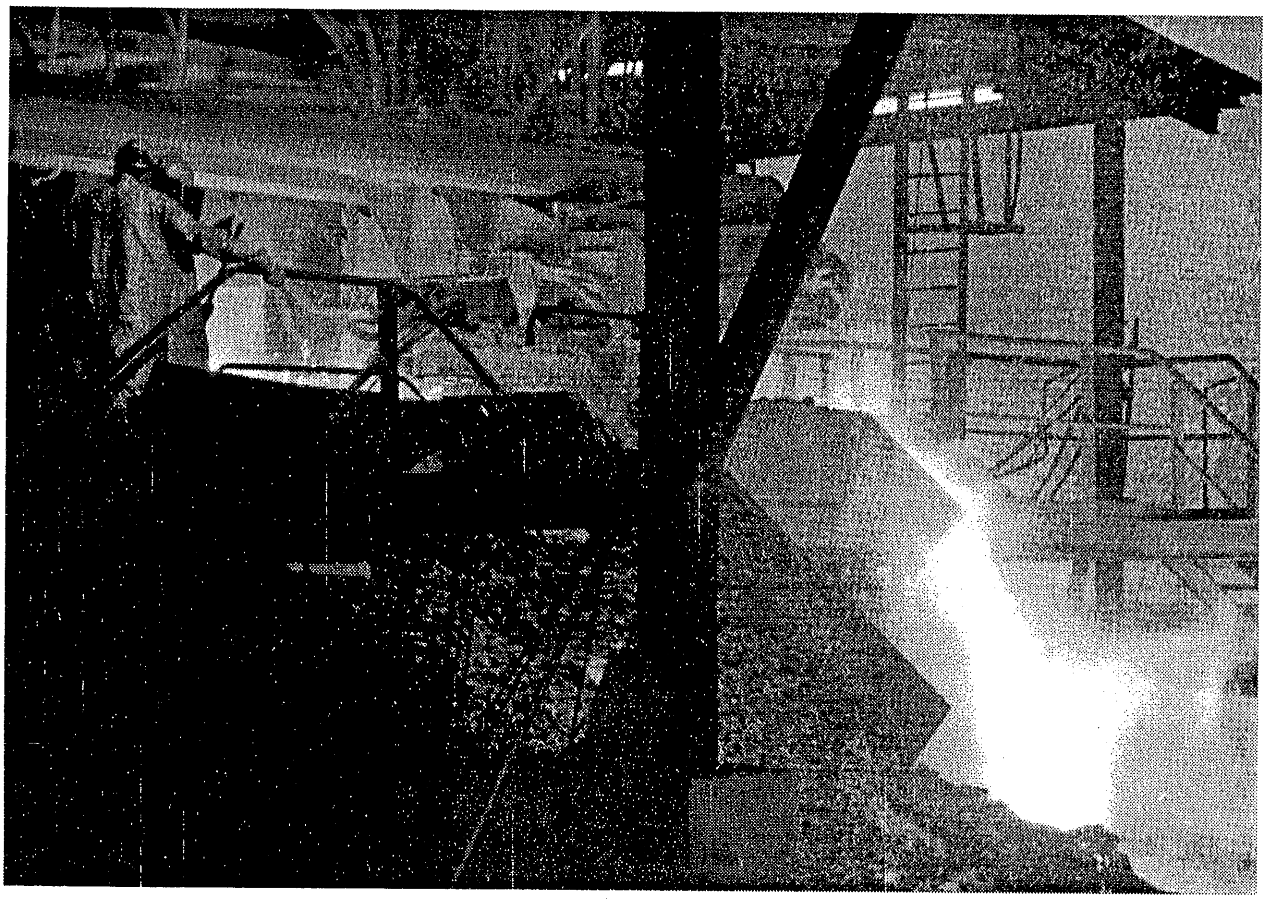
EL: A BLUEPRINT FOR PROGRESS



Minnesota Department of Natural Resources

Minerals Division

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MINNESOTA STEEL: A BLUEPRINT FOR PROGRESS

Minnesota Department of Natural Resources

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INTRODUCTION

This report was written at the direction of the legislature under 1993 Minn. Laws, Chap. 172, sec. 5, subd. 2, "to produce a report on the feasibility of locating a steel mill in northern Minnesota." Its purpose is to provide updated information on the economic feasibility of steel production in Minnesota and a framework for the development of value-added processing in the taconite industry. The updated information, reflected in a spreadsheet located in Appendix A, was used for many of the conclusions drawn in this report. This information and the particular sources from which it is gathered is maintained by the Division of Minerals to assess the economics of various processes. In this report, the framework for development of value-added processing is set forth as the basis for the first step necessary to steel production, which is iron-making, either as direct reduced iron (DRI) or hot metal (pig iron).

SUMMARY

BACKGROUND

The conventional route to steel from iron ore through the blast furnace has been perfected over the last 250 years so that it is thermally efficient and capable of high-quality production. Over the last few decades, the economic size of blast furnaces has grown to the point where construction of completely new facilities based on the coke oven/blast furnace technology is unlikely in the United States. For the last few years the research emphasis of the integrated steel companies has been on process improvement and upgrading downstream technology, e.g., continuous casting and cokeless iron-making technology to replace aging coke ovens and provide more operating flexibility. It is expected that these efforts will extend the economic life of blast furnace technology for many years, so that Minnesota has a major responsibility to improve the quality and reduce the cost of taconite pellets made in the plants located here.

While much has happened to make the integrated steel producers more efficient, the electric furnace/mini-mill segment of the industry has been growing and taking a larger share of the domestic steel market. The latest estimates by World Steel Dynamics[1] place their share of the market at just under 40 percent. The operating success of NUCOR's Crawfordsville plant has generated shock waves in the industry, as they opened the way to higher quality market segments. The growth of the mini-mill segment of the industry has created a new demand for direct reduced iron (DRI) and placed greater pressure on North American pellet capacity.

Dr. Peter J. Kakela of Michigan State University projects a relatively small drop in pellet demand over the next 6 years, but a relatively large, 12 million ton, reduction in pelletizing capacity from closure of excess production capacity.[2] For Minnesota this is a double barrel threat: demand is growing for products which are not currently produced here, and demand will be shifting to the most efficient producers for those products we do make. Actions taken during the next year or so will have a significant impact on the economic future of the the Iron Range. Excessive delay on DRI production will allow the growing demand to be absorbed by other producers, and lack of action to reduce costs will heighten threats to existing plants.

The impact of the strains currently being felt by the industry could be partially offset by producing DRI. However, economic results could be even better if the state could once again become a steel producer. While steel production should be the state's ultimate objective, it is really the second step in a progression. The logical first step is to prove that plants in Minnesota can compete in the growing DRI market. The major subject of this report was to be steel production, but it became evident during the writing that the economics of a Minnesota steel plant would depend on its ability to access inexpensive high-purity iron units. This report lays out a blue print for progress that could focus the efforts of many people on a few tasks.

The DRI processes available today use either natural gas or coal as their primary source of energy. The natural gas-based DRI processes are not likely to be competitive when located in Minnesota, as they appear to be at least $30 per ton more expensive than imported DRI (See Table 1). Also, the coal-based processes appear to work best on eastern coal, and "greenfield" facilities appear to be too costly. The closure of the conventional routes means that the state must pursue a solution that is specifically designed to exploit Minnesota's strengths and minimize its weaknesses, for example, its access to inexpensive western subbituminous coal. Development of a Minnesota-specific action plan is possible, but a constant attention to new ideas, flexibility in thinking, and a willingness to change direction will be necessary ingredients for eventual success.

IRON PRODUCT COSTS	
IRON-MAKING PROCESS	$/TON-Delivered
Grate-car Retrofit	110
MIDREX-Natural Gas	151
Venzuelan DRI	118
MIDREX-FASTMET	125
COREX-Pig iron	177

Table 1. Iron Product Costs

SHORT-TERM OBJECTIVES

In the short run, the state must concentrate its efforts on technologies that are commercially available. This involves some technical and economic risks, which can be controlled by careful engineering and due diligence. Two objectives should be emphasized in the short run: 1.) complete the engineering on flowsheets that produce taconite concentrate containing 2 percent silica, and 2.) concentrate on the implementation of coal-based DRI technologies that maximize the use of the existing infrastructure. Achieving these two objectives should result in the lowest costs for DRI production in Minnesota. Table 1. shows comparisons of customer costs for several DRI technologies, assuming that the plants are located in Minnesota. The data indicate that the Allis-Chalmer's Grate-car process and a process like MIDREX's FASTMET could be competitive with imported DRI. Emphasis on short-term technologies could generate construction decisions during calendar 1994 or early 1995. Several construction possibilities have already gone well beyond the early discussion stage. The short-term picture is constantly changing, but the frame seems to be constant, i.e., to concentrate on "nearly commercial" concepts.

INTERMEDIATE-TERM OBJECTIVES

Success with DRI production in the short time frame will increase the likelihood of steel production in the intermediate time frame. Like the state's short-term objectives, its intermediate objectives should aim at finding or developing technologies which draw from Minnesota's strengths. These objectives can be divided into three streams of effort. The first objective should be to find or develop energy sources, the second stream of effort should be to develop DRI processes utilizing Minnesota's strengths, and the third should be to use the attainments of the short-term objectives to further the possibilities of steel production in Minnesota.

It may be possible to find ways of using western subbituminous coals as energy sources in metallurgical processes. Minnesota utilities and industries currently use these coals for combustion, but they can also be upgraded to produce a range of products including synthetic gas or char for DRI processes. Research performed on coals from the Powder River Basin in Montana and Wyoming has proven that medium Btu gas and/or low-sulfur char can be produced. Selection of appropriate operating conditions and the costs and scale of facilities are the remaining engineering issues.

One technology that deserves careful evaluation is being marketed by ThermoChem, Inc. It is a gasification technology that appears capable of two modes of operation. In the first mode it could produce a high-hydrogen synthetic gas for DRI production without the use of an oxygen plant. In the second mode it would produce a lower quality gas and significant quantities of low-sulfur char for DRI production. The vendor currently has access to federal demonstration funds through the U. S. Department of Energy's Clean Coal Technology Program. The state is attempting to have that demonstration plant built in Minnesota.

RESEARCH COMMITMENTS TO DRI PRODUCTION IN MINNESOTA	
PROCESS/PROJECT	COMMITMENT
Low-Silica Concentrate	$156,000
Steam Gasification of Western Coal-USDOE Clean Coal Project	$25,000
Oxidation/Reduction and Metalization	$60,000
Lean Ore Reduction-LEANOX	$50,000
Fine Concentrate Reduction	$25,000
Iron Carbide on Low-grade Ore	$25,000

Table 2. Research Commitments

As Table 2. indicates, DRI research covers three areas: concentrate production, energy requirements, and innovative reduction processes. The low-silica concentrate project, which is being done at the Coleraine Minerals Research Laboratory (CMRL), aims to make Minnesota's taconite concentrate comparable with foreign ore. The objective of the second project is to develop a low-sulfur energy source from western subbituminous coal for iron ore reduction. The other four projects emphasize innovative iron ore reduction processes. Oxidation/Reduction and Metallization utilizes the oxidative power of magnetite to provide high internal pellet temperatures that can be carried into the reduction process. It has similarities to processes like FASTMET, but with differences that give it a Minnesota flavor.

Reduction of lean ore containing 35 to 45 percent iron followed by concentration is an old idea that is being investigated at Midland Research using today's technologies for crushing, grinding and separation. The fine concentrate reduction process concept uses magnetic fields to control very fine particles during reduction. It is being investigated by the Minnesota Department of Natural Resources. The fourth investigation, also by CMRL, will look at using relatively coarse-grained natural ore as feedstock to the iron carbide process with subsequent concentration of the product to produce commercial iron carbide.

Success with DRI production in the short-term will increase the likelihood of steel production in the intermediate-term; but issues of technology and location must be resolved. Regarding technology, today's reference steel plant is NUCOR's plant in Crawfordsville, Indiana. Technology is likely to change as other companies try to profit from the opportunities created by NUCOR's success. New plants will be even more efficient. These changes might not be beneficial for a Minnesota location, and it is very difficult to predict which plant model might be applied to a prospective plant in Minnesota. Regarding location, current thinking in the industry is to locate a smaller steel plant near customers. Minnesota has a distinct locational disadvantage which must be overcome by product quality and raw material or energy cost advantages. The combination of Minnesota taconite concentrate and western coal presents an attractive opportunity which should be developed. Table 3. shows today's estimates of the cost of steel from a Minnesota plant compared to plants in other locations. The data indicate that we are close to being competitive.

STEEL PRODUCTION COSTS		
PROCESS	LOCATION	LOWER LAKE PRICE $/TON
Imported DRI/EAF	Gulf Coast	233
Grate-Car/EAF	Minnesota	245
MIDREX-gas/EAF	Minnesota	255
FASTMET/EAF	Minnesota	256
FASTMET/EAF	Chicago	248
COREX/EAF	Minnesota	233

Table 3. Steel Product Costs

LONG-TERM OBJECTIVES

Long-term success will be built on short-term accomplishments. The construction of even one DRI plant making a competitive product in the next few years will stimulate activity across a broad range of organizations and companies. Success in research on Minnesota-specific DRI technologies will generate thinking about other possibilities. All objectives must remain focused on steel production -- and perhaps even beyond to consumer products -- to convert our iron resources into products demanded across a broad range of industries.

STEEL PRODUCTION METHODS

CONVENTIONAL STEEL PRODUCTION

The conventional steel production process which has been perfected over the last 250 years is quite efficient and capital intensive. The conventional process consists of five major steps, each of which is more or less independent of the others. The processing steps are:

Iron-making in blast furnaces
Steel-making in oxygen furnaces
Refining and alloying
Casting
Rolling

Iron-Making

Hot molten iron is produced in a blast furnace which uses iron ore, coke, and limestone for raw materials. The pig-iron product of the iron-making process contains about 95 percent iron, 4 percent carbon, and 1 percent or less silicon. Other impurities, like sulfur and phosphorus, occur in small amounts and have very deleterious effects on the metal. Another product taken from the furnace is slag. Slag contains the silica and alumina (gangue) impurities which are contained in the iron ore and coke. While the blast furnace process is essentially continuous, tapping of the hot metal and slag occurs periodically so downstream the metal is handled in batches.

The source of energy for the blast furnace, coke, is produced in coke oven batteries. The coke stabilizes the iron ore bed during reduction and burns near the bottom of the furnace where hot air is injected through nozzles (tuyeres). Coking coal is heated in the coke ovens to drive off volatile hydrocarbons, leaving a strong, solid material that has a high heating value. The gas produced in the coke ovens is burned in the plants, primarily for process heat. Coke ovens have been identified as a serious source of pollution, some of which is due to the units' age which (in the U.S.) averages over 25 years. The problems associated with coke production and utilization have fostered considerable research on new iron-making technologies.

Limestone is used to reduce the viscosity (flux) of the molten impurities in the iron ore and coke. The impurities are mostly silica (SiO_2) and alumina (Al_2O_3), i.e., metal oxides which do not reduce in the blast furnace. The limestone is calcined to calcium oxide (CaO) in the furnace, and the resulting mixture of impurities melts to form a slag layer on top of the metal layer. The slag also has an important role in removing sulfur from the hot metal through the formation of calcium sulfide (CaS). The slag produced is a nonhazardous solid waste. In some cases it goes into landfills, but more often it is used as an aggregate material in road construction.

Steel producers are working hard to improve the operation of blast furnaces. They have recently moved to the use of fluxed pellets which improves furnace operation by increasing and narrowing the range of temperature during which pellets soften and melt. Several organizations are also injecting coal as a way of reducing the amount of coke needed. Other changes made in the areas of

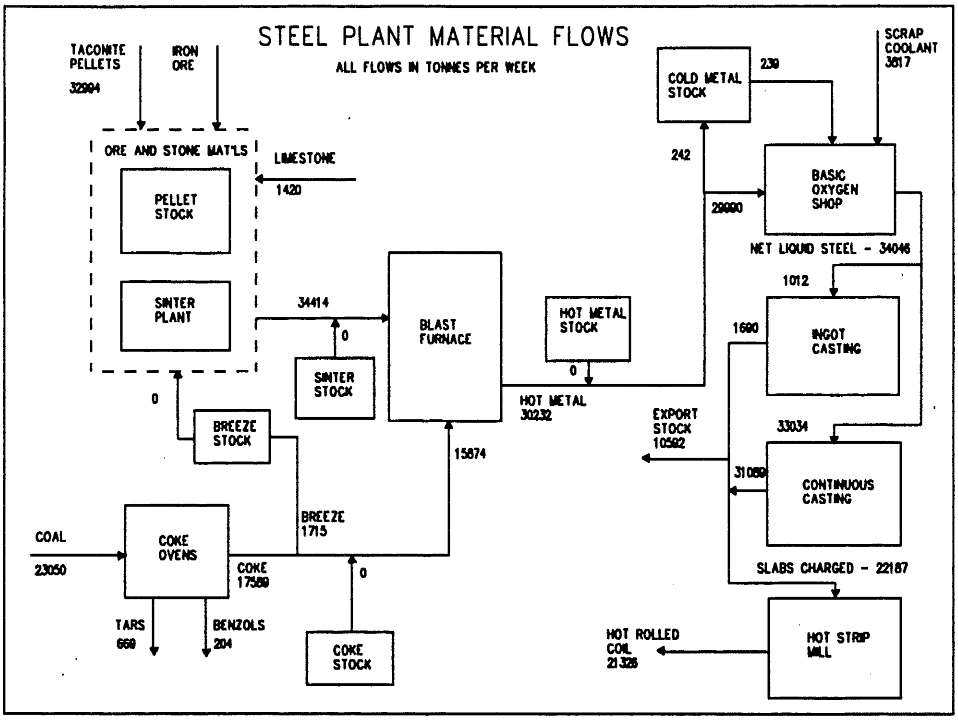


Figure 1. Integrated Steel Production

raw material charging, hot metal tapping and control systems are all aimed at ensuring that the blast furnace will remain the primary producer of hot metal for some time to come.

Steel-making

In the conventional steel-making process the primary object is to remove carbon, silicon, sulfur, and phosphorus from pig iron, so that almost pure molten iron remains. To do this, oxygen is injected into a vessel holding the hot metal. Argon gas for stirring might also be injected through a porous plug in the bottom of the vessel. The carbon and silicon are oxidized in the bath giving off heat, the carbon is removed from the gas stream as carbon monoxide, and the silica is removed from the slag as SiO_2. Other impurities are also removed from the slag. Since the temperature must be controlled within rather narrow limits, steel scrap is added as a coolant.

Slag-forming materials, like lime, are added in the steel-making step to enhance the removal of impurities from the metal. The slag chemistry must be controlled within close tolerances to achieve very low levels of sulfur and phosphorus in the liquid steel. Usually a large portion of the steel-making slag is recycled through the blast furnace prior to its ultimate disposal.

Liquid steel is produced in batches, which means that the timing of material handling from blast furnace to refining and casting is critical for the product's temperature to be maintained. As will be discussed later, an important area of international research is continuous steel-making.

Refining and Alloying

Steel is made in many grades and is alloyed with many other materials to provide the properties desired by end-users. Steel can be brittle or ductile depending on how it is treated and alloyed. Its forming properties can be affected by dissolved gases, like nitrogen. The adjustments of product composition are made during the refining step. The refining step is a significant contributor to the eventual quality of the product.

Casting

The casting step is perhaps the one which has seen the greatest amount of change over the last decade. The industry has moved strongly into continuous slab-casting by making large investments in casting and rolling equipment. In the older technologies the liquid steel was cast into ingots prior to its final forming. Ingot casting generally created a large amount of internal scrap which was recycled to the steel-making operation. However, it also generated quality problems during the subsequent rolling step and led to lower energy efficiencies due to heating and cooling of the material.

Slab-casting is an important research subject topic with particular emphasis on thin slab-casting, i.e. reducing the slab thickness from approximately 10 inches to perhaps 3/4 inch or less. Another important research area is casting to near-net shape, wherein the material is cast to minimize downstream forming operations. Computers and computational fluid dynamics have been used to model cooling and solidification to identify quality issues. High intensity magnetic fields have been used to magnetically levitate the liquid steel during the casting process, and alternating electric fields have been used to improve surface quality of the slabs. While the move to continuous casting has improved the products, it has decreased the supply of high quality, clean steel scrap and likely has had an effect on the prices in the scrap market.

Rolling

Conventional rolling practice requires the use of large, expensive equipment to convert slabs that may be 10 inches thick to coils of steel perhaps as thin as 1/32 of an inch. Several types of rolling practices are used, with hot-rolling techniques being the most common and cold-rolling techniques being the most expensive. Surface quality and freedom from blemish are important quality features in the final products, so a considerable amount of work has gone into removing or eliminating surface defects. The largest area of innovation is perhaps the use of four-stand rolling mills to produce material that may be as thin as 1/10 inch. It is this smaller, less expensive type of rolling that allowed NUCOR Steel to build and operate its new mill in Crawfordsville, Indiana.

MINI-MILL STEEL PRODUCTION

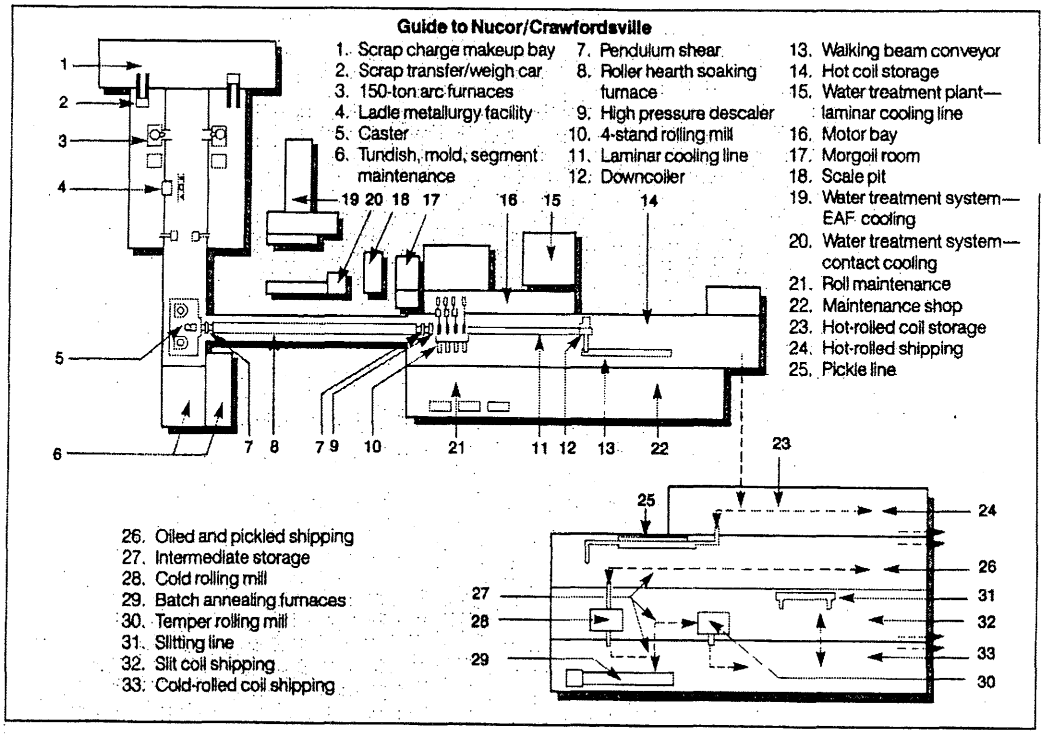
Originally mini-mills used alternating current (AC) electric arc furnaces to melt scrap and produce lower-quality steel products like reinforcing bars and light structural shapes. The mills did very little refining, and the liquid steel was cast as billets, i.e., shapes approximately 8 inches by 8 inches. The billets were then rolled to form the wire or structural materials.

Over the years mini-mills have captured a greater share of the market by being price and quality competitive. At the present time mini-mills and integrated producers are in even stronger competition as the mini-mills are taking bigger pieces of the higher quality markets. Some of the recent innovations that make the advance of the mini-mills possible are the use of direct reduced iron (DRI) (to make a less contaminated end product), thin slab casting, lower cost rolling mills, use of heated charges (to reduce energy costs), and conversion to direct current (DC) arc furnace (to improve control and efficiency). As will be discussed later, plants like the one recently built by NUCOR threaten to take another 10 percent of the market within the next 10 years or less. A major issue currently facing the mini-mills is the high cost of high quality scrap. In the face of today's high prices, mini-mill companies are turning to scrap substitutes like DRI and iron carbide to provide the clean iron units needed to compete with the integrated producers.

The successful startup and subsequent operation of the NUCOR facility has sparked a revolution in the structure of the steel industry. In its publication, *World Steel Dynamics*, PaineWebber identifies a number of insights gained through the operation of this plant:

> "The further a facility progresses towards a higher value-added product, the greater the cost advantage. The more complex the product, the greater the advantage from mini-mill management techniques and the utilization of computers to control and link processes.
>
> "Steel plants can be run with so few people that there is little need to go to the developing world to get low wage rates in order to hold down employment costs per ton. Very low wage rates are not necessary, if the work force is highly trained and well motivated.
>
> "Traditional steel company management approaches are no longer adequate when it comes to labor relations, production facilities and the overall strategic approach to the steel business.
>
> "Workers can be trained quite quickly to perform the most complex tasks in a steel plant.
>
> "Within the next decade we [*WSD*] look for non-blast furnace steelmakers the world over to be growing factors in the production of flat-rolled steel on a lower scale basis than the traditional integrated [blast furnace] producers."[3]

World Steel Dynamics further predicts that by the year 2000, 4 to 6 thin-slab/flat-rolling plants will be operating in the United States.[4] The annual hot-rolled band capacity of these mills will be 4 to 7 million tons per year. Success at Crawfordsville motivated NUCOR to build a similar mill in Hickman, Arkansas.



REFERENCE STEEL PLANT AND NEW STEEL TECHNOLOGY

REFERENCE STEEL PLANT

The reference plant for new steel-making technology is currently NUCOR's plant in Crawfordsville, Indiana. That plant, which cost about $400 million to build, opened new markets for mini-mill producers by being the first mini-mill to challenge integrated producers' hold on the hot-rolled steel market. It was reported that many of the plant drawings are "as built," an indication that many decisions were made "on the fly" as the plant was being constructed. It operated rather poorly for the first few months, but after its first year and half of operation exceeded the expectations of its builders.

The facility is based on the Electric Arc Furnace (EAF) melting technology, using a charge of about 80 percent scrap and 20 percent DRI. The innovative part of the mill is its thin slab-casting technology which is coupled with a state-of-the-art rolling mill via a soaking furnace. The mill can produce 800,000 to 1 million tons of hot and cold rolled coils per year. The rolling mill uses the SMS concept of Compact Strip Production, in which molten metal is continuously cast into a slab 2 inches thick and 52 inches wide. The slabs, moving at a rate of about 14 feet per minute, are cut into 150 foot lengths. These lengths then move through a soaking furnace, a descaler, and a four-stand finishing mill, which reduces sheet thickness to a minimum of 1/10 inch.

The mill employs approximately 400 people and averages 0.7 to 0.8 person hours per ton of hot-rolled material and 1.3 to 1.4 person hours per ton of cold-rolled material. The direct payroll is in the range of $20 million per year. This means that about 6 to 7 percent of product cost is attributed to labor, a percentage that is quite low when compared to integrated producers. It has been said that the newer mills will have even lower labor costs per ton of product, but none of these mills have been built yet. New ideas for steel plants are surfacing almost continuously. Mr. Robert Garvey, Chief Executive Officer of North Star Steel Corporation, has told members of Minnesota's taconite industry that his new West Coast plant will set a record for tons of output per employee.

CONTINUOUS STEEL-MAKING

The area of continuous steel-making was recently investigated by Dr. R. J. Fruehan, professor of Metallurgy at Carnegie-Mellon University, Pittsburgh, PA, under a contract with the U. S. Department of Energy (USDOE). His final report stated that the purpose of the study was to "examine the existing and some proposed processes for refining the metal produced by the AISI smelter."[5] The American Iron and Steel Institute (AISI) project originally aimed at direct steel-making to replace the blast furnace, coke oven, and steel shop. Its recent results, as published in AISI's annual reports[6], indicate that cokeless iron-making may be a more reasonable target.

Fruehan investigated 8 steel-making processes for yield, productivity, refining capability, scrap usage, metal feeding and tapping. He grouped the processes into the following five categories:

Trough processes
Post-hearth refining
IRSID Continuous Steel-making, a European process
Electric Arc Furnace (EAF)
Energy Optimizing Furnace (EOF)

He discounts the research on trough processes and post-hearth refining because of heat loss and mechanical considerations. He is generally favorable toward IRSID, even though it has not been developed commercially. The EAF route has been demonstrated by ISCOR in South Africa and soon will be implemented by Mitsubishi Steel. The EOF has been demonstrated commercially and has been operated successfully in a Brazilian plant for over 10 years. Fruehan's report states that "the EOF appears to be a good match for the [AISI] smelter and offers high scrap melting capability when using a 40 - 60 percent hot metal charge."[7] The EOF could also be combined with a COREX iron-making plant or cupola, which would melt DRI to provide the clean, hot metal needed for steel-making.

STEEL-MAKING OPTIONS FOR MINNESOTA

Certain combinations can be selected from the foregoing as the basis for a Minnesota steel plant. The clearest option is to build a plant similar to the ones being proposed by several of the mini-mill companies. The plant would be similar to NUCOR's facility in that it would rely mainly on scrap using a DRI material to control the level of contaminants in the final product. The EAF technology is well developed, although questions of scrap supply and transportation costs remain. Data researched by the Minnesota Department of Natural Resources (DNR) show a cost penalty for using steel from Minnesota of $0 to $23 per ton compared to the use of steel from the Gulf Coast, utilizing offshore DRI (see Table 3). The biggest source of the difference is in the cost of scrap. Minnesota's scrap would be brought in from Chicago. As will be shown later, Chicago is one of the country's tightest scrap markets due to the number of operating steel mills. The price of scrap accounts for about 89 percent of the cost difference. This difference could be reduced if the composite price of scrap to all producers meets or exceeds the price of Minnesota DRI, or if the use of larger amounts of DRI could allow the use of lower quality scrap for the same product mix. Neither of these possibilities appear likely at the present time.

The only steel-making option which appears favorable at this time is the construction of a large COREX plant which would sell part of its product as pig iron and send the remainder to an EAF-based steel plant. The plant could also generate its own electricity using the export gas from the COREX plant. While that combination appears to generate the lowest costs, the capital investment required is over $535 million in 1992 dollars, an amount which might be very difficult to obtain.

IRON PRODUCT COSTS	
IRON-MAKING PROCESS	$/TON-Delivered
Grate-car Retrofit	110
MIDREX-Natural Gas	151
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COREX-Pig iron	177

Table 4. Iron Product Costs

The economics for DRI production in Minnesota look more favorable with three technologies that appear to be competitive with imports (see Table 4). Allis Minerals' Grate-car process appears to generate favorable economics when retrofitted into an existing grate-kiln pelletizing line. The FASTMET and INMETCO processes also look favorable when installed at a taconite plant. Only the INMETCO process has been tested at a commercial scale. The gas-based MIDREX process does not appear to be competitive when natural gas is used as the energy source. The data presented in Table 4, coupled with what is happening in the steel scrap market, has lead the department to concentrate on DRI production. When Minnesota DRI becomes a commercial success, the industry's focus can shift to steel production.

HISTORICAL BACKGROUND

HISTORICAL STEEL PRODUCTION

United States Steel Corporation (USS) produced steel from iron ore at a plant in Morgan Park near Duluth from the early part of this century until the 1970s. Also at that time, two coke plants operating to supply the mill's blast furnaces were closed when the need for their output no longer existed. The Morgan Park mill was obsolete by the time it was abandoned, as its blast furnaces were quite small by the standards of the time. More importantly, however, the wire products it produced could be made much less expensively in the new mini-mills which were being built at that time. The closing of the Duluth steel mill was an early signal of market abandonment, a major problem that has plagued the integrated steel industry for the last twenty years. It was one of the first steps in a long retreat that is still occurring.

In 1967 North Star Steel Corporation built a steel mill in South St. Paul based on the then-new EAF technology. The plant melted inexpensive scrap to produce lower grade steel products like wire and light structural products which were much more expensive to produce in conventional steel plants. The company had access to an interruptible electric rate which also helped reduce the cost of scrap-based steel. The plant continues to operate successfully. North Star Steel has since become a subsidiary of Cargill, Inc. and now ranks as one of the larger mini-mill companies.

FEASIBILITY STUDIES OF DIRECT REDUCED IRON AND STEEL PRODUCTION

In the early 1980s Minnesota took interest in the economic feasibility of DRI production. The Department of Economic Development hired Battelle Memorial Institute to study the feasibility of constructing a "greenfield" DRI plant in northeastern Minnesota. The Institute studied the MIDREX process which was, at that time, the most popular of the new DRI processes. The study, released in mid-1981, offered a negative view of the prospects, based on the projected costs for natural gas and the then-current level of silica in Minnesota taconite pellets. Occasionally one will still find this study referenced. Although much has changed since the study was written, it did serve to identify barriers to DRI production in Minnesota.

In 1982, Minnesota's economy experienced the lowest level of iron ore and taconite shipments since the depression of the 1930s. The industry was filled with gloom about the Brazilian ore deposits which were then being developed, and some felt that the taconite industry had a short life expectancy. At this point the Iron Range Resources and Rehabilitation Board (IRRRB) hired Economic Consulting Services, Inc. (ECS), a Washington, D.C.-based consulting firm to conduct a steel product market study. The board hoped to identify several market niches which could be filled by iron-based products from Minnesota. The report, released in 1983, identified two areas which might be exploited. The first was the growing market for semi-finished steel. At that time it appeared that the domestic integrated producers would be forced to purchase several million tons of steel slab per year from foreign producers. The situation has since changed with the introduction of thin-slab casting and mini-mill production of higher quality steel. ECS did not identify a technology or speak to the economic feasibility of its ideas. The second area ECS identified was the production of high-purity pig iron for use in ductile iron foundries. The size of the domestic market was estimated at about 300,000 tons per year. The results of the ECS study were used in several of the initiatives described below.

Direct Smelting and DRI Initiatives

Shortly after Governor Rudy Perpich took office in 1983 he proposed several initiatives to stimulate the taconite industry. One of these initiatives was an attempt to move the industry from natural gas to coal or peat-based fuels by accessing the USDOE's synthetic fuels program. Another initiative was an appropriation to the DNR for direct reduction research. At about the same time the IRRRB, in cooperation with Pickands Mather, Westinghouse, and Minnesota Power began the Mesabi Metals project, a major iron ore reduction project based on plasma torches. Between 1983 and 1986, over $4 million was expended on research and development aimed at value-added production from the taconite industry.

Plasma Related Efforts

During the 1980s several organizations were active in research on the reduction of iron ore using plasma technology. A plasma torch uses strong, confined electric arcs as the source of heat for gas passing through the torch. They are capable of creating temperatures over 3000°C. Most of the research was done in Sweden by SKF Corporation, but significant efforts also took place in Minnesota. The Minerals Resources Research Center (MRRC) of the University of Minnesota received state funding to buy and install a 750 kilowatt facility at its site on the Minneapolis campus. Work continued for several years, but no economically feasible route to hot metal production could be found. Much the same can be said of the other efforts. SKF piloted its PlasmaSmelt Process and was able to reduce electric consumption to about 1200 kilowatts per ton of hot metal. This still put energy costs in the $60 per ton range, which was well above the costs of competing coal or gas-based processes. The Mesabi Metals project also achieved technical feasibility, but at the price of high energy costs. At this time most of the plasma-based ideas have been supplanted with less expensive options, even in Scandinavia where electric costs are still relatively low.

Programs Supported by Appropriations to DNR

The DNR used its appropriations to foster three initiatives: conversion of existing pelletizing capacity to produce DRI, research to improve the quality and reduce the cost of pellets, and acquisition of a direct-smelting "hot-metal" technology for implementation in northeastern Minnesota. The research portion of the effort led to the creation of the Iron Ore Cooperative Research Program, which has been quite successful. From 1987 to 1993 about $3.6 million of federal, state and industry money has been allocated to taconite research under this program. Fifty-seven projects were funded; and as of today, 38 projects have been completed. Of these, 20 were information projects not amenable for plant trials. Of the remainder, 15 have been carried into the plant trial stage, 4 have been adopted, and several others are "in the pipeline." The high success ratio is most likely due to the project selection method which gives the plants the right to prioritize the projects.

Allis Minerals Systems managed a project on converting existing, unused grate-kiln pelletizing machines to DRI production. Allis also supplied a one-third share of the cost of the effort. The cooperators in the study were USX Minntac, Eveleth Taconite, and National Steel Pellet Company. Allis called this conversion its Grate-car process. The study demonstrated that pelletizing lines could be converted, but production would decrease dramatically. A pelletizing line capable of 2 million long tons per year of pellet production would only produce about 200,000 tons per year of DRI. The state was not privy to the economic analyses of the companies, but its own analysis indicated a delivered price for the DRI that was close to the then-current prices. However, none of the companies chose to convert their excess lines at that time. Allis has continued to develop its ideas and is now proposing conversions that would double the production rates found in the 1985 study.

The largest DNR the initiative was its efforts to locate a COREX plant in northeastern Minnesota. After the DNR received the direct reduction appropriation in 1983, it conducted a technology search that identified direct-smelting as the most likely route to steel production in Minnesota. The search also identified four possible technologies, the most advanced of which seemed to be the KR Process (now the COREX Process) which was under development by Korf Engineering, a West German company. Two other processes based on electrical energy, INRED and PLASMELT, were dropped from consideration after preliminary review. A fourth process, the K-S process, was then only in the early stages of development. The K-S process led to what is now known as the HiSmelt Process, which smelts fine ore in a single vessel with coal and lime injection. That process is still under development, and a demonstration plant is being operated in Australia. The COREX Process is a commercial success with a 330,000 ton per day plant operating in South Africa, another on order for Korea, and a third may be built in the United States by LTV Steel in Cleveland.

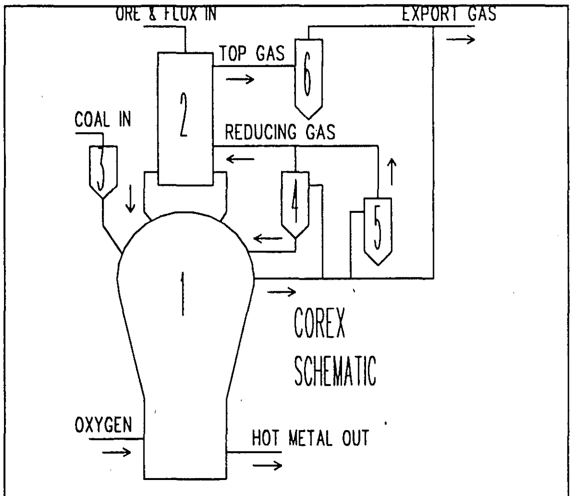

Figure 3. COREX Schematic: 1. Melter gasifier 2. Reduction shaft furnace 3. Coal feed system 4. Hot dust cyclone 5. Cooling scrubber 6. Top gas scrubber.

The state, in cooperation with the AISI, sponsored the first successful pilot trial of the COREX process in late 1984. This led to an attempt by the state to have the first demonstration of the COREX technology built here using a combination of USDOE Clean Coal Technology I funds, state loan guarantees from the IRRRB and industry funding. The state's bid for the plant was rejected in place of one from Weirton Steel Company, but in 1987 the state received another opportunity to build the demonstration when Weirton dropped out of the process. At the time, a potential plant operator would have had access to about $82 million of public financing, which would have limited the private investment to less than $25 million. However, no company stepped forward to take the offer, so the federal money was reallocated to other purposes. The project proposal data show that the demonstration plant would have been capable of producing about 400,000 tons of pig iron per year at a cost of about $120 per ton. That price would be very attractive in today's market.

Iron Carbide

The DNR has investigated iron carbide (Fe_3C) material on several occasions, and in 1990 it wrote a proposal for additional testing using lower-grade, natural ore feed material. The proposal was written due to the poor fit between the iron carbide production process as it was then defined and the Minnesota setting. Very preliminary testing of the process with lower-grade natural ore indicated only a small energy penalty and possibilities for iron carbide liberation to a 2 to 3 percent silica level. However, those results cannot be verified without substantial investment in a research program which might not be supported by the companies holding the patents on the technology. With many people still retaining an interest in iron carbide, the state and the university are sponsoring a small research program on the use of low-grade natural ore in the iron carbide process.

Recent Efforts

Between 1990 and 1992 work on DRI was scaled back because of a lack of interest and funding. The department maintained a data gathering effort to identify promising options and to track progress made by researchers in other locations. Several small-scale basic research efforts were supported using funds from the department's appropriation for mineral diversification, but no major pilot or demonstration efforts were attempted. During this period Minnesota researchers concluded that conventional technologies would not be economical. Ideas and concepts specific to Minnesota conditions were needed.

Interest in value-added production was reawakened in the middle of 1992 by two events. The first was the startling success of NUCOR's new steel mill in Crawfordsville, Indiana, which made it apparent that the mini-mills could now compete for a larger share of the steel market. Several plant construction announcements were made, indicating that the mini-mill companies intended to gain an additional 10 percent of the market by the year 2000. If this actually happens, the demand for pellets could drop by as much as12 million long tons per year. At the same time, the market for DRI is projected to increase by approximately 3 million tons per year.[8] The scrap market has already begun to reflect the increased demand for high-purity raw materials. The recent "idling" and subsequent reopening of National Steel Pellet Company has driven home the importance of these external factors. The public sector's reaction in Minnesota has been dramatic. For example:

> In 1992, The Governor established a Commission on Mining and Minerals, which has made recommendations to the legislature for the both the 1993 and 1994 sessions.
>
> In the middle of 1992, Congressman James Oberstar, concerned about the impact of the mini-mills on taconite production, formed the Taconite Enhancement Committee. That group has met continuously for the last twenty months and during that time has recommended several research initiatives. Its Research Priorities Subcommittee has recommended that 50 percent of the available research funds be spent on value-added research, with the remainder going to taconite process research.
>
> The DNR also increased its commitment to value-added processing by assigning an engineer, full-time, to evaluate technologies specific to Minnesota's conditions.
>
> In 1993, the legislature directed more money into taconite research by establishing a research fund in the University's Permanent Trust Fund. Minn. Stat., sec 137.022, requires that 50 percent of the new income from rents and royalties on University Trust Fund land be placed in the research fund and that the interest on such money be used for mineral research.

Private companies are also becoming more active in the DRI arena. In late-1992 Cyprus Northshore Mining Company became the first Minnesota taconite producer to announce a strong interest in DRI production. Quite recently the possibility of reopening National Steel Pellet Company as a DRI producer was discussed. Other firms are evaluating the Allis Grate-Car Technology. The high level of current activity means that this report is scanning a moving target.

The foregoing discussion primarily lists the efforts of public agencies, as their work is available for inspection. Over the next several years, private companies will make many investigations into the feasibility of value-added production. While the results of these investigations are not open for inspection, it is easy to surmise that only one of them has resulted in identification of an economically feasible route to DRI at a Minnesota location.

CURRENT CLIMATE FOR VALUE-ADDED PRODUCTION IN MINNESOTA

The current climate for value-added production in Minnesota is shaped by external factors like the domestic demand for steel scrap substitutes, the pricing of steel scrap, and energy supply and costs. It us also shaped by internal factors like the quality of Minnesota's raw materials and the available economic and social infrastructures. This section presents an overview of these topics.

NORTH AMERICAN PELLET DEMAND

In this section we will rely on estimates published in PaineWebber's October 1993 issue of "Iron Ore Monitor." In that document Dr. Peter J. Kakela looked at several "Macro Factors Affecting Iron Ore Demand" He estimates that by the year 2000:

- "The revitalization of the U.S. manufacturing sector will add 5 million tons additional steel consumption over the cycle. This will increase the demand for pellets by 7 million long tons.

- The improved cost competitiveness of American steel production will reduce net U.S. steel imports from 13 million short tons in 1992 to perhaps only 7 million short tons in 2000. This will increase demand for iron ore pellets by about 8 million long tons.

- U.S. electric furnace steel production will capture an additional 9 million tons of raw steel demand. This will eliminate 12.5 million long tons of pellet demand. [An estimate that was recently supported by Mr. Robert Garvey the CEO of North Star Steel, Inc.]

- World prices for iron ore will remain weak in the short term. Longer term EC (European Community) steelmaking capacity will be reduced by a minimum 13 million tonnes. The combination of these will keep European Markets for eastern Canadian iron ore soft and thus reduce demand for North American pellets by about 5 million long tons.[9]"

The net effect of these factors is an overall drop in pellet demand by some 2.5 million long tons. However, Kakela also predicts that pellet capacity will be trimmed by 10 to 12 million long tons by the year 2000[10]. While Kakela implies permanent closing of production lines, one could also create a scenario in which a portion of the lost capacity is converted to production of value-added products like DRI.

STEEL SCRAP SUPPLY

PaineWebber predicts a 3 million ton per year increase in the demand for scrap substitutes, like DRI or iron carbide, by the year 2000[11]. Announcements about new mini-mills support that prediction. The only open question appears to be whether the increased demand will be supplied from domestic sources. Clearly, it is in the state's long-term interest to be a producer of scrap substitutes.

Many prior discussions about the advance of mini-mills and steel scrap substitutes have treated scrap as a single commodity. Some industry sources use low or composite scrap prices to reinforce the idea that Minnesota cannot produce economical substitutes. However, a closer look at historical

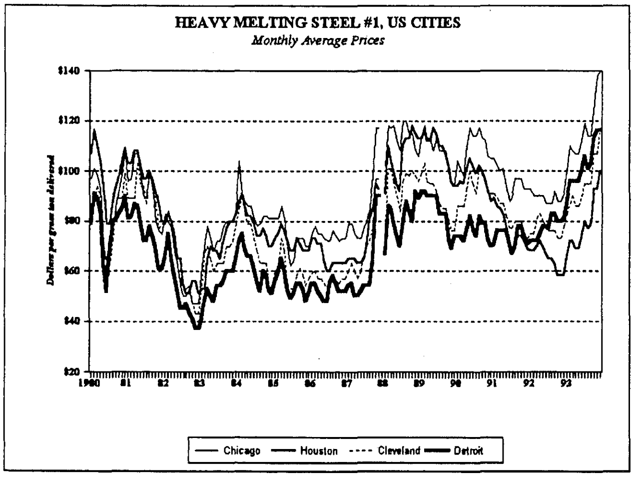

Figure 4. Scrap Prices

pricing of scrap can be used to isolate the trends which should shape the scrap substitute market in the near future.

Figure 4. shows the monthly prices for heavy melting scrap at four U.S. locations over the last 14 years. The striking element of this figure is the instability of the prices. The figure also shows only modest evidence of an overall upward trend in scrap prices, e.g., between 1980 and 1982 prices ranged from \$54 to \$108 per ton while 1990 to 1992 prices ranged from \$58 to \$118 per ton.

Figure 5. shows the prices of two grades of scrap in one location: A.) Plate and Structural less than 5 feet long: a high quality, less contaminated grade and B.) #1 Heavy Melting: a lower quality grade of scrap. The data reveal a trend of increasing prices and similar pricing patterns for both grades.

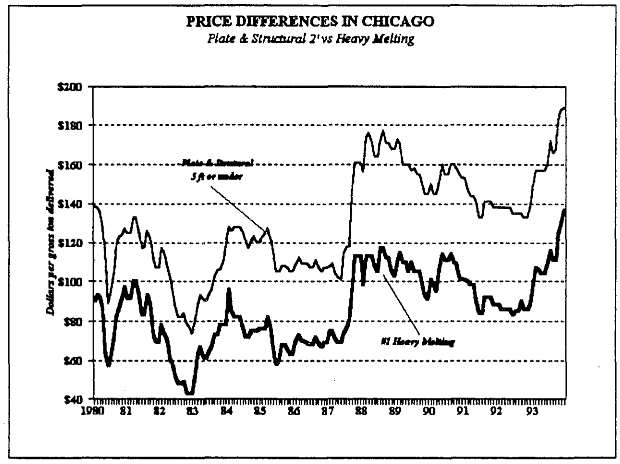

Figure 5. Scrap Differential

The difference in prices between Structural and Heavy Melting scrap in Chicago is shown in Figure 6. This figure has real importance to producers of scrap substitutes, as it indicates the value of quality to electric furnace steel producers. They have been willing to pay a premium for the high-quality grades that ranged from \$26 to \$65 per ton. The difference has been increasing over the last 14 years and is now more than \$50 per ton .

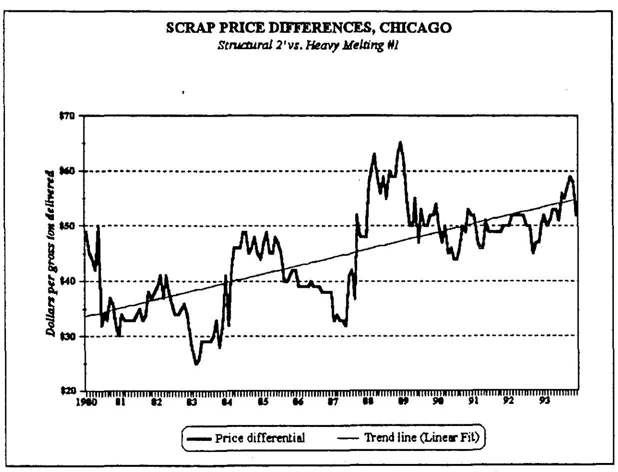

Figure 6. Scrap Price Differential

The aforementioned data can be used to estimate a floor price for a steel scrap substitute on the Great Lakes. During the last five years the price for high-quality scrap has been over \$135 per long ton 100 percent of the time, and over \$150 per long ton 60 percent of the time. A floor price for DRI of \$135 per long ton delivered with suitable offsets for quality, melting costs, etc., seems reasonable, considering the cost of alternatives.

Data collected about 7 years ago indicated a 300,000 ton per year market for low-manganese pig iron in the production of ductile iron castings. The primary source of this material in the North American market is Quebec Iron and Titanium, where Sorel metal is a coproduct in the production of titanium-bearing slag. This material regularly sells for prices over $200 per short ton delivered in the U.S. However, the company could drop its price substantially. Offers in the range of $175 per ton were reported in 1987 when the state was pursuing construction of a COREX plant. That figure perhaps sets an upper limit on price for a high-purity pig iron.

RAW MATERIALS

The primary goal for mineral research in Minnesota should be to reduce the cost and improve the quality of taconite pellets. The quality of the raw materials available in Minnesota will also have a strong effect on the state's ability to attract value-added production. Therefore, raw material research is a key factor in a systematic approach to economic development.

The state and the industry have several ongoing programs aimed at this target. The largest is an effort to find economical flowsheets that will yield concentrate containing less than 2 percent silica. By the end of 1994, industry and the state and federal governments will have invested over $1.2 million in the silica-reduction program. The flowsheets generated look quite promising and could lead to elimination of impurity levels as one of the major barriers to DRI production in Minnesota.

Another major effort is aimed at reducing the costs of crushing and grinding. The work consists of using digital image analysis techniques to improve blast fragmentation and to pilot scale operation of various mills, e.g., the Vertimill, the KHD high-pressure roll mill, and a Vibramatic ball mill. Eventually all of the ideas which survive testing will be formed into a new blasting, crushing and grinding flowsheet, which could lead to substantial reductions in power consumption.

In another area, the Minerals Coordinating Committee[12] supported a study of the use of lime/dolomite hydrate as a pellet binder and flux. The test work was successfully completed, and plant trials were run at the USS Minntac plant. The flux work may link into another project which identified a possible Minnesota source for flux material.

Several organizations are investigating process control concepts. Control International, Inc. has established an office in northeastern Minnesota to be closer to its customers. The DNR is working with computational fluid dynamics (CFD) to better understand the pellet oxidizing and hardening (induration) process. The CFD research has generated ideas for simple-machine modification that should improve air flow and distribution at Eveleth Taconite.

There are simply too many projects currently underway to discuss them all. Each of them, however, has a chance to make an improvement in some area of the taconite production process. Clearly, the evolution of the industry will be shaped to a great extent by the success of raw materials research programs.

ENERGY

The "Oil Crisis" of 1974 triggered a chain of events whose impacts are still being felt. Few people realize that while oil was the energy source that captured the headlines, major restructuring also started for electric utilities and natural gas suppliers.

Electric utilities are facing a more competitive, and perhaps a more integrated, future. Several years ago export gas was considered a burden for technologies like COREX. Now export gas is a key factor in projects like the one announced by LTV Steel and Cleveland Light and Power, in which export gas from a large COREX plant will used in combined cycle gas turbines to generate electricity. Clearly, utilities' monopoly on generation has been replaced by cooperation, competition, and negotiation.

In 1975 the natural gas industry was regulated from wellhead to burner tip; but during the late-1970s industries saw the beginning of deregulation for pipelines and larger customers. Furthermore, explorers found considerable quantities of gas while looking for oil, so the "gas bubble" of the 1980s was generated. Deregulation has probably run its course, and the bubble has burst. It seems unlikely that prices will fall to previous levels. If the economy strengthens as predicted, alternatives to natural gas, like coal gasification, will probably get more attention in the future.

For the last several months, the state has been studying an innovative coal gasification technology which uses pulsed combustion in an indirect-fired, fluidized bed gasifier. According to the claims of its sponsors, the technology will produce a medium (300 Btu/scf) gas from western coal without an oxygen plant. The company which owns the technology has received an $18 million commitment from the USDOE to build a 20 ton per hour demonstration plant. The state is trying to find a site for this plant at a Minnesota taconite plant. Once demonstrated, the technology might help Minnesota in three ways: 1.) as a source of gas for pellet induration, 2.) as a source of low-sulfur char for processes like FASTMET, and 3.) as a source of reducing gas to replace natural gas in DRI processes like MIDREX or HYL.

Other technologies which produce a char product from western coal might also provide products which could aid DRI production in Minnesota. For example, the firms which are supporting the technology used in the ENCOAL plant in Gillette, Wyoming are interested in extending their processes to produce metallurgical char. The state is also investigating these possibilities.

VALUE-ADDED TECHNOLOGIES

The DNR tries to keep abreast of iron and/or steel-making developments in order to assess whether a particular technology should be pursued. A summary of this effort is contained in the spreadsheet located in Appendix A which contains the cost estimates of various technologies based on material and energy balances and estimates of capital costs that have been gathered over the years. The technologies will not be described in this report, but an attempt will be made to give the reader the department's assessment of their economics in a Minnesota setting. In general, the economics appear more favorable now than at any time in the recent past. Also, as was indicated above, gasification of western subbituminous coal might open some doors that have been closed until now.

DIRECT REDUCTION PROCESSES

These processes are aimed specifically at the growing need for steel scrap substitutes. Minnesota has at least three routes that could be pursued to take advantage of this increased demand:

FASTMET

This technology appears to have an economic edge. However, several technical questions remain to be answered by the first commercial plant. It appears that a low-sulfur carbon source will be needed to minimize hot-metal desulfurization costs at steel plants; and a low-ash coal is desirable since the ash remains in the DRI product. Even with those considerations, use of FASTMET appears able to compete with imported DRI at Lower Lakes' steel plants. This technology was chosen first by Cyprus Northshore Mining Company (Cyprus Northshore) for its DRI venture. It was also the technological choice for Inland Steel Mining during its evaluation of DRI production at the Minorca mine, and it was mentioned in connection with a reopening of National Steel Pellet Company. The product might be even more competitive if it can be shown that the ThermoChem, Inc. gasifier can produce a low-sulfur, highly reactive char which would be used as the reducing agent. The INMETCO DRI process, which is currently being considered by Cyprus Northshore, is very similar to FASTMET.

Gas-based DRI Processes: MIDREX or HYL

The MIDREX and HYL processes are commercial technologies dependent on inexpensive natural gas. The need for natural gas is a well-known problem that is raised whenever a gas-based DRI process is considered in a Minnesota setting. Our cost estimates indicate about a $30 per ton economic penalty on the Lower Lakes for DRI produced by the MIDREX process when compared to DRI imported through gulf port (See Table 4). Use of a gasifier like the one being proposed by ThermoChem, Inc. might decrease the cost of energy by $1.00 to $1.50 per million Btu, an amount which might be enough to make gas-based DRI economic in Minnesota. The concept might be even more attractive when coupled to a taconite plant that could use export gas for pellet induration.

Coal-Based Processes: Grate-car (Allis-Chalmers now Boliden-Allis)

In 1984 Allis-Chalmers, three taconite plants, and the department financed a study of the conversion of grate-kiln lines to produce DRI using eastern coal. The study suggested that the grate portions of the machines could be modified to reduce the operating width, and the kilns could be modified to operate in reduction mode. Allis estimated that the production rate in a modified line would be about 200,000 tons per year of DRI. The company has some new ideas that might increase annual production to about 400,000 tons per year per line. At least one taconite plant appears interested in evaluating the modification option. The process could also use western coal, but export gas production would increase.

Cost estimates for the Grate-car process indicate a cost to customers of about $117 per ton for a "brown-field" facility producing briquetted material. The process appears to generate costs which are close to those of imported DRI and FASTMET, so the Grate-car process might be used to convert a plant's surplus pelletizing capacity to DRI production.

Other Solid Iron Processes: Iron Carbide and Lean Ore Reduction (LEANOX)

The iron carbide process deserves more consideration by Minnesota companies. Iron carbide appears to have some very good properties when used in a steel mill: it contains 6 percent carbon (so it is an energy source itself), it can be heated to relatively high temperatures without decomposition, and it dissolves easily in molten steel. One should be able to add it to molten steel without incurring an energy penalty. The iron carbide process has both positive and negative characteristics when viewed in a Minnesota setting.

On the negative side, taconite concentrate is too fine to be used in the fluidized bed reactor used in the process. Another drawback is the process' reliance on natural gas, a relatively expensive energy source in Minnesota. Furthermore, the process needs a five-component gas stream whose composition must be controlled to very close tolerances, so coal gasification may be problematic.

While the process does not seem to be a good fit with conventional taconite concentrate, it might be used with intermediate taconite products or natural non-magnetic (hematitic) ores. In 1990, the department conducted some bench scale tests of the process under the direction of its inventors. Natural ore from Minnesota containing 7 to 10 percent silica was used in those tests. Subsequent liberation grinding tests at CMRL indicated that the impurity level in the iron carbide product could be reduced to 2 or 3 percent by simple dry-grinding. This work opened the possibility of using reserves of noncommercial natural ore or intermediate taconite products as the raw material in an iron carbide plant. The state is sponsoring additional tests to verify the earlier results.

A new idea with an old basis is the reduction of lean natural ore with (subsequent) liberation of the relatively soft iron product from the more brittle gangue matrix. Conventional grinding techniques do not seem to generate a product of sufficient purity. However, newer techniques with lower or differing energy inputs might be used. The Research Priorities Subcommittee of the Taconite Enhancement Committee recommended testing these ideas at a laboratory scale with the primary goal being development of liberation methods.

DIRECT SMELTING PROCESSES AND STEEL PRODUCTION

Processes like COREX, AISI and HiSMELT look best in a steel plant environment, since they were designed to be blast furnace replacements. ISCOR in South Africa has developed methods for charging about 45 percent hot metal from a COREX plant to its electric arc furnace, so coupling a COREX plant to an EAF-based steel plant is a real possibility. Data also indicate that the export gas taken from these processes can be used for electric generation in combined cycled gas turbines. Therefore, the processes might fit into a tightly integrated EAF-based steel plant which could make location in Minnesota feasible.

The COREX technology is already commercial, and its owner, Voest Alpine, is now offering 900,000 ton per year units. The AISI technology is ready for demonstration according to its sponsors; however, they have backed away from direct steel-making and are concentrating on iron-making. Pilot plant tests of the AISI process have shown that 40 percent post-combustion of reducing gas can be achieved while maintaining control of metal and slag chemistries. The sponsors of the HiSMELT process said that pilot plant results would be available in 1993. The HiSmelt concept promises to achieve low costs of production, as the feed materials are raw concentrate, low-rank coal, and oxygen.

A tightly integrated steel plant using direct smelting or DRI production, on the NUCOR casting or rolling model, and operating on western coal should be economically feasible in Minnesota, if the scrap prices can be controlled. However, this concept would not be easy to sell. The industry's current thinking is to locate a steel plant where scrap is easily accessible and close to a customer where "just in time" delivery can be accomplished. Furthermore, the investment in a steel plant could easily be three or four times the amount needed for a DRI facility, so any perception of risk could make a plant very difficult to finance.

OTHER IDEAS

Some concepts that may appear to be quite "far out" might generate positive outcomes in a long-term time frame. One of these concepts is the dissolution of silica from an iron oxide matrix. Laboratory work completed thus far is very preliminary, but it has shown preferential dissolution of silica. Important questions regarding reaction kinetics, energy requirements and costs remain to be answered. However, the results appear tantalizing when one considers the prospect of producing virtually pure iron oxide powders.

The area of fine concentrate reduction also deserves some attention. No one has found a way to handle fine iron powders at high temperatures; and, in fact, the sticking tendency of the material is a major problem for several technologies. Recently, however, the DNR has considered some process concepts in which stickiness is an advantage, so more work in the area seems warranted.

CURRENT INITIATIVES

Steel industry market factors, the state of technological research and the state's desire to take advantage of the new demand for DRI are the driving forces behind the current initiatives described below. These will be discussed in two categories. The first is a list of projects aimed at short-term development of DRI options. In these cases some test work is needed, but the major technological development has already been done. The second is a series of research projects aimed at a third generation of DRI processes specifically targeted for implementation in Minnesota. The first set of projects may allow Minnesota to take advantage of the demand increases in the period out to the year 2000. The second set of projects is aimed at providing a stable economy in northeastern Minnesota well into the 21st century. The work is based on a premise that we have to show the economic feasibility of iron production before anyone will take steel production in Minnesota seriously.

INITIATIVES FOR SHORT-TERM IMPLEMENTATION

The problems caused by the advance of mini-mills and the opportunity for DRI production have not gone unnoticed. The Minerals Coordinating Committee and the Taconite Enhancement Committee have supported research to reduce silica levels and improve pellet quality as needed precursors to DRI production. The governor formed the Commission on Mining and Minerals to provide recommendations to help the minerals industry, and the Taconite Enhancement Committee's

Value-added Subcommittee is working to develop plans that will lead to production of DRI in Minnesota. Several taconite plants have expressed interest in DRI production, and one plant has applied for permits to build an INMETCO plant. At the January 1994 American Institute of Mining Engineers (AIME) conference in Duluth several speakers went beyond the "cost reduction, cost reduction, cost reduction" theme to express their favored approach to DRI production.

Following the AIME conference a small group of engineers representing several organizations met on an ad hoc basis to define a work plan to take advantage of the existing window of opportunity for DRI production in Minnesota. The group focused on the short term and ways to take advantage of the new demand without major research. It considered "off-the-shelf" or nearly commercial technologies in developing a proposed work plan which would enhance the current value-added plans of companies interested in FASTMET and open DRI possibilities for others. It also identified persons or organizations which could supply the information needed for decision making.

The list below, which is in priority order, outlines three projects which were started by the organizations represented. These organizations are using current budgets for their part of the effort. It is estimated that contributions will be in excess of $50,000. The first project builds on work begun in 1984 which studied conversion of grate-kiln lines to produce DRI; the second project is aimed at eliminating a major quality problem associated with the FASTMET process; and the third is an attempt to find a low-cost substitute for natural gas which could make gas-based processes, like MIDREX, economically feasible in Minnesota.

SHORT-TERM DRI PROJECTS

Project/task	Responsibility	Budget
Conversion of grate-kiln lines to DRI production by doubling the length of the kilns to produce approximately 400,000 tons per year of DRI per line.		
Capital cost estimatesAllis Minerals		
Production of low-silica concentrate		
Flowsheets and incremental costs	NRRI/Coleraine	
Capital Costs for low-silica concentrate production	Noramco Engineering	$8,300 from DNR/Minerals
Coal unloading and handling at taconite plants		
Capital Costs	Normaco Engineering	(see above)
Overall cost estimation and comparison	DNR/Minerals	
Coal cleaning for the FASTMET Process to yield 1 percent ash, 0.1 percent sulfur and 75 percent fixed carbon		
Literature search, analysis and reporting	UMD Department of Chemical Engineering	
Production of low-sulfur char using gasification technology	DNR/Minerals	
Western coal cleaning processes	IRRRB/Consultant	

Steam gasification of western coal to provide reducing gas for DRI processes which currently use natural gas.

Plasma gasification cost package	Jerry Fineman/SKF Gasification Technologies
Pulse combustion, indirect fired coal gasification	DNR/Minerals
Material and energy balances, process integration	DNR/Minerals

None of these projects have been completed.

INITIATIVES FOR LONG-TERM IMPLEMENTATION

The Research Priorities Subcommittee of the Taconite Enhancement Committee recommended three value-added research projects for funding under the Mineral Diversification and University Trust Fund programs. The committee consists of representatives from taconite companies, unions, public sector research organizations, and the state. At the present time only about $341,000 is available from all sources; but since the work is at the bench scale level, the funds will be sufficient for the next fiscal year. However, if any of the initiatives yield promising results, the need for funding could escalate dramatically in FY96-97. The projects which are currently being supported are:

Oxidation/reduction and Metallization

The process concept is somewhat similar to FASTMET, except that carbon is not added to the pellets. The goal is to capture the heat from pellet oxidation to improve the kinetics of a subsequent reduction reaction, which would take place on a circular hearth. If the work is successful, it could lead to a process that would yield a low-gangue, low-sulfur DRI product which would be competitive with imported products. A patent disclosure on this process has been filed by Dr. Rodney Bleifuss, Director of Coleraine Minerals Research Laboratory of the Natural Resources Research Institute.

RESEARCH COMMITMENTS TO DRI PRODUCTION IN MINNESOTA	
PROCESS/PROJECT	COMMITMENT
Low-Silica Concentrate	$156,000
Steam Gasification of Western Coal-USDOE Clean Coal Project	$25,000
Oxidation/Reduction and Metalization	$60,000
Lean Ore Reduction-LEANOX	$50,000
Fine Concentrate Reduction	$25,000
Iron Carbide on Low-grade Ore	$25,000

Table 5. Research Commitments

LEANOX (Lean Ore Oxidation)

The concept of producing a metallized product from low-grade ores has been looked at several times over the last few decades. Most of the significant work was done in the late 1950s and early 1960s before the taconite industry became firmly established. Metallization of the iron oxides is the easy part, but liberation of the product from the silica matrix has always been the stumbling block. Under conventional grinding methods, the softer iron material tends to smear onto the harder, more brittle silica/silicate material. Consequently, magnetic separation does not yield a clean low-silica product.

A combination of new processing conditions and new grinding technology may yield a clean concentrate. Furthermore, it may be possible to float the particles that are mostly silica to achieve a better concentrate. Several new combinations of time and temperature during reduction will be tested at a bench scale. Laboratories in the state have acquired several of the newer mills (e.g., the Vibramatic Mill) for other research purposes, so testing of the LEANOX concept can proceed with a minimum of equipment purchases.

Iron Carbide and Low Grade Ore

CMRL's research on the production of iron carbide from low-grade materials will be expanded to verify its reaction kinetics, iron oxide conversion, carbon deposition and liberation to achieve a low-silica end product. Lab scale equipment will be used to produce small batches of material for testing.

If additional funds were made available, the first allocation would be used to strengthen the projects listed above. A second priority would be to look at new ideas, particularly those related to fine-concentrate reduction (a process which is being considered by DNR/Minerals within its existing budgets).

POSSIBLE FUTURE INITIATIVES

INFRASTRUCTURE

While government should play a role supporting process research and the development of new technologies, it should also be prepared to assist by providing infrastructure to support multiple technologies. When the state invests in the development of a particular technology it is betting on the success of a single initiative. On the other hand, when it provides infrastructure it is providing a means for perhaps several initiatives.

One idea that has not been investigated is the creation of a "Metallurgical Park" to minimize the cost of raw materials, electric power, fossil fuels, transportation, waste processing, and training, among others. To accomplish this one would likely work outside of what would be considered normal arrangements. In the recent past the Electric Power Research Institute (EPRI) tried to develop a similar concept as an "EnergyPlex." It may be possible to revitalize this concept, and while cooperating with EPRI, work toward the establishment of such an industrial park at a location in northeastern Minnesota. It is clear from examples in other parts of the country that these clusters do not appear by chance. They are the result of combined resources, talents, governmental initiatives, and private sector investments.

TECHNOLOGY INTRODUCTION FOR MINERAL DEVELOPMENT

The work needed to bring a new technology to the market is both expensive and time consuming. One commonly hears pleas for research dollars, but research is only the tip of the iceberg. It is also likely to be the least expensive part of any development. As the table below shows, the costs of development escalate rapidly as one progresses beyond research into the engineering stages of a project. Development is not really hampered by a shortage of research funds, but more by a shortage of funds to go beyond the early stages. The following schedule is presented to give some perspective on the potential costs and benefits. The annual percent return estimates are based on amounts potentially returned to the state's treasury.

Development Stage	Potential Cost	Probability of Success	Annual Return Percent
Bench-scale testing	\$25,000 to \$250,000	<1%	10% once
Continuous Process Development Unit- 10 to 50 pounds per hour	\$500,000 to \$3,000,000	20%	10% once
Continuous Pilot Plant- 1 to 5 tons per hour	\$10 to \$50 million	40%	10% once
Commercial Demonstration- 40 to 60 tons per hour	\$50 to \$150 million	85%	10% annually

Our federal government is engaged in technology development through programs like the Metals Initiative, which has spent over \$70 million in the last 7 years on a new iron-making technology. Another domestic example is the USDOE Clean Coal Technology program which has allocated about \$3 billion to demonstration projects over the last 7 years. Like Japan, with its Ministry of Trade and Industry, most developed countries have some public mechanism for financing technology development.

The timing of departmental budgets, legislative sessions and appropriations does not fit the needs of process developers very well. If it were possible to establish something more like the process used by private companies, without an attendant personnel and paperwork hierarchy, the success rate might be higher. Process developers need flexibility in timing and access to funds. On the other hand, the funding source needs adequate oversight so that it can step in at any time to expand, trim, or stop the effort.

Flexibility seems to be the operative need. As Thomas Peters says in "Thriving on Chaos," the nature of opportunity is like a butterfly crossing a field, in that changes in speed and direction appear random. Opportunities present themselves at unexpected times, and a breakthrough or failure can occur at any time. One can expect that there never will be money "in the budget" to take advantage of a new opportunity. Also, there is probably no single recipe for success. However, a staged approach will likely work better than the normal solicitation approach used by the government. A fundamental component of the staged approach is a review panel with the technical and economic capability to understand the issues and recommend changes in the funding level. In order to implement a staged approach to development, it appears that:

1. A funding source could allocate personnel and financial resources on a continuous basis to maintain a "lookout" for new technologies.

2. When a technology is located, a relatively small amount of money would be needed to analyze it by bench scale testing, calculation of energy and material balances, capital cost estimates, and *proforma* operating statements. The amount of money needed to analyze could be kept to a minimum if the engineering capability exists within, rather than outside of, the evaluating organization.

3. If the results of the previous step are positive, a report would be submitted to the technical and economic review panel who would then make a recommendation regarding further funding.

4. That recommendation would go a body capable of providing the necessary funding in a timely fashion.

Funding for steps 1 and 2 are incorporated into the DNR Minerals Division's budget. A technical and economic review panel does not exist, but the Minerals Coordinating Committee, currently authorized under state law, could be expanded to include private sector representatives who might give a somewhat different perspective on the viability of an initiative. In order to have access to funding in a timely fashion, mineral development matters could be added to the list of items that would be considered by the Legislative Advisory Committee when the legislature is not in session. In this way, the need for critical review and timely access can be met without the creation of new structures and/or appropriations. Furthermore, the issues surrounding the appropriation of large amounts of money can be handled by requiring matching funds from private industry, so that the technical risk is shared.

CONCLUSION

As one can easily see from the discussion above there are opportunities, but no obvious, no-risk winners; furthermore, there is probably no way to estimate accurately which of the several alternative courses of action will yield the best results. Since all of the options which appear to have some merit, it would be wise to avoid paralysis by analysis. (If the answers were obvious, someone would have already implemented DRI in Minnesota.) In this situation the only relatively sure way to make progress is to invest in several alternatives simultaneously, making larger investments in those processes which are generating favorable results, and trimming those that look less favorable. However, in order to do this efficiently the state should make some changes in its process to identify and fund mineral development opportunities.

The existing research programs have been successful, and they have made an impact on the mineral industry. At this time, however, more commitment is needed if Minnesota is to gain a share of the new demand for scrap substitutes and low-cost, high-quality steel. We believe Minnesotans can shape the future of this region and that action must be taken to introduce new, economically competitive products and technologies. This action will go well beyond research into cooperative support for engineering testing and commercial demonstration.

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APPENDIX A: SPREADSHEET

DESCRIPTION				GRATE-CAR REBUILD	MIDREX - GAS	MIDREX	MIDREX-FASTMET	COREX	
PLANT LOCATION				IRON RANGE	IRON RANGE	VENEZUELA	IRON RANGE	IRON RANGE	DULUTH
FEEDSTOCK				LOW SILICA CONC	LOW SILICA PELL	GULF PORT ENTRY	LOW SILICA CONC	STD ACID PELLETS	STD ACID PELLETS
ANNUAL FEED CONSUMPTION		MTPY		957,086	867,480		1,028,781	948,904	948,904
COMPOSITION %WT	FE2O3				0.98			0.95	0.95
	FE3O4			0.98			0.94		
	SIO2			0.02	0.02		0.06	0.05	0.05
PLANT OUTPUT		MTPY		725,000	635,000		800,000	660,000	660,000
EQUIVALENT FE OUTPUT		MTPY		678,530	594,411		699,589	630,300	630,300
PRODUCT % WT TOTAL FE				0.9359	0.9361		0.8745		
PRODUCT GANGUE %WT				0.0264	0.0273		0.0772		
PRODUCT CARBON %WT				0.0198	0.0205		0.0283	0.045	0.045
PRODUCT OXYGEN %WT				0.0179	0.0161		0.0201		
%O2 REMOVED				0.95	0.96		0.94		
% METALLIZATION				0.93	0.94		0.92		
CONCENTRATE/PELLET COSTS $/LT				$20.00	$28.00		$20.00	$28.00	$28.00
	ADD'L BENEF. TO 2.0% SIO2			$2.50	$2.50		$2.50		
	ADD'L BINDER						$1.60		
	FREIGHT			$1.50	$1.50		$1.50	$1.50	$4.50
	TOTAL COST $/LT CONC OR PELLETS			$24.00	$32.00		$25.60	$29.50	$32.50
	TOTAL COST $/MT HBI			$31.19	$43.03		$32.41	$41.75	$46.00
DIRECT REDUCTION RATE	FUEL	COAL MT/MTHBI		1.32			0.52	1.17	1.17
		GAS GCAL/MTHBI			2.60				
	EXPORT FUEL	GCAL/MT		3.2				2.44	2.44
	ELECTRICAL	KWH/MTHBI		121	130		60	55	55
	OXYGEN	NM3/MT						553	553
	NITROGEN	NM3/MT DRI					3		
	LIMESTONE	KG/MT					6	270	270
	LABOR	mH/MTHBI		0.20	0.36		0.30	0.25	0.25
	MAINTENANCE	mH/MTHBI		0.11	0.12		0.15	0.15	0.15
	FUEL	COAL		$50.33			$19.63	$44.29	$44.29
		GAS			$23.73				
		FUEL CREDIT		($25.70)				($19.60)	($19.60)
		ELECTRICAL		$5.46	$5.85		$2.70	$2.48	$2.48
PROD COSTS		OXYGEN						$22.12	$22.12
		NITROGEN					$0.00		
		LIMESTONE					$0.05	$2.43	$2.43
		LABOR		$3.67	$6.55		$5.40	$4.50	$4.50
		MAINTENANCE		$1.92	$2.18		$2.70	$2.70	$2.70
		BRIQUETTING/PIGG		$8.50	$8.50		$8.50	$2.00	$2.00
		SUPPLIES		$4.00	$4.42		$4.00	$4.00	$4.00
		ADMINSTRATIVE		$3.00	$3.00		$3.00	$4.00	$4.00
	TOTAL COST FOR REDUCTION			$51.18	$54.24		$45.98	$68.92	$68.92
TOTAL PRODUCTION COST $/MT HBI				$82.37	$97.27	$80.00	$78.39	$110.67	$114.92
SITE DEVELOPMENT CAPITAL				$0	$5,000,000		$5,000,000	$7,000,000	$7,000,000
PELLETIZING/REDUCTION	USE EXISTING KILN			$20,000,000	$140,000,000		$112,000,000		
BRIQUETTING PLANT				$29,000,000	$0		$32,000,000		
PIG IRON CASTING								$12,000,000	
SUBTOTAL REDUCTION PLANT				$49,000,000	$140,000,000		$144,000,000	$210,000,000	$198,000,000
MINN. LOCATION INCENTIVE				$0	$0		$0	$0	$0
TOTAL CAPITAL INVESTMENT				$49,000,000	$145,000,000		$149,000,000	$217,000,000	$205,000,000
ANNUAL DEPRECIAT.	YEARS		12	$4,083,333	$12,083,333		$12,416,667	$18,083,333	$17,083,333
EQUITY FUNDS	%EQUITY		0.10	$4,900,000	$14,500,000		$14,900,000	$21,700,000	$20,500,000
DEBT FUNDS	%DEBT		0.90	$44,100,000	$130,500,000		$134,100,000	$195,300,000	$184,500,000
ANNUAL LOAN PAYM'T TERM YEAR 10	INTEREST		0.09	$6,871,666	$20,334,522		$20,895,474	$30,431,664	$28,748,807
RETURN ON EQUITY	ANNUAL ROE %		0.20	$980,000	$2,900,000		$2,980,000	$4,340,000	$4,100,000
STLINE DEP COST $/MT				$5.63	$19.03		$15.52	$27.40	$25.88
COST OF DEBT	$/MT			$9.48	$32.02		$26.12	$46.11	$43.56
REQ'D RETURN ON EQUITY $/MT				$1.35	$4.57		$3.73	$6.58	$6.21
HBI COST (FOB PLANT)	(PROD COST+DEPRC COST)			$88.00	$116.30		$93.91	$138.07	$140.80
HBI PRICE (FOB PLANT)	(PROD COST+DEBT COST+REQ'D ROE)			$93.20	$133.86	$105.00	$108.23	$163.36	$164.69
FREIGHT CHARGES	RAIL PLANT TO PORT			$6.50	$6.50		$6.50	$6.00	
	VESSEL TO LOWER LAKES OR GULF PORT			$7.40	$7.40	$11.00	$7.40	$4.70	
	HANDLING AND STORAGE			$3.00	$3.00	$2.00	$3.00	$3.00	
SUB TOTAL FREIGHT CHARGES				$16.90	$16.90	$13.00	$16.90	$13.70	
HBI PRICE LOWER LAKE OR GULF PORT				$110.10	$150.76	$118.00	$125.13	$177.06	

COAL	$/MT SITE	$38.000
GAS	$/GCAL	$9.127
EXPORT FUEL CREDIT	$/GCAL	$8.032
ELECTRICAL	$/KWH	$0.045
LABOR	$/MHR	$18.000
LIMESTONE	$/KG	$0.009
OXYGEN	$/NM3	$0.040
NITROGEN	$/NM3	$0.055
COAL %WT FIX C		0.38

			BOLIDEN ALLIS	MIDREX-GAS	MIDREX-GAS	MIDREX-FAST	MIDREX-FASTMET	COREX	COREX
STEELMAKING CAPACITY MT/YR			1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
PLANT LOCATION			DULUTH	DULUTH	NEW ORLEANS	DULUTH	CHICAGO	DULUTH	DULUTH
PURCHASED HBI/DRI/PIG MT/YR			250,000	250,000	250,000	250,000	250,000	0	250,000
SOURCE OF HBI/DRI/PIG			IRON RANGE	IRON RANGE	VENEZUELA	IRON RANGE	IRON RANGE	IRON RANGE	DULUTH
PURCHASED SCRAP MT/YR	TYPE: NO 1 HEAVY MELTING		861,574	850,485	860,485	879,132	879,132	0	770,838
SOURCE OF SCRAP			CHICAGO	CHICAGO	GULF REGION	CHICAGO	CHICAGO	CHICAGO	CHICAGO
STEELMAKING/REFINING									
CONSUMMABLES	HBI LOSS TO SLAG/DUST (50% OF FEO TO LOSS		0.0401	0.0361	0.0361	0.0450	0.0450		0.03
	SCRAP LOSS TO SLAG/DUST (10% OF SCRAP TO		0.0862	0.0860	0.0860	0.0879	0.0879		
RATES	MT HBI/MT STEEL		0.25	0.25	0.25	0.25	0.25		0.25
	MT SCRAP/MT STEEL		0.86	0.86	0.86	0.88	0.88		0.77
	COAL MT/MT STEEL		0.00	0.00	0.00	0.00	0.00		0.00
	ELECTRICAL KWH/MT STEEL		502.58	500.94	500.94	520.17	520.17		460.94
	LABOR DIRECT MHR/MT		0.30	0.30	0.30	0.30	0.30		0.30
	MAINTENANCE MHR		0.15	0.15	0.15	0.15	0.15		0.15
	OXYGEN NM3/MT		12.00	12.00	12.00	12.00	12.00		12.00
	ELECTRODE CONSUMPTION KG/MT		5.00	5.00	5.00	5.00	5.00		0.00
UNIT PRICES	HBI $/MT		$93.20	$133.86	$105.00	$108.23	$108.23		$164.69
	HBI FREIGHT TO EAF $/MT		$4.50	$4.50	$13.00	$4.50	$16.90		$0.00
	SCRAP $/MT		$85.00	$85.00	$65.00	$85.00	$85.00		$85.00
	SCRAP FREIGHT TO EAF $/MT		$3.50	$3.50	$2.50	$3.50	$1.50		$3.50
	COAL $/MT		$40.00	$40.00	$40.00	$40.00	$40.00		$40.00
	ELECTRICITY $/KWH		$0.045	$0.045	$0.045	$0.045	$0.045		$0.045
	LABOR $/MHR		$28.00	$28.00	$28.00	$28.00	$28.00		$28.00
	OXYGEN $/NM3		$0.055	$0.055	$0.055	$0.055	$0.055		$0.055
	ELECTRODES $/KG		$1.20	$1.20	$1.20	$1.20	$1.20		$1.20
PROD COSTS	HBI (INCLUDES FREIGHT)		$24.42	$34.59	$29.50	$28.18	$31.28		$41.17
	SCRAP (INCLUDES FREIGHT)		$76.25	$76.15	$58.08	$77.80	$76.04		$68.22
	COAL		$0.00	$0.00	$0.00	$0.00	$0.00		$0.00
	ELECTRICAL		$22.62	$22.54	$22.54	$23.41	$23.41		$20.74
	TOTAL LABOR		$12.60	$12.60	$12.60	$12.60	$12.60		$12.60
	OXYGEN		$0.66	$0.66	$0.66	$0.66	$0.66		$0.66
	ELECTRODES		$6.00	$6.00	$6.00	$6.00	$6.00		$0.00
	FERRO ALLOYS $/MT STEEL		$12.00	$12.00	$12.00	$12.00	$12.00		$11.00
	FLUXES $/MT STEEL		$5.00	$5.00	$5.00	$8.00	$8.00		$5.00
	REFRACTORIES $/MT STEEL		$5.00	$5.00	$5.00	$6.00	$6.00		$5.00
	SUPPLIES $/MT STEEL		$3.00	$3.00	$3.00	$3.50	$3.50		$3.00
	MAINTENANCE SUPPLIES $/MT		$4.00	$4.00	$4.00	$4.50	$4.50		$3.00
	ADMINSTRATIVE $/MT		$6.80	$6.80	$6.80	$6.80	$6.80		$6.80
	HOT METAL OR HBI CHARGE CREDIT $/MT		$0.00	$0.00	$0.00	$0.00	$0.00		($10.00)
TOTAL PRODUCTION COST			$178.35	$188.35	$165.19	$189.45	$190.80		$167.19
CAPITAL COSTS	ELECTRIC FURNACE SHOP @$150/ANMT		$150,000,000	$150,000,000	$150,000,000	$150,000,000	$150,000,000		$150,000,000
	CONT. CASTER THIN SLAB @ $40/ANMT		$40,000,000	$40,000,000	$40,000,000	$40,000,000	$40,000,000		$40,000,000
	HOT STRIP MILL @ $140/ANMT		$140,000,000	$140,000,000	$140,000,000	$140,000,000	$140,000,000		$140,000,000
MINN. LOCATION INCENTIVE			$0	$0	$0	$0	$0		0
TOTAL STEELMAKING CAPITAL COST			$330,000,000	$330,000,000	$330,000,000	$330,000,000	$330,000,000		$330,000,000
ANNUAL DEPRECIAT.	YEARS	12	$27,500,000	$27,500,000	$27,500,000	$27,500,000	$27,500,000		$27,500,000
EQUITY FUNDS	%EQUITY	0.25	$82,500,000	$82,500,000	$82,500,000	$82,500,000	$82,500,000		$82,500,000
DEBT FUNDS	%DEBT	0.75	$247,500,000	$247,500,000	$247,500,000	$247,500,000	$247,500,000		$247,500,000
ANNUAL LOAN PAYM'T	INTEREST	0.09	$38,565,472	$38,565,472	$38,565,472	$38,565,472	$38,565,472		$38,565,472
	TERM YEAR	10							
RETURN ON EQUITY	ANNUAL ROE %	0.20	$16,500,000	$16,500,000	$16,500,000	$16,500,000	$16,500,000		$16,500,000
STLINE DEP COST $/MT			$27.50	$27.50	$27.50	$27.50	$27.50		$27.50
COST OF DEBT $/MT			$38.57	$38.57	$38.57	$38.57	$38.57		$38.57
REQ'D RETURN ON EQUITY $/MT			$16.50	$16.50	$16.50	$16.50	$16.50		$16.50
STEEL STRIP COST (PROD COST+DEPRC COST)			$205.85	$215.85	$192.69	$216.95	$218.30		$194.69
STEEL STRIP PRICE (FOB PLANT) (PROD COST+DEBT COST+ROE)			$233.41	$243.41	$220.25	$244.52	$245.86		$222.26
SHIPPING TO LOWER LAKE MARKETS									
	VESSEL TO LOWER LAKE PORT $/MT		$5.50	$5.50		$5.50			$5.50
	BARGE FROM GULF TO LOWER LAKE PORT $/MT				$7.00				
	UNLOADING AND STORAGE $/MT		$6.00	$6.00	$6.00	$6.00	$2.00		$6.00
STRIP PRICE LOWER LAKE MARKET			$244.91	$254.91	$233.25	$256.02	$247.86		$233.76

APPENDIX B: ENDNOTES

1. Marcus, P.F. and Kirsis, K.M. Accelerating Change Threatens Traditional Producers, 1991.
2. Kakela, Peter J.; Marcus, Peter F.; Kirsis, Karlis M. Iron Ore Monitor, *World Steel Dynamics,* October 1993 (Hereafter cited as Kakela).
3. Kakela, 1993.
4. ibid.
5. Fruehan, R.J. *Evaluation of Steelmaking Processes-Topical Report,* 1994 (Hereafter cited as Fruehan).
6. Fruehan, 1994.
7. ibid.
8. Kakela, 1993.
9. ibid.
10. ibid.
11. ibid.
12. The Minerals Coordinating Committee consists of representatives from the Minnesota Geological Survey, Natural Resources Research Institute, University of Minnesota Department of Civil Engineering, Pollution Control Agency, U.S. Bureau of Mines and the Department of Natural Resources.

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