be, Cd, Cr, Pb, Hg, Se, Ag, Cu, Ni, Tl, V, Zn

Figure 24. AMD experimental procedure.



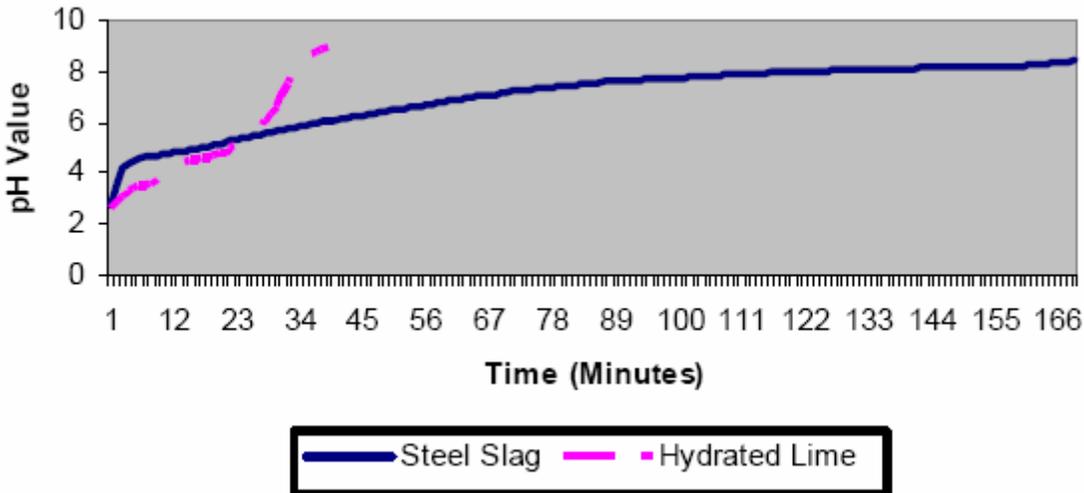
8.1.4 Laboratory Results

8.1.4.1 Neutralization Efficiency

8.1.4.1.1 Steel Slag vs Hydrated Lime

Researchers determined how much alkaline material it would take to raise the pH of the oxidized AMD to 8.3 and added that amount initially, tracking how long it would take to reach the desired pH. The neutralization research results indicate that for the slag particle size evaluated in these tests, 0.6 grams of hydrated lime were required while 2.4 grams of processed steel slag were needed to do the same thing. The results are shown in Figure 25.

**Figure 25. Time to Neutralize Oxidized AMD
Steel Slag(2.4 gm) vs Hydrated Lime (0.6 gm)**



It takes roughly four times as much slag to neutralize the oxidized AMD to a pH of 8.3 as hydrated lime. The time of reaction was also very different. The researchers also investigated varying rates of feeding the alkaline materials to raise the pH of the oxidized AMD to 8.3. They added 0.1 gram of hydrated lime or slag to the AMD solution at one minute intervals as well as at five minute intervals. A summary of the results is presented in Table 32.

Table 32. Summary of Experimental Results of Neutralization Tests.

<u>Material</u>	<u>Test 1</u>	<u>Test 2</u>	<u>Test 3</u>
<i>Feed Rate</i>	<i>(0.1 gm/5min)</i>	<i>(0.1 gm/1 min)</i>	<i>Added Initially</i>
Steel Slag			
Minutes to pH 8.3	116	34	82
Grams Added	2.3	3.4	2.4
Mass Filtered (gm)	2.038	2.942	2.090
Hydrated Lime			
Minutes to pH 8.3	26	9	17
Grams Added	0.52	0.9	0.6
Mass Filtered (gm)	0.506	0.759	0.470

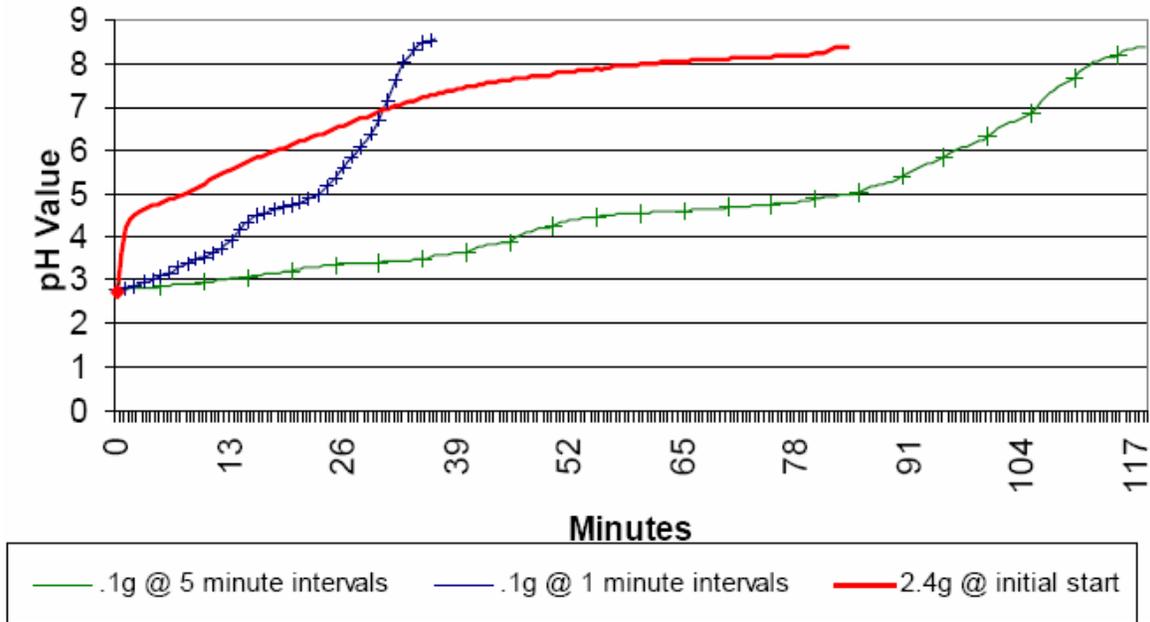
In neutralizing the AMD, hydrated lime is about four times faster and requires about one fourth the mass of steel slag. It also produces about one fourth the solids of steel slag neutralization. Steel slag is, however, effective in neutralizing the AMD.

The results of the three tests using steel slag to neutralize the AMD are presented in Figure 26. For the steel slag, neutralization curves for the sequential feed rate experiments are quite different from the experiment where the material was added at the start of the test. The neutralization curves for the two sequential feed rates are similar, but the amount of material required to reach the desired pH is different (3.4 gm at the one minute interval vs 2.3 gm at the five minute interval feed rate). A benefit of feeding at one minute intervals was that the reaction time to reach a pH of 8.3 was roughly half the time required when the material was added initially (34 minutes vs 82 minutes). Offsetting this benefit was the extra alkaline material required (3.4 gm total vs 2.4 gm). Adding 0.1 gm at five minute intervals required only 2.3 gm of slag, but it took 116 minutes to reach the desired pH. Adding the slag in small amounts at shorter intervals shortened the time it took to reach a pH of 8.3.

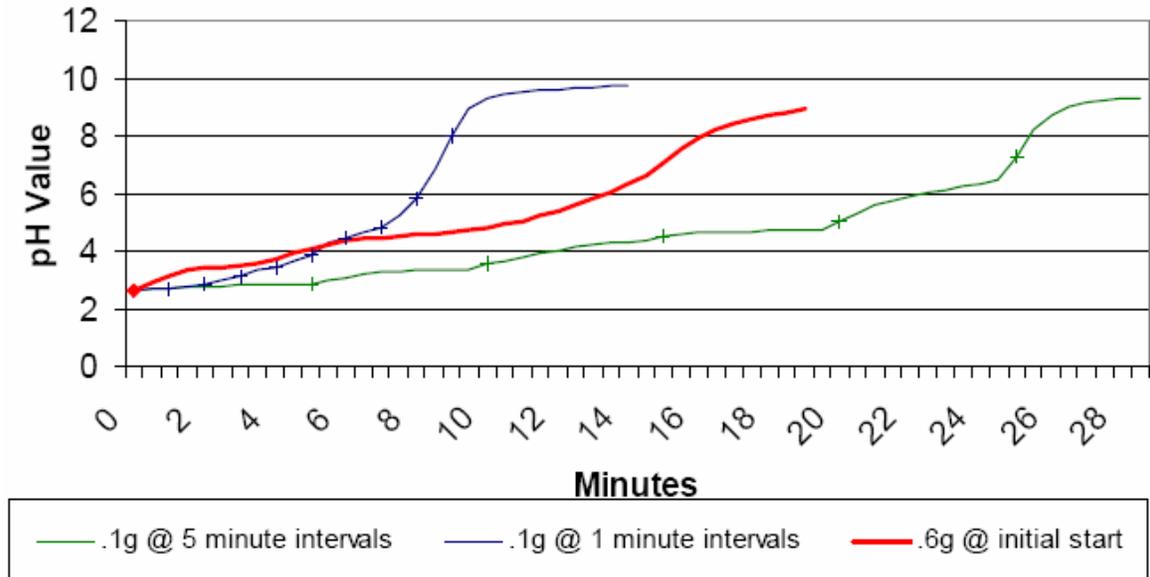
Similar studies using hydrated lime are in Figure 27. It took 17 minutes to reach a pH of 8.3 when 0.6 gm of lime was added to the oxidized AMD and mixed. It took 9 minutes to reach the desired pH when lime was fed at 0.1 gm/minute, but it took 0.9 gm of lime. It took 26 minutes to reach the desired pH when lime was fed at 0.1 gm/5 minutes, but it only took 0.5 gm of lime.

The longer reaction time for the slag may be partly due to the observation that the slag was similar to a powder that tended to stay on the surface of the water until the constant mixing eventually blended it into the water column. Slag with a coarser particle size might have shorter reaction time since it should not be held on the top of the water by surface tension.

**Figure 26. Time to neutralize oxidized AMD using steel slag.
Adding Steel Slag over Time**



**Figure 27. Time to neutralize oxidized AMD using lime.
Adding Hydrated Lime Over Time**



8.1.4.2 Water Quality Results

8.1.4.2.1 Neutralization With Steel Slag vs Hydrated lime

The processed steel slag has a neutralization potential of 928 tons of CaCO_3 and contains a wide range of metals including some known for their toxicity at relatively low concentrations. The concentrations are included in Table 33. The slag contained several metals. Listed in decreasing concentrations in mg/kg they are: iron = 215,000; manganese = 27,300; aluminum = 18,950; chromium = 1,530; vanadium = 810; zinc = 85.5; nickel = 51; barium = 29.5; lead = 11.3; arsenic = 10.8; selenium 0.6; cadmium = 0.4. All others were at or below the laboratory's detection limit.

The neutralization of AMD removes metals from solution so the data on the metals concentrations in the raw AMD and the final water quality after neutralization are important. The data from the studies using slag as well as by hydrated lime are listed in Table 34. There were significant differences in the results when comparing slag vs lime in only six parameters: magnesium, aluminum, manganese, chromium, nickel, and vanadium. The final water from the slag neutralization vs lime neutralization had higher magnesium, manganese, copper, nickel, and vanadium. Slag was superior to hydrated lime in removing aluminum from the AMD. The finished filtrate from treatment with slag had only 0.06 mg/L of aluminum while the filtrate from the lime treatment had 1.06 mg/L of aluminum. Details of the testing data are shown in Table 35 and Table 36 for the steel slag and hydrated lime, respectively.

Slag was effective in removing several other metals from the AMD. The slag neutralization reduced or removed below detection limits the following metals present in the raw AMD: Fe, Al, Mn, Be, Cu, Ni, Zn. The slag neutralization increased the concentration of four metals above what was in the raw AMD. Magnesium went from 40.5mg/L to 57.6 mg/L; Calcium went from 233mg/L to 441mg/L; Chromium went from $> 0.05\text{mg/L}$ to 0.07mg/L; and Vanadium went from 0.1mg/L to 0.277mg/L. Chromium was the only metal was not detected in the raw AMD but present in the filtrate from the slag neutralization process. This slight increase in the concentration of chromium is near the detection limit of the analysis.

8.1.5 Conclusions and Recommendations

Based on the results of the laboratory testing, steel slag is suitable for neutralizing acid mine drainage. Our results have also found that slag is superior to lime in removing aluminum from the AMD used in these experiments. However, additional studies should be conducted on how particle size of the slag affects the rate of neutralization with additional studies conducted on evaluating optimal feed rates. And lastly, additional studies should be conducted on how the slag reacts with other acid mine drainage having more trace metals present.

Table 33. Composition of steel slag for AMD treatment.

Parameter	Detection Limit (mg/kg)	Concentration (mg/kg)
Fe	2.5	215,000
Al	2.5	18,950
Mn	0.5	27,300
Sb	0.25	<0.25
As	0.05	10.8
Ba	5	29.5
Be	0.25	<0.25
Cd	0.25	0.4
Cr	2.5	1,530
Pb	0.05	11.3
Hg	0.25	<0.25
Se	0.1	0.6
Ag	0.5	<0.5
Cu	1.0	26.5
Ni	2	51
Tl	0.05	<0.05
V	5	810
Zn	0.25	85.5

Table 34. Laboratory results for raw AMD water and filtrate water from neutralization.

Parameter (Units)	Detection Limit	Raw AMD	Lime Filtrate Avg.	Slag Filtrate Avg.	U.S. Drinking Water Quality Stds.
pH (Std. Units)	0.1	2.8	9.5	8.5	
Acidity (mg/L)	1	405	0.0	0	
E. Acidity (mg/L)		343.1	6.3	1.8	
Alkalinity (mg/L)	1	0.0	73.7	40.7	
Acid-Alk (mg/L)		343.1	-67.4	-38.9	
Mg (mg/L)	0.01	40.5	32.2	57.6	
Ca (mg/L)	0.01	233	455.3	441.0	
Fe (mg/L)	0.05	32.7	<D.L.	<D.L.	
Al (mg/L)	0.05	31.2	1.06	0.06	
Mn (mg/L)	0.01	1.4	0.12	0.74	
SO ₄ (mg/L)	1	900	949	999	
Sb (mg/L)	0.005	<D.L.	<D.L.	<D.L.	0.006
As (mg/L)	0.0001	0.001	0.001	0.001	0.05
B (mg/L)	0.10	<D.L.	<D.L.	<D.L.	
Ba (mg/L)	0.10	<D.L.	<D.L.	<D.L.	2
Be (mg/L)	0.005	0.009	<D.L.	<D.L.	0.004
Cd (mg/L)	0.005	<D.L.	<D.L.	<D.L.	0.005
Cr (mg/L)	0.05	<D.L.	<D.L.	0.07	0.1
Pb (mg/L)	0.001	<D.L.	<D.L.	<D.L.	0.015
Hg (mg/L)	0.0002	<D.L.	<D.L.	<D.L.	0.0002
Se (mg/L)	0.002?	<D.L.	<D.L.	<D.L.	0.05
Ag (mg/L)	0.01	<D.L.	<D.L.	<D.L.	
Cu (mg/L)	0.02	0.12	<D.L.	<D.L.	1.3
Ni (mg/L)	0.04	0.32	<D.L.	0.08	
Tl (mg/L)	0.001	<D.L.	<D.L.	<D.L.	0.002
V (mg/L)	0.005	0.1	0.100	0.277	
Zn (mg/L)	0.005	0.789	0.006	0.007	
Cond (Std.)	1	3160	2610	2563	

NOTE: <D.L. = Less than detection limit.

Table 35. T&T AMD water neutralized with steel slag.

sampling station	units	method	US Primary	T&T	Rep 1	Rep 2	Rep 3	Average
		detect. limit	DW Std.	RAW AMD	5 min	1 min	@ initial	
pH	std units			2.8	8.3	8.9	8.2	8.5
acidity	mg/L			405	0	0	0	0.0
est. acidity	mg/L			343.1	2.1	1.3	2.0	1.8
alkalinity	mg/L			0	35	58	29	40.7
acid-alk	mg/L			343.1	-32.9	-56.7	-27.0	-38.9
Mg	mg/L	0.1		40.5	55.4	56.9	60.6	57.6
Ca	mg/L	0.1		233	444	456	423	441.0
Fe	mg/L	0.1		32.7	0.05	0.05	0.05	0.05
Al	mg/L	0.1		31.2	0.05	0.06	0.06	0.06
Mn	mg/L	0.1		1.4	0.94	0.46	0.83	0.74
SO4	mg/L	10		900	968	978	1050	998.7
Sb	mg/L	0.005	0.006	0.005	0.005	0.005	0.005	0.005
As	mg/L	0.005	0.05	0.001	0.001	0.001	0.001	0.001
B	mg/L			0.1	0.1	0.1	0.1	0.100
Ba	mg/L	0.005	2	0.1	0.1	0.1	0.1	0.100
Be	mg/L	0.005	0.004	0.009	0.005	0.005	0.005	0.005
Cd	mg/L	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Cr	mg/L	0.005	0.1	0.05	0.1	0.05	0.05	0.067
Pb	mg/L	0.005	0.015	0.001	0.001	0.001	0.001	0.001
Hg	mg/L	0.005	0.0002	0.0002	0.0002	0.0002	0.0002	0.000
Se	mg/L	0.005	0.05	0.002	0.002	0.002	0.002	0.002
Ag	mg/L	0.005		0.01	0.01	0.01	0.01	0.010
Cu	mg/L	0.005	1.3	0.12	0.02	0.02	0.02	0.020
Ni	mg/L	0.005		0.32	0.09	0.06	0.1	0.083
Tl	mg/L	0.005	0.002	0.001	0.001	0.001	0.001	0.001
V	mg/L	0.005		0.1	0.24	0.31	0.28	0.277
Zn	mg/L	0.005		0.789	0.008	0.005	0.007	0.007
Cond	Umhos/cm			3160	2600	2680	2410	2563.3

Table 36. T&T AMD water neutralized with hydrated lime.

sampling station	units	method	US Primary	T&T	Rep 1	Rep 2	Rep 3	Average
		detect. limit	DW Std.	RAW AMD	5 min	1 min	@ initial	
pH	std units			2.8	9.6	10.1	8.8	9.5
acidity	mg/L			405	0	0	0	0.0
est. acidity	mg/L			343.1	7.8	7.7	3.2	6.3
alkalinity	mg/L			0	78	91	52	73.7
acid-alk	mg/L			343.1	-70.2	-83.3	-48.8	-67.4
Mg	mg/L	0.1		40.5	26.2	30.7	39.6	32.2
Ca	mg/L	0.1		233	447	460	459	455.3
Fe	mg/L	0.1		32.7	0.05	0.05	0.05	0.05
Al	mg/L	0.1		31.2	1.35	1.3	0.53	1.06
Mn	mg/L	0.1		1.4	0.07	0.21	0.09	0.12
SO4	mg/L	10		900	901	960	986	949.0
Sb	mg/L	0.005	0.006	0.005	0.005	0.005	0.005	0.005
As	mg/L	0.005	0.05	0.001	0.001	0.001	0.001	0.001
B	mg/L			0.1	0.1	0.1	0.11	0.103
Ba	mg/L	0.005	2	0.1	0.1	0.1	0.1	0.100
Be	mg/L	0.005	0.004	0.009	0.005	0.005	0.005	0.005
Cd	mg/L	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Cr	mg/L	0.005	0.1	0.05	0.05	0.05	0.05	0.050
Pb	mg/L	0.005	0.015	0.001	0.001	0.001	0.001	0.001
Hg	mg/L	0.005	0.002	0.0002	0.0002	0.0002	0.0002	0.000
Se	mg/L	0.005	0.05	0.002	0.002	0.002	0.002	0.002
Ag	mg/L	0.005		0.01	0.01	0.01	0.01	0.010
Cu	mg/L	0.005	1.3	0.12	0.02	0.02	0.02	0.020
Ni	mg/L	0.005		0.32	0.04	0.04	0.04	0.040
Tl	mg/L	0.005	0.002	0.001	0.001	0.001	0.001	0.001
V	mg/L	0.005		0.1	0.1	0.1	0.1	0.100
Zn	mg/L	0.005		0.789	0.007	0.005	0.006	0.006
Cond	Umhos/cm			3160	2600	2540	2690	2610.0

8.2 ECONOMIC EVALUATION FOR AMD TREATMENT

8.2.1 Introduction

In the absence of markets for commodities such as these, estimates of the price of the commodity can be determined in one of two ways. One way is by estimating a required selling price from the suppliers' perspective that would entail estimating the cost of production with an acceptable rate of return on the investment. The second way is by estimating the amount consumers would be willing to pay for the commodity based on its attributes. The value of the attributes may be estimated on an equivalence basis which derives attribute values from a comparable commodity. Although the actual price of the slag product would immediately be determined through the interaction of the market force of supply and demand, the adoption of either of these two methods would provide an indication of the price for asserting the economics of the slag recycling process. Figure 28 provides an overview of influential price factors for the potential steel slag market. As can be seen in this figure, one method employs a supply side approach while the other employs a demand side approach to attempt to estimate the slag price.

8.2.2 Analysis

The value estimated in this report is derived using the equivalence method comparing the AMD treatment characteristics of the slag product to that of hydrated lime. The amount that consumers would be willing to pay is estimated based on the attributes of the slag product. The value of the slag as an alkaline material may be established in relation to its acid neutralizing potential. Results from Laboratory experiments Task comparing the acid neutralization capacity of the steel slag product with that of hydrated lime suggest that the slag is approximately one fourth as effective at neutralizing AMD, as is hydrated lime. This would suggest that the maximum amount that consumers would be willing to pay for its use in this capacity is about \$26 per ton. This range is based on f.o.b. hydrated lime prices of \$104 per ton. Therefore, the cost of processing the slag plus any required return on investment must not exceed this range if the process is to be deemed economical.

However, other attributes of the slag must also be considered in the evaluation process such as the introduction of metals into the water by the slag product, reaction times, metal removal performances, and any difference in shipping handling requirements and costs. These attributes may enhance the value of the slag product should they be positive as suggested by the superior performance of slag in aluminum removal in these experiments or they may reduce the value should they be negative as suggested by the increased concentration of four metals above the levels present in the raw AMD used in the experiments. The magnitude and sign of all the attributes must be known to assess the true value of the slag. Other factors, which influence the price of the slag, are illustrated in Figure 28.

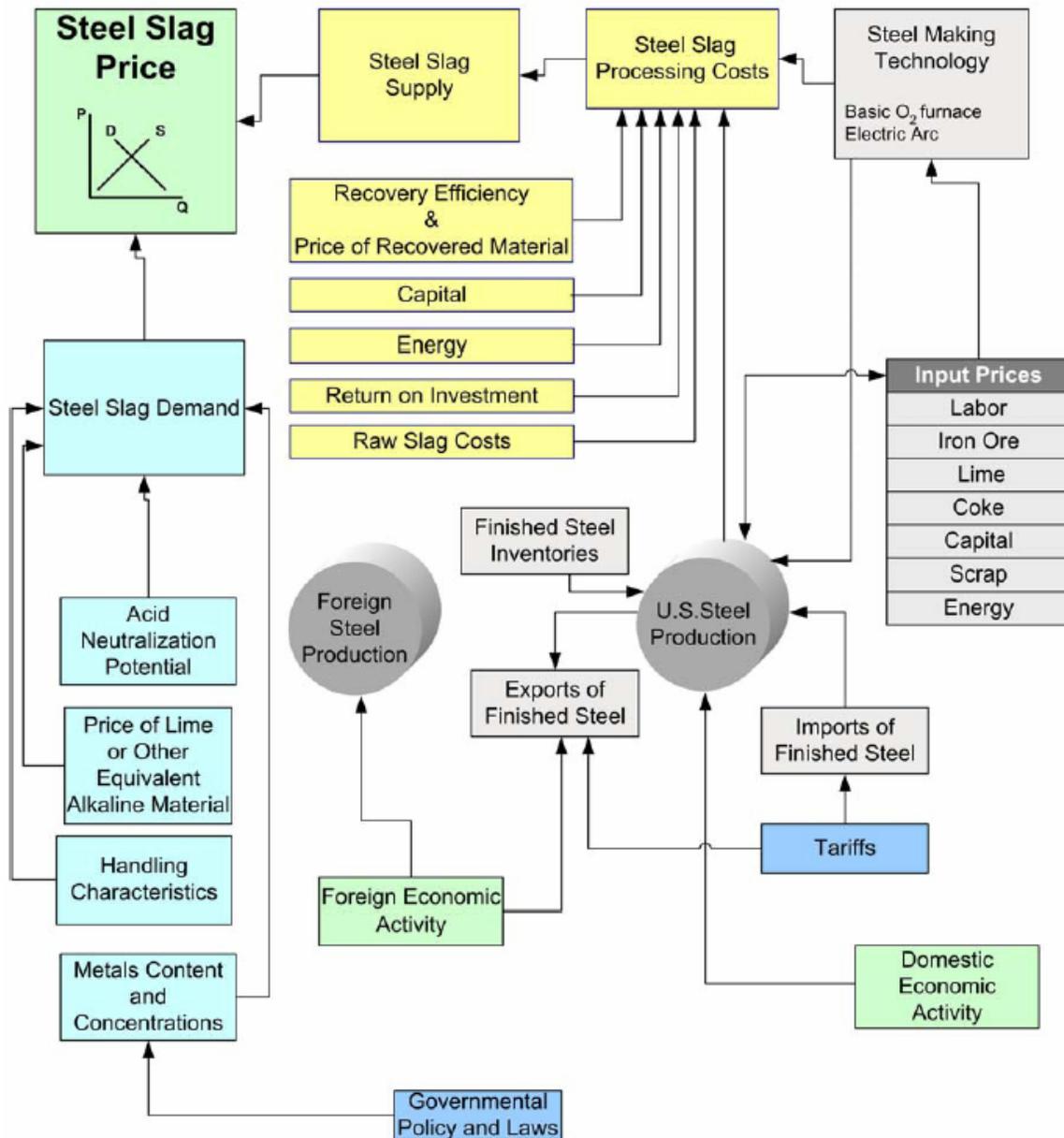
It can be seen from this figure that the steel production influenced by the level of economic activity and governmental policy influences the slag supply and ultimately the price. Additionally, it can be seen that the price of lime exhibits influences on both the supply and demand sides of this potential market. Lime prices have increased over the past year due to

tightening supply and increased demand for lime by domestic steel producers. This trend will favor the use of steel slag for AMD treatment in the future.

Figure 28. Factors influencing the value of the processed steel slag for AMD treatment.

Price Structure of Potential Steel Slag Market

Arrows indicate major directions of influence



9.0 ECONOMIC ANALYSIS

The cooling efficiency numbers and hot metal penalty amounts determined in Section 7 can be correlated to a dollar value. Realizing that market conditions, along with scrap costs, change, an average value of \$220/ton scrap and \$370/ton hot metal were utilized in determining economic benefit for Mill A with Sample 1B as the basis (see Figure 15 and Table 31 for data). The calculations are portrayed in Table 37. Based on separation yields experienced at pilot scale and incorporating a well recognized briquetting cost of \$50/ton, the revenue from on-site operation would be \$39.56/ton feed slag. The processing costs were determined to be \$10.31/ton feed, with supporting cost data provided in Table 38. From an iron unit recovery aspect the net revenue would be \$29.25/ton feed. This is profitable. If the sale of the residuals can be realized through AMD treatment, projected lime equivalency would result in an estimated \$15.92/ton feed, creating a more favorable net revenue of \$45.17/ton feed.

Table 37. Economic Calculations Based on Mill A Furnace Model

1. Sample 1B HGI Product	
$(3.8\text{T Scrap} - 0.1\text{T Hot metal}) / 4\text{T 1B HGI} = (3.8 \times \$220 - 0.1 \times \$370) / 4 = \$199.75/\text{Ton}$	
2. Sample 1B MGI Product	
$(4.3\text{T Scrap} - 1.9\text{T Hot metal}) / 4\text{T 1B MGI} = (4.3 \times \$220 - 1.9 \times \$370) / 4 = \$60.75/\text{Ton}$	
3. On-site Revenue	
0.2546 T HGI Briquettes @ \$92.00/Ton	\$50.86
0.1332 T MGI Briquettes @ \$60.75/Ton	\$ 8.09
Briquette Cost: \$50 x (0.2546+0.1332)	<u>(\$ 19.39)</u>
Subtotal	\$ 39.56/Ton Feed
4. Processing Cost	
Capital	\$ 0.92
Operating	<u>\$ 9.39</u>
Subtotal	\$10.31/Ton Feed
5. External Revenue	
(0.6122 T Residuals x 0.25 Lime) @ \$104/Ton	= \$15.92/Ton Feed
6. Net Revenue	
$\$39.56 + \$15.92 - \$10.31$	$= \$45.17/\text{Ton Feed}$

**Table 38 Iron Slag Processing Facility (50 tph)
Capital Cost, Operating Cost, Energy Requirements - Preliminary Estimate**

		Capital Cost (\$)		Operating Cost (\$/hr)											
				Labor					Equipment			Utilities		Energy (\$/hr)	
Phase of Process	Est. Cost	Factor	Total Cost	Labor		Equipment			Utilities		Diesel Fuel	Energy SubTotal	Total		
				Direct	Maint.	Repair	Lube	Tires	Elec.	Nat. Gas					
Off-Loading Facilities	386,000	1.00	386,000												
Loader	29,000	1.50	43,500	16.80	3.80	5.84	2.50					5.41	21.88		
Grizzly	30,000	1.20	36,000		1.13	0.82	0.17	4.33		1.12	5.41	1.12	3.24		
Conveyance					0.86	0.85	0.20			0.37		0.37	2.28		
Impact Hammer	10,000	1.10	11,000	4.40	0.97	0.94	0.13			0.20		0.20	6.64		
Primary Crusher	76,500	1.30	99,450		2.38	3.19	0.44			2.28		2.28	11.39		
Conveyance	20,000	1.20	24,000	3.10	0.85	0.83	0.20			0.37		0.37	2.25		
Surge Bin	10,000	1.30	13,000												
Feeder	7,000	1.20	8,400		0.13	0.13	0.03			0.04		0.04	0.33		
Rotary Kiln	252,000	1.60	403,200		0.67	0.90	1.44			4.19		4.19	7.20		
Dryer	60,000	1.40	84,000		2.13	2.08	0.50			0.75		0.75	5.46		
Conveyance															
Primary Screen	91,200	1.30	118,560	0.80	0.56	0.55	0.15			0.37		0.37	2.43		
Conveyance	25,000	1.20	30,000		0.85	0.83	0.20			0.19		0.19	2.07		
Primary D.C.	49,600	1.80	89,280		1.10	0.55	0.15			3.74		3.74	6.46		
Conveyance	15,000	1.20	18,000		0.85	0.83	0.20			0.19		0.19	2.07		
Primary Rod Mill	65,000	1.40	910,000		16.53	9.31	2.93			18.71		18.71	51.98		
Conveyance	20,000	1.20	24,000	4.50	0.85	0.83	.20			0.30		0.30	2.18		
Surge Bin	20,000	1.30	26,000												
Feeder	9,000	1.20	10,800		0.13	0.13	0.03			0.04		0.04	0.33		
Secondary Screen	37,700	1.30	49,010	0.80	0.38	0.37	0.10			0.11		0.11	1.76		
Conveyance		1.20			0.38	0.37	0.10			0.19		0.19	1.04		
Air Classification	96,000	1.50	144,000		0.64	0.85	0.09			5.43		5.43	8.81		
Conveyance	20,000	1.20	24,000	1.80	0.85	0.83	0.20			0.19		0.19	2.07		
Conveyance	15,000	1.20	18,000		0.43	0.41	0.10			0.11		0.11	1.05		
Air Classification	40,000	1.60	64,000		0.81	1.09	0.21			0.19		0.19	2.30		
D.C.	15,000	1.20	18,000		0.72	0.80	0.15			0.37		0.37	1.94		
Conveyance															
Secondary D.C.	40,200	1.80	72,360		0.94	1.19	0.23			2.24		2.24	4.59		
Compressed Air	21,000	1.30	27,300		0.87	0.85	0.12			2.81		2.81	4.65		

**Table 38 Iron Slag Processing Facility (50 tph)
Capital Cost, Operating Cost, Energy Requirements - Preliminary Estimate**

		Capital Cost (\$)			Operating Cost (\$/hr)								
										Energy (\$/hr)			
Phase of Process	Est. Cost	Factor	Total Cost	Labor		Equipment			Utilities		Diesel Fuel	Energy SubTotal	Total
				Direct	Maint.	Repair	Lube	Tires	Elec.	Nat. Gas			
Load-Out Facilities													
Feeders (4)	28,000	1.20	33,600										9.20
Bin Vent	16,000	1.30	20,800	9.20	0.52	0.52	0.12		0.16			0.16	1.32
Filters (4)	56,000	1.30	72,800										
Silos (4)	60,000	1.20	72,000										
Conveyance	10,000	1.30	13,000		1.70	1.70	0.40		0.76			0.76	4.52
Concrete Pad(s)													
Sub Total			2,964,060	41.00	42.03	38.28	11.37	4.33	45.42	0.00	5.41	50.83	187.84
Contingency (30%)			<u>889,218</u>					Conv.	0.060	2.650	0.649		<u>9.39</u>
Sub Total			3,853,278					Per Hour KWH/hr MCF/t gal/t	757.00	0.00	8.34		
Simple Interest (10% for 5 years)			<u>1,926,639</u>					Per Ton KWH/hr MCF/t gal/t	15.14	0.00	0.17		
Total			5,779,917										
Capital Cost (\$/ton)			<u>0.92</u>										

10.0 ENERGY ANALYSIS

Energy analysis was performed using two methodologies. The first methodology is related to the model results of cooling efficiency and hot metal penalties, which is portrayed in Table 39. The on-site energy benefit has been calculated to be 5.85×10^6 BTU/ton feed. Processing energy required would be 0.17×10^6 BTU/ton feed. When the energy of alternative lime production is incorporated into the analysis, the overall net energy benefit has been determined to be 6.76×10^6 BTU/ton feed.

Table 39. Energy Calculations Based on Mill A Furnace Model	
1. HGI Product	
$\frac{3.8T \text{ Scrap} - 0.1T \text{ Hot Metal}}{4T \text{ Skimmer} + 90} = \frac{3.8(26.823 \times 10^6 \text{ Btu}) - (0.1)(26.823 \times 10^6 \text{ B})}{4}$	$= 24.8 \times 10^6 \text{ Btu}$
2. MGI Product	
$\frac{4.3T \text{ Scrap} - 1.9T \text{ Hot Metal}}{4T \text{ Skimmer} + 60} = \frac{(4.3 \times 100) - (1.9 \times 120)}{4}$	$= 16.1 \times 10^6 \text{ Btu}$
3. On-site Energy Benefit	
	$0.2546 \text{ T HGI @ } 24.8 \times 10^6 \text{ Btu/Ton} \quad 6.31 \times 10^6 \text{ Btu}$ $0.1332 \text{ T MGI @ } 16.1 \times 10^6 \text{ Btu/Ton} \quad \underline{2.14 \times 10^6 \text{ Btu}}$ $8.45 \times 10^6 \text{ Btu/Feed Ton}$
4. Processing Energy	
	$= 0.17 \times 10^6 \text{ Btu}$
5. Lime Energy	
$(0.6122 \text{ T Residuals} \times 0.25 \text{ Lime}) @ 5.90 \times 10^6 \text{ Btu/ton}$	$= 0.90 \times 10^6 \text{ Btu}$
6. Net Energy Benefit	
	$(6.31 + 2.14 + 0.90 - 0.17) \times 10^6 \text{ Btu/Ton} = 9.18 \times 10^6 \text{ Btu/Ton}$

The second method of energy evaluation was performed by project cost share contributor, Combustion Resources, LLC (CR). CR was provided the analyses presented in Tables 18 through 21 and given instruction that the ~90% FeT products would report to the BOF and the ~60% FeT products would report to the BF. CR was asked to determine the furnace energy benefit or penalty associated with the iron bearing products from all mills, with emphasis on replacing typical iron scrap in the charge scheme. A description of the methodology employed and the results follow. CR's in-house models were used to determine the furnace energy differential of the materials.

In order to evaluate furnace energy requirements for processing different feed materials, the extent of reaction of each feed material component must be determined. Efforts to locate kinetic parameter values for the various high-temperature chemical reactions that occur in an industrial furnace were unsuccessful. Accordingly, the extent of reaction of each feed material component had to be estimated from general blast furnace slag/hot-metal component distribution values reported in literature [1]. Table 40 summarizes the assumed extent of reaction of the different feed material components. Note that only the reactions involving the iron-bearing-burden feed materials are considered in this study. Reasonableness of these assumptions was checked against information reported by internet sources [2,3]

Table 40. Assumed Input Component Extent of Reaction	
Feed Material Component	Assumed Extent of Reaction
Al ₂ O ₃	No Rxn
C	No Rxn
CaO	No Rxn
Cr ₂ O ₃	55% Reduction to Cr
Fe	No Rxn
FeO	100% Reduction to Fe
Fe ₂ O ₃	100% Reduction to Fe
K ₂ O	100% Reduction to K
MgO	No Rxn
MnO	70% Reduction to Mn
Na ₂ O	100% Reduction to Na
P ₂ O ₅	100% Reduction to P
Pb	Neglected
S	97% Reacted to CaS
SiO ₂	7% Reduced to Si
Sr	Neglected
TiO ₂	100% Reacted to TiC
Zn	No Rxn
ZrO ₂	100% Reacted to ZrC

Heats of reaction for individual feed material components were determined by using thermodynamic property values found in several sources [4, 5, 6, 7]. Note that the heat of formation of TiC and ZrC from TiO₂ and ZrO₂, respectively, was estimated by first completely reducing the metallic oxides and then reacting them with carbon to form their respective carbides. All reactions were assumed to take place at 1500°C in the furnace. Although some reactions will actually take place at temperatures much lower than 1500°C, this assumption simplifies furnace energy calculations and provides a conservative estimate of the energy requirements.

Table 41 summarizes the furnace energy requirement differentials calculated for each iron-rich material in this study.

Table 41. Approximate Furnace Energy Requirements for Specified Iron-Rich Materials		
Iron-Rich Input Material	Approximate Furnace Energy Requirement (kJ/kg)	Reduction in Energy Required Relative to Iron Scrap (kJ/kg)
Typical Iron Scrap (+99.5 metallic Fe)	5.46×10^4	—
Steel Mill A ~90 FeT Desulf. Fines Product	4.67×10^4	7.83×10^3
Steel Mill A ~60 FeT Desulf. Fines Product	1.88×10^4	3.58×10^4
Steel Mill A ~90 FeT BOF Mag Fines Product	5.38×10^4	7.81×10^2
Steel Mill A ~60 FeT BOF Mag Fines Product	2.88×10^4	2.58×10^4
Steel Mill B ~90 FeT Desulf Fines Product	5.16×10^4	2.96×10^3
Steel Mill B ~60 FeT Desulf Fines Product	2.78×10^4	2.67×10^4
Steel Mill B ~90 FeT BOF Mag Fines Product	5.17×10^4	2.87×10^3
Steel Mill B ~90 FeT BOF Mag Fines Product	2.09×10^4	3.37×10^4
Steel Mill C ~90 FeT Desulf Fines Product	5.36×10^4	9.12×10^1
Steel Mill C ~60 FeT Desulf Fines Product	4.44×10^4	1.02×10^4
Steel Mill C ~ 90 FeT BOF Mag Fines Product	5.36×10^4	9.98×10^2
Steel Mill C ~60 FeT BOF Mag Fines Product	3.71×10^4	1.74×10^4
Steel Mill D ~90 FeT Desulf Fines Product	4.61×10^4	8.50×10^3
Steel Mill D ~60FeT Desulf Fines Product	2.50×10^4	2.96×10^4
Steel Mill D ~90 FeT BOF Mag Fines Product	5.16×10^4	3.00×10^3
Steel Mill D ~60 FeT BOF Mag Fines Product	2.38×10^4	3.08×10^4

11.0 COMMERCIALIZATION

The economic assessment on Section 9 shows that the technology is economically feasible. For steelmaking slags with sufficient metallic iron contents, there is a potential to make a profit from \$20 to \$45 per ton, depending on if the LGI can be marketed or not. This favorable economic outlook has drawn commercial interest. ICAN GLOBAL, Inc., a Michigan based company, has come forward and signed a licensing agreement. The company invested to build a one ton per hour pilot testing facility with assistance from the project team. Materials from various sources were evaluated. The success of this operation has attracted the interest of a bigger entity, Westwood Land, Inc., also based in Michigan. It obtained all the rights from ICAN GLOBAL and invested to construct a 50 ton per hour testing facility in Michigan. The Michigan Tech team participated in all the technology transfer activities to make the commercialization successful.

One important issue for commercialization is to find a use for the residual fines, the LGI product, from the processing. The LGI material may be up to 70% of the weight of the original slag. If the material has to be disposed, the economics will be less favorable. Transportation of the material to a mine site may not always be feasible. Therefore, there is a need to continue this research in the future to investigate other applications for the LGI material.

Another issue worthy of more research is agglomeration. This has two concerns, with one of them being addressed through the course of this research. The first concern is the coarse nature of the products. The size distribution of the products is such that pelletizing would be impossible, thus, leaving briquetting as the most viable option. To prove that the material could be briquetted, project cost share provider, FERCO, ran some briquetting tests on segments of their production line equipment, using their proprietary binder. The testwork proved that both the HGI and MGI materials could be agglomerated, producing up to 4" diameter cylinder sections. It is also apparent that hot briquetting processes require sufficient input energy, and subsequent project agglomeration work should focus on ambient temperature agglomeration applications.

The cost of briquetting is the other concern. The cost penalty of approximately \$50/ton of feed has a major impact on material and process economics. It is realized that steel producers not only need quality, but structure for agglomerates to effectively endure the rigors of material handling, charging, and bearing loads put upon it in the BF in particular. In future research, in addition to binders, other approaches to solve the overall agglomeration cost issue should be addressed.

12.0 REFERENCES

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