Blasting for Improved Autogenous Milling at Hibbing Taconite Company

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Abstract

Blending ores of various grades is an essential function of mine engineers. Iron ore blending focuses on a number of properties, liberation values, weight recovery and concentrate silica being the most important. Other chemical and metallurgical factors are also commonly controlled. Recent research has fueled an emerging interest in blending on physical ore properties as well.

Fully autogenous mills rely on the large, competent fraction of feed to act as grinding media. Research indicated that Hibtac mills require specific amounts of 6 to 10-inch ore. High recirculating loads require a steady influx of large rock. Blast designs, therefore, are presently characterized by wide patterns and low powder factors. Current efforts are aimed at improving mill throughput while reducing overall energy costs.

Based on research and published case studies and the advent of measuring devices; Hibtac has embarked on a blast optimization program to identify optimum mill feed and to design blast fragmentation goals for each mining horizon and each mining area.

This paper describes an ongoing, broad-based, team effort which requires close cooperation of geologists, mine engineers, crushing and milling personnel. Three specific areas of investigation are described: 1) Historical relationships between powder factor and mill performance,. 2) Blast fragmentation modeling using the Kuz-Ram model and 3) Drill core measurements relating bed thickness to mill performance. Early findings indicate that in-situ bed thickness has an effect on mill throughput. A second finding is that even high powder factor blasts still produce a large amount of the coarse feed needed by the autogenous mills.

Introduction

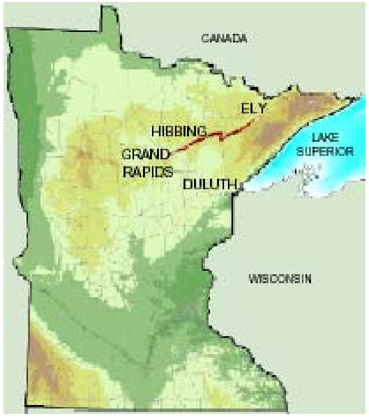
Hibbing Taconite Company

Hibbing Taconite Company (Hibtac) is located on the Mesabi Iron Range near the town of Hibbing in northern Minnesota.

At a rated capacity of 8.1 million tons of iron pellets annually, it is owned 62.3% by International Steel Group, 14.7 % by Stelco Inc. and 23% by Cliffs Mining Company, which is also the managing agent.

Hibbing Taconite mines an average of 30 million tons of ore, and 50 million tons all material, annually.

The HTC processing consists of nine 36-ft diameter autogenous grinding mills, two stages of magnetic separation, four balling drums per indurating line and three traveling grate pelletizing machines. HTC began pellet production during the third quarter of 1976 and made its initial shipment to the port of Superior, Wisconsin in January of 1977.



Physical Ore Specifications

Mine engineers and plant metallurgists recognize the importance of close control of feed to the plant. Every operation has developed key parameters on which the daily blend is based. Mesabi Range iron ore is no exception. Weight recovery, liberation values, silica and ferric/ferrous ratios must be controlled as well as slaty versus cherty rock percentages.

Hibbing Taconite Company (Hibtac) has a long history of also specifying a maximum powder factor (lbs. of powder per long ton of rock) used in blast design. Fully autogenous (AG) mills require feed which includes a percentage of coarse sizes. Early research pointed to an optimum feed of 40% minus 3-inch, 20% 3 to 6-inch and 40% 6 to 10-inch rock. Actual blasted and crushed feed exhibits a spectrum of size fractions reflecting: rock properties, blast design and crusher setting. Given the recent advances in computer modeling and in fragment size measurement; revisiting these size specifications may be helpful. Two obvious questions include: What is the best feed for the AG mills and what blast designs are required to economically produce such feed?

Today, Mesabi Range iron ore producers are challenged, as never before, to reduce costs or face closure. High grade deposits were depleted during the past century of mining. Worldwide competition from high grade producers is intense. Exacerbating the situation is the rising cost of energy. Flint-hard taconite must be ground to 75% minus 325 mesh in order to liberate magnetite from the gangue. Concentrate is subsequently pelletized in another energy-intensive process to facilitate shipping and blast furnace productivity.

In response to this challenge, Hibtac has embarked on efforts to fully understand the relationship between blasting practices and mill performance. Optimizing the throughput and energy efficiency of the AG mills is the object of a three year study which has received funding from the Department of Energy (DOE) plus matching contributions from industrial partners. Following herein is a review of the developing study of blast/mill relationships at Hibtac.

Blast Design Factors

Identifying customers is a key part of a successful business. Blasting engineers must know who their customer is; if they endeavor to produce the best product at the best price. The list includes:

- Shovels have to dig the blast
- Crushers must be able to efficiently handle the rock
- Mine operations must avoid excessive blast delays and safety problems
- Neighbors must not be exposed to excessive airblast, vibration or dust
- Mills must maximize throughput while minimizing energy consumption

Failure to achieve any of these goals is unacceptable. Unfortunately, blasting to provide maximum mill throughput, while minimizing mill energy consumption, is a poorly understood relationship. Unless other important contributing factors such as:

- Geological variation
- Crusher performance
- Seasonal temperature variations
- Setpoints and operational parameters
- Maintenance issues

are recorded and comprehended; blast design effects will simply be part of the 'noise' in a sea of variability of mill performance. As a result, few metal mines have capitalized on the economic potential of energy optimization.

Previous Work

Grinding theory dates back to 19th century Germany where Rittinger (1867) and Kick (1885) proposed models based on surface area and particle volume respectively. Bond (1951) proposed a third theory of comminution which is still widely used today. King and Schneider (1995) at the University of Utah have recently demonstrated improved modeling of grinding circuits.

Overall blast/mill optimization has more recent roots. MacKenzie (1966) reported on costs in iron ore from drilling through crushing. Udy and Thornley (1977) reviewed optimization through crushing. Gold (1987) tabulated and modeled overall mining cost related to blasting at Fording Coal. LeJuge and Cox (1995) reported overall costs in quarrying. Eloranta (1995, 2001) published costs in iron ore from blasting through grinding. Moody et al (1996) related dig times, crusher speeds and particle size to fragmentation in quarry operations. Furstenau (1995) used single-particle roll mill crushing to demonstrate a 10% energy savings in the drilling through grinding process by increasing powder factor by 25%. Paley & Kojovic (2001) detailed the complex relationship between blasting, crushing and grinding at the Red Dog mine. Modeling indicated that a tripling of the powder factor would save 25 to 30 million dollars in grinding annually.

Recent laboratory work has been aimed at tying mine and processing size reduction to common factors. These efforts include the work of Revnivtsev (1988), who related micro-cracks from blasting to energy use in subsequent crushing and grinding. McCarter

(1996) quantified blast preconditioning through the use of an ultra fast load cell. Nielsen (1996) performed extensive grinding tests on preconditioned rock and demonstrated changes in Bond work indices of nearly 3 to 1.

Geology

A previous description of Hibbing mine geology was compiled by Djerlev (1993). Hibtac's reserve is in the Lower Cherty member of the Biwabik Iron-Formation, a tabular chemical sedimentary deposit dipping gently to the southeast. Taconite denotes the bedded or wavy-banded, massive and granular to laminated ferruginous rock found in the greater Lake Superior iron-mining district. Principal minerals in fresh, unoxidized taconite typically include quartz, chert, magnetite, and minnesotaite with lesser amounts of goethite, siderite, ankerite, and greenalite (Gruner, 1946; White, 1954). Stilpnomelane and hematite also occur at Hibtac (Djerlev, 1993). Taconite varies from non-magnetic to highly magnetic; magnetite occurs as disseminated individual octahedra, aggregates of octahedra, and layered clusters formed by interconnecting aggregates of grains (Morey, 1993). Two different types of iron-formation are distinguished in the Biwabik Formation (Gruner, 1946; White, 1954; French, 1968). *Cherty* taconite is massive and quartz-rich, and characteristically has a granular texture due to the occurrence of iron silicates in rounded or irregular, 0.5 to 2.0 mm granules. *Slaty* taconite is generally dark, fine-grained, and finely laminated; it is composed mainly of iron silicates and carbonates, argillite, and carbonaceous matter.

The taconite mined at Hibtac averages 18.7 percent crude magnetic iron. Five local subunits of the Lower Cherty member comprise the orebody. Ore units are ascribed the nomenclature "slaty" or "cherty" based on the relative proportions of the two material types. The higher-grade ore consists of the 1-6 and 1-5 cherty taconite subunits, with a thickness of roughly 100 feet. These are overlain by the 1-7 lean cherty taconite subunit, which is approximately 20 feet thick. The cherty subunits consist of 2- to 12-inch-thick massive silicate chert zones with disseminated magnetite separated by 1/10th- to 2-inch-thick, slaty argillite-magnetite bands (Djerlev, 1993). Beneath the 1-5/6 zone is lean slaty taconite of the 1-4 and 1-3 subunits totaling 30 feet in thickness. This interval consists of interbedded argillite, magnetite, and minor hematite forming laminated bands from 2 to 10 inches in thickness separated by 2- to 4-inch-thick massive cherty zones (Djerlev, 1993). Total mineable stratigraphic thickness of the Hibbing orebody is approximately 150 feet.

Blast Fragmentation

Kuz-Ram Model

Five pattern designs used at Hibtac were modeled using with the Kuz-Ram model (Cunningham, 1983). Kuz-Ram modeling is a simple, empirical model which predicts fragment sizes for varied blast parameters. Kuz-Ram is well-suited to predict how changes in blast design will affect fragmentation relative to the results of the original design.

Typical ore blasts at Hibtac have the following parameters:
40 foot depth
5 feet of sub drilling
18 feet of stemming
water resistant anfo blend (70/30)
Burden and spacing is varied according to the following table:

Design	Burden	Spacing
#1	38	44
#2	36	42
#3	35	40
#4	33	38
#5	31	36

Table 1 Burden and Spacing for Kuz-Ram model

Applying the Kuz-Ram model to these parameters results in the following size distributions:

Size passing (Inches)	Design #1 38 x 44	Design #2 36 x 42	Design #3 35 x 40	Design #4 33 x 38	Design #5 31 x 36
0	0%	0%	0%	0%	0%
2	7%	7%	8%	9%	10%
4	14%	16%	17%	19%	21%
6	22%	24%	26%	28%	31%
8	30%	33%	35%	38%	41%
10	37%	40%	43%	46%	50%
12	44%	47%	50%	54%	58%
14	50%	54%	57%	60%	65%
16	56%	60%	62%	66%	70%
18	61%	65%	68%	71%	75%
20	66%	70%	72%	76%	80%
22	70%	74%	76%	80%	83%
24	74%	77%	80%	83%	86%
26	77%	80%	83%	86%	89%
28	80%	83%	85%	88%	91%
30	83%	86%	88%	90%	92%
32	85%	88%	89%	92%	94%
34	87%	89%	91%	93%	95%
36	89%	91%	92%	94%	96%
38	90%	92%	94%	95%	97%
40	92%	93%	95%	96%	97%
42	93%	94%	96%	97%	98%
44	94%	95%	94%	97%	98%
46	95%	96%	95%	98%	99%
48	95%	97%	95%	98%	99%

Table 2 Kuz-Ram resulting size distribution

Reviewing these results, it can be seen that all five pattern designs supply an abundance of coarse sizing (greater than 6”). An adequate blend of coarse ‘media’ rock is needed to act as balls or rods would in a conventional mill.

Mill engineers have established the following specification for optimum autogenous milling at Hibtac.

40%	6 inch to 10 inch
20%	3 inch to 6 inch
40%	minus 3 inch

Compiling these distributions into the mill specification groups, we see that design #5 most closely matches the mill specification. It is interesting to note that design #5 has the highest powder factor due to the tighter burden and spacing.

Size (Inches)	Design #1 38 x 44	Design #2 36 x 42	Design #3 35 x 40	Design #4 33 x 38	Design #5 31 x 36
minus 3 inch	12%	12%	11%	14%	15%
3 to 6 inch	14%	13%	12%	15%	16%
6 to 10 inch	17%	16%	15%	18%	19%

Table 3 Kuz-Ram size distribution sorted according to mill feed specification

Planned tests will attempt to verify these predictions. The challenge in blast design may be to maximize the minus 3-inch fraction while maintaining adequate 6 to 10-inch ‘media’ rock. The figure below is a plot of fragmentation results from the five modeled designs.

All designs result in at least 50% plus 10-inch rock. Kuz-Ram predicts the large fragments primarily because of the large burden and spacing used. Therefore, in the areas of the blast pattern furthest from the blast holes, the fragmentation is predetermined by the geology, (joints, fractures, bed thickness, and lithology). This is much like toppling a brick wall, where the bricks are uncoupled rather than individually broken. However, in the areas close to the blast holes, significant fragmentation occurs.

Reviewing Table 3, it can be seen that even the most energetic blast falls short of producing the minimum amount of –3” feed, according to the mill specification of 20%.

It should be noted that crushing normally does not generate a significant amount of fines. When the +10” material is broken by the crusher, much of the product reports to the 6 to 10-inch category.

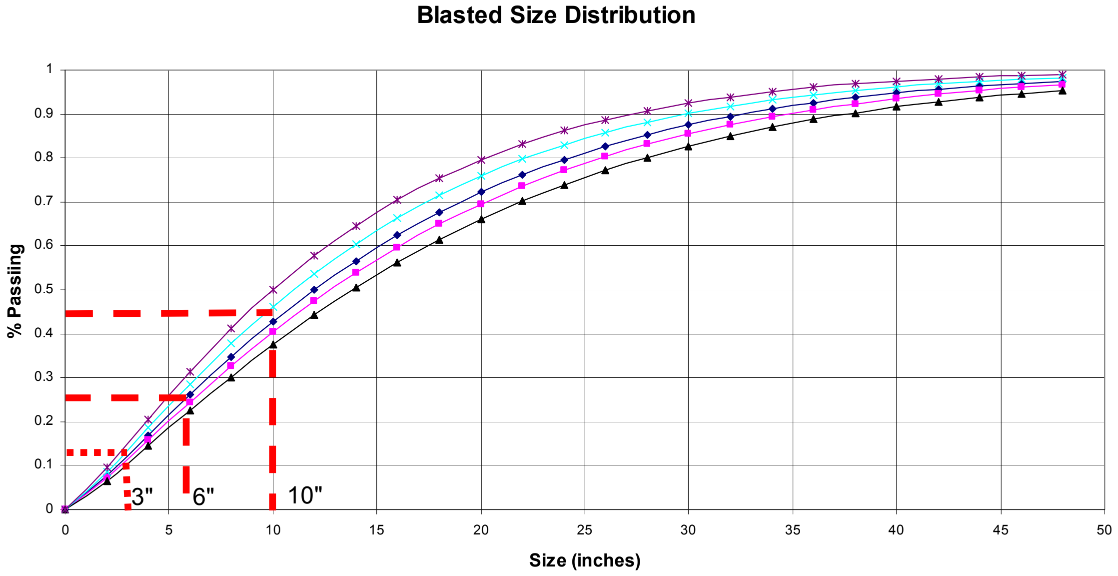


Figure 1 Size distribution for 5 Kuz-Ram models

Historical analysis of blasting, crushing, and mill performance.

Hibtac production data from startup in the mid 1970's to the present is charted in this section. Numerous flow sheet changes, changes in mining areas plus changes in blast design occurred over the past 3 decades, which makes interpretation difficult. However, fundamental efficiencies of each process in fragmentation may be evident.

Blast energy and crusher energy

Figure 2 chart is a plot of annual powder factor in pounds of powder per long ton of ore versus the crusher kw-hr per long ton. Higher powder factors result in increased kw-hr/LT at the crusher. This may reflect an increased amount of finer fragments which tend to draw higher amps.

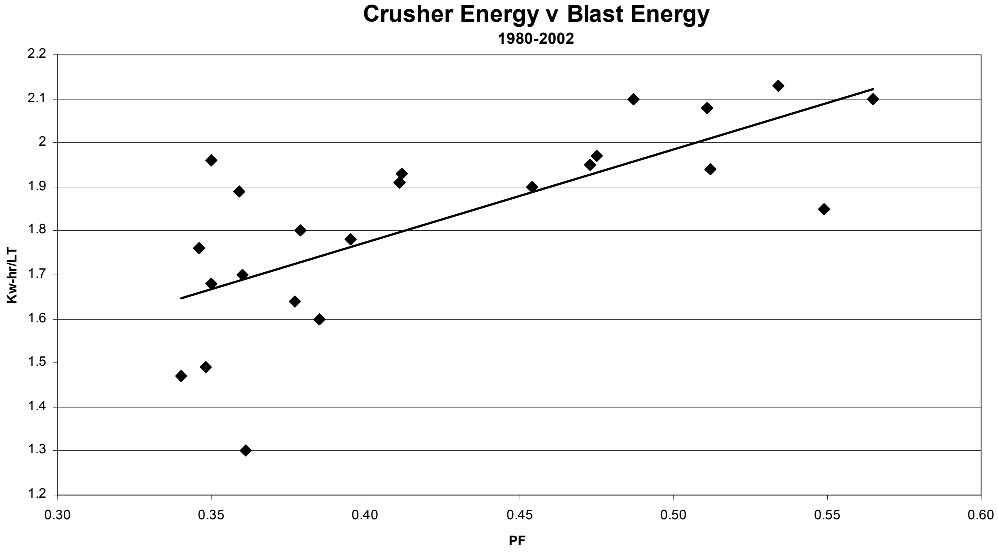


Figure 2 Crusher energy versus blast energy

Crusher energy and total energy

Figure 3 is a similar plot comparing kw-hr/LT for the crusher versus total Hibtac kw-hr/LT. Total energy consumption is dominated by milling. As crushing energy rises, total energy falls. The following observations may explain this phenomenon:

1) Crushing is more efficient at producing surface area. Efficiencies in the order of 50% for crushing and of 1% for grinding have been estimated (Hukki, 1975, Morrell et al, 1992)
2) Finer blasting causes crusher amps to rise, while mills may drop due to the additional minus 3-inch fraction

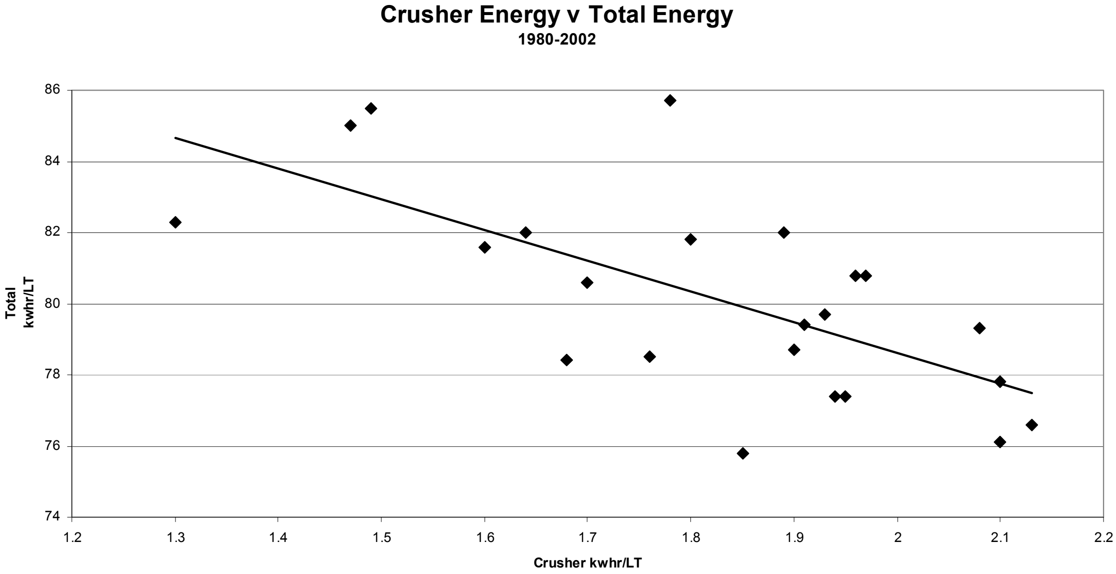


Figure 3 Crusher energy versus total energy

Blast energy and total energy

Figure 4 compares total electrical usage at Hibtac to the energy used in blasting. Again, it may be due to the additional fines produced in higher energy blasts. Crushing is not thought to generate a significant amount of fines. The crusher does draw higher amps with finer material and may end up doing more of the work at a higher efficiency compared to milling.

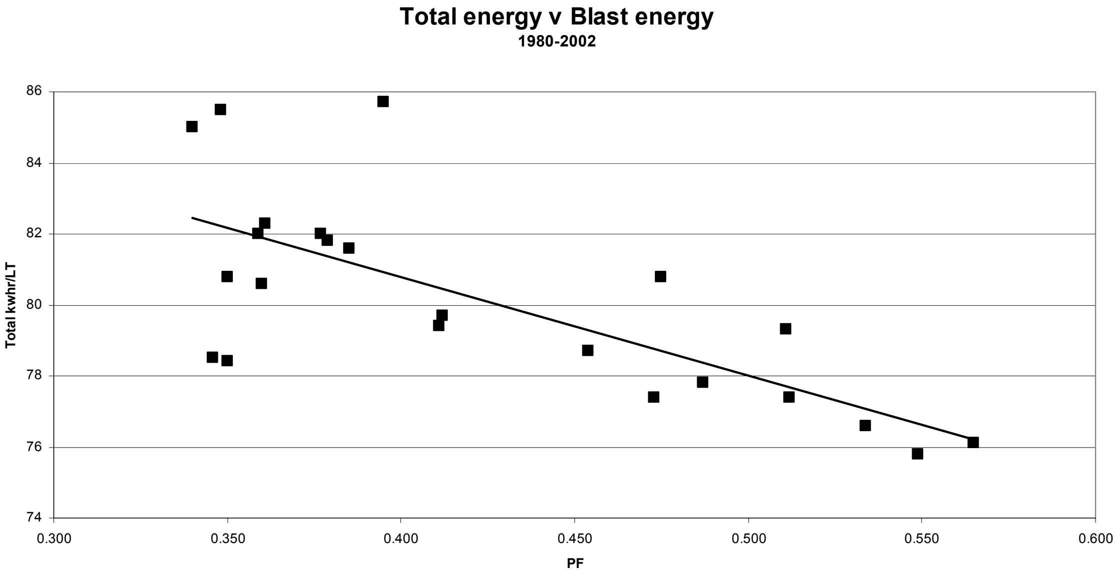


Figure 4 Blast energy versus total energy

Modeled energy cost

Figure 5 assumes the cost of powder to be $.15/lb and the cost of electricity at $.05/kw-hr. These costs are multiplied times the powder usage and the total electrical consumption respectively. Total energy cost is the sum of electricity and powder. As powder factor rises, the sum of the cost of electricity plus powder declines.

It appears that an increase of 0.20 in powder factor is associated with a $0.15 savings in electrical and powder factor energy costs.

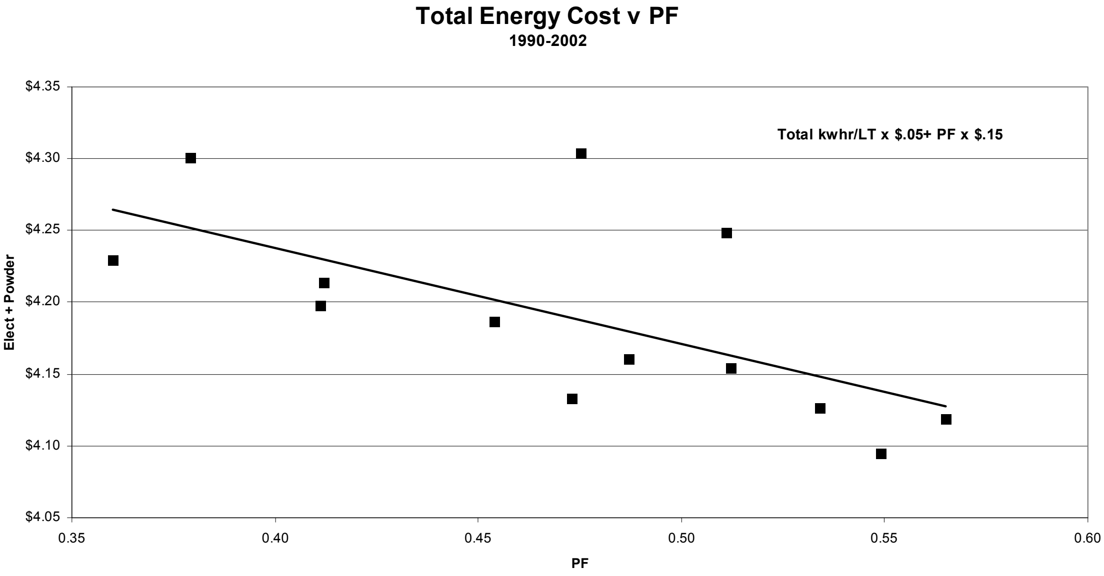


Figure 5 Total energy costs versus powder factor

Mill throughput and powder factor

Figures 6 and 7 compare the history of powder factor and mill tons. Figure 6 is a trend chart of mill tons per hour compared to monthly average powder factors since startup.

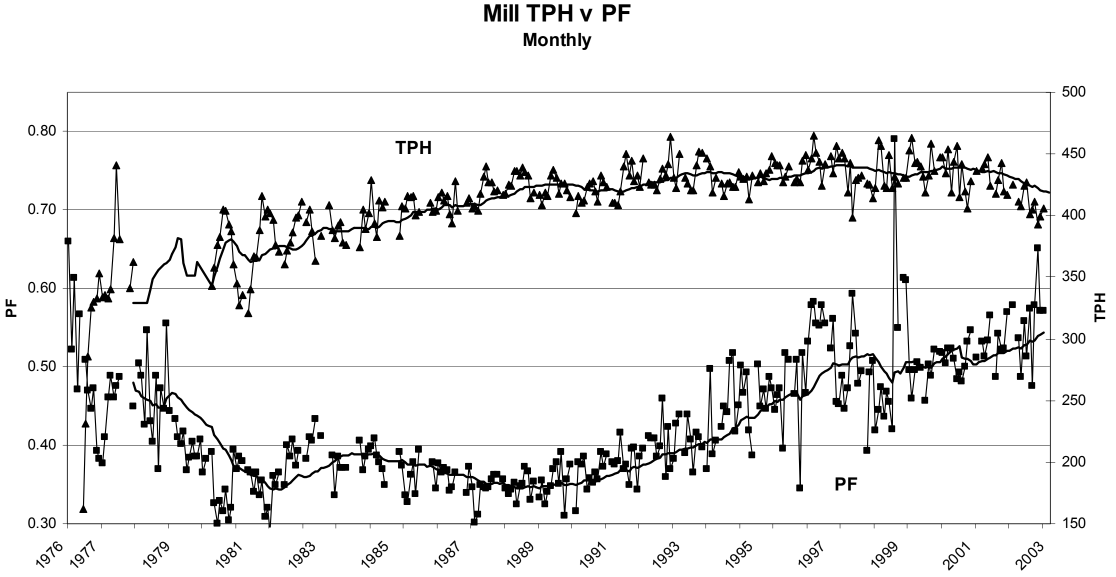


Figure 6 Mill throughput and powder factor

Figure 7 is an x-y plot of the annual results for past 15 years comparing powder factor to mill tons per hour. With the exception of the year 2002, higher powder factors coincide with higher mill throughput.

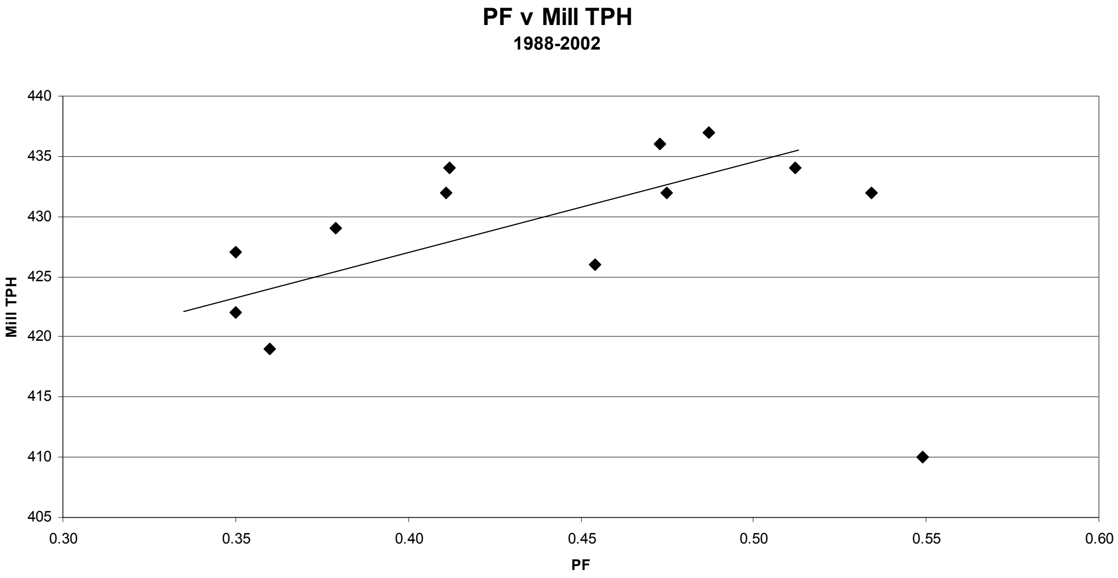


Figure 7 Powder factor versus mill productivity (tph)

Due to changes in all mining and processing areas, the apparent correlations in figures 2 through 7 may or may not be significant. However, given the high cost of energy; continued investigation seems to be appropriate.

In-Situ size affects mill rate

Hibtac blast patterns are characterized by wide burden and spacings and low powder factors. As a result, the fragmentation level of run-of-mine rock may be largely a function of the frequency of joints and bedding planes. In order to begin to quantify in-situ fragment size, drill core was measured to model the percentage of material within different size fractions. Each core was broken into discrete geotechnical intervals that were measured for the cumulative lengths of pieces greater than 2 inches, greater than 4 inches, greater than 8 inches, and greater than 10 inches, and divided by the total length of the interval to determine the percentage of summed lengths of pieces. Care was taken to avoid measuring to obvious man-made fractures in the core box. Also, heavily oxidized intervals with poor core recovery do not reflect taconite ore, and were not measured. From these measurements, additional bins were created that reflect the percentage of core pieces less than 2”, between 2” and 4”, between 4” and 8”, and between 8” and 10”. Through weight averaging, the various geologic units were roughly modeled by mining area. Core length values were then assigned to historical daily mine production through reconciling blast patterns in the daily blend with weight averaged geologic unit determinations from the nearest cluster of diamond drill holes. In this fashion, a daily, weighted average of core length was generated. The attached chart Summarizes core length versus mill throughput.

Core piece length measurements are a recent initiative at Hibtac, and the geotechnical database consists of only 42 diamond drill holes in four clusters marginal to the active mining areas. Therefore, the blasts could be quite distant from the drill hole cluster on which their sizing model was based. Furthermore, all diamond drill holes at Hibtac are vertical, and the mostly steeply dipping joint sets were not consistently intersected. Also, the daily weighted fragment size data do not reflect sporadic contributions to crusher feed derived from active stockpiles to which no sizing model was applied. Despite these limiting factors, preliminary results suggest a possible correlation between core length and mill productivity. Decreasing mill throughput trends with increasing amounts of coarsely bedded material. Likewise, as the less than 2” inch portion rose, so did the mill throughput. These results do not seem to be consistent with the current mill demands for feed a coarse as possible, and may, through further investigation, shed new light on what constitutes optimum feed for autogenous milling. Geotechnical core measurements will continue, and as mining progresses into the areas with measured core holes, enough data may exist to warrant digital modeling of in-situ fragment size.

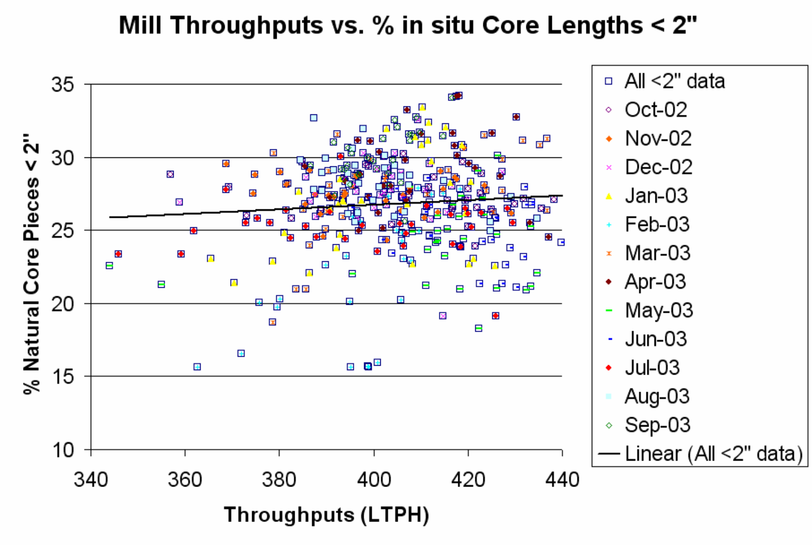


Figure 8 Mill throughputs verses in-situ core lengths < 2"

Figure 8 compares the mill throughputs to the percentage of mill feed represented by diamond drill core lengths less than 2 inches – fine material. This covers 13 months of production, and has a lot of noise. It is difficult to draw conclusion from this except that additional fine material did not seem to hurt tons per hour, and perhaps even improved tons per hour.

The same noise exists for figure 9, where mill throughputs is compared to the percentage of mill feed represented by diamond drill core greater than 8 inches – coarse material. Again it is difficult to draw conclusions from this except that a greater percentage of coarse material didn’t seem to help throughput.

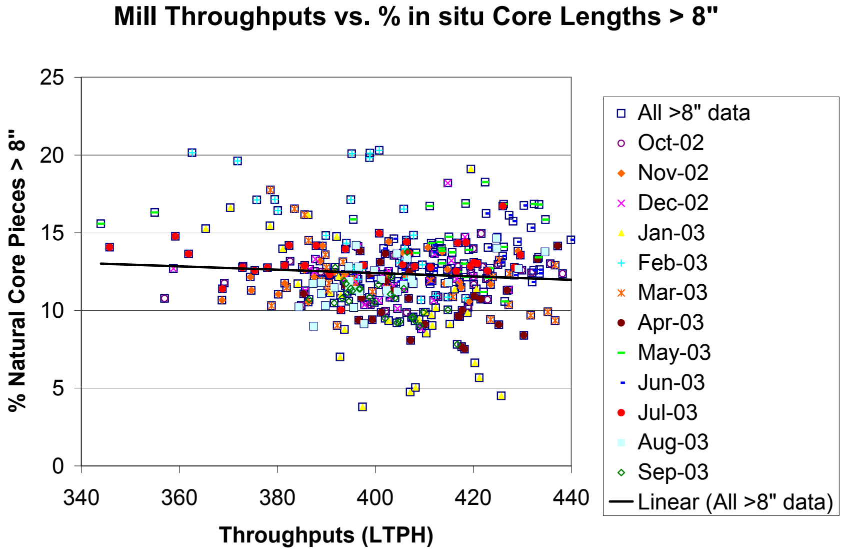


Figure 9 Mill throughputs versus in-situ core lengths > 8"

However, breaking up the charts into separate months shows some stronger trends. Here January and February 2003 are shown in Figures 10 and 11. In both cases additional fine material enhanced productivity, and additional coarse material depressed productivity.

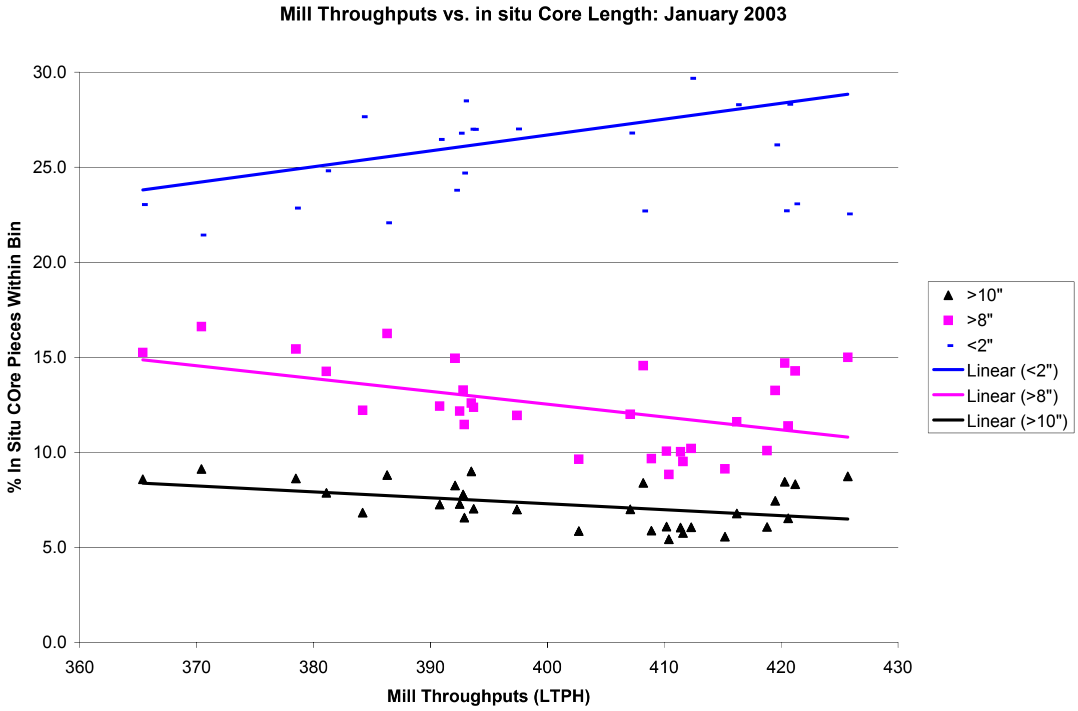


Figure 10 Mill throughputs versus thin and thick bedding in-situ core length, for January 2003

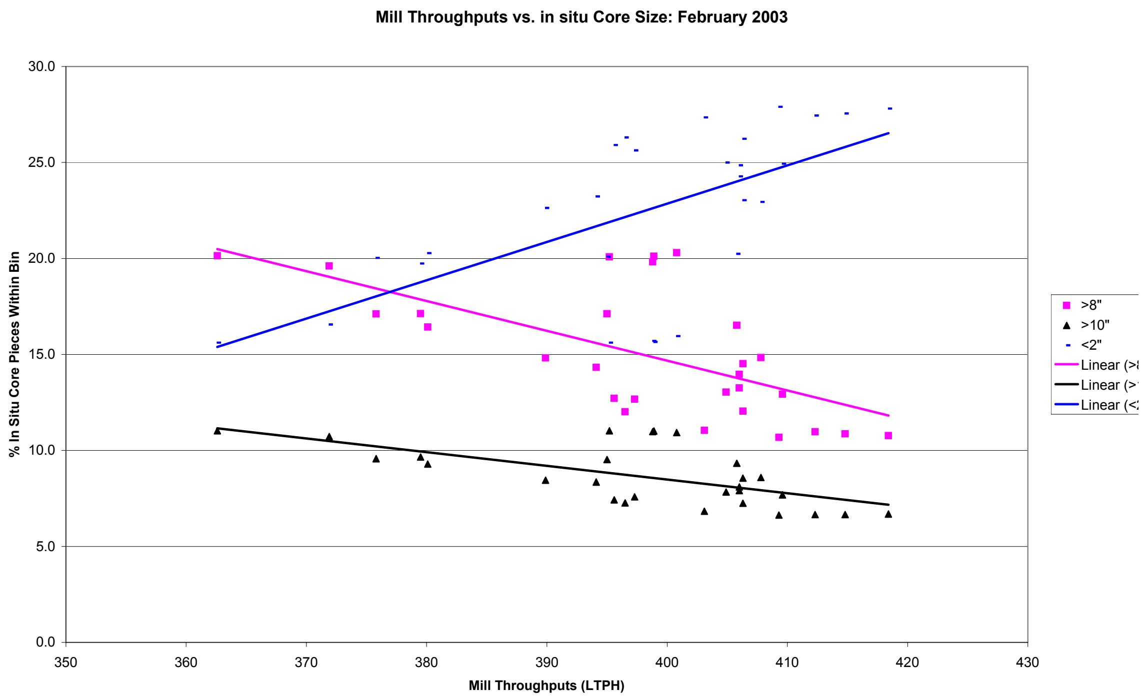


Figure 11 Mill throughputs versus thin and thick bedding in-situ core length, for February 2003

This trend wasn't universal for the 12 months studied. Over the period of a year, 6 months showed a similar trend as the above, 4 months were neutral, and 2 showed a reversal of the trends.

Again, the database for in-situ core length is small, and several of the blasts were located a significant distance from the representative drill core. However, these charts are encouraging, and suggest more investigation.

Conclusions

Initial results indicate that:

1) Bedding thickness affects mill productivity. Thicker beds tended to depress throughput while thinner beds yield higher tons per hour.
2) Blast fragmentation modeling indicates that higher powder factor designs may match mill specifications more closely than low powder factor designs
3) In Hibtac's large spacing blasts, fragmentation is predetermined by in-situ bedding and fragment size, and powder factor plays a secondary role.
4) Models of all current Hibtac blast designs produce excess plus 10-inch fragments. None of the designs produce even one-half of the minus 3-inch material called for in the mill feed specification.

If these early indications prove to be correct, blasting and milling practices may be poised for improvements.

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