# Nodulizing and Inoculation Approaches for Year 2000 and Beyond - Part 1

by

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**Abstract:** Nodu-Bloc, a new iron-magnesium briquette, offers ductile iron foundries a powerful alloy that can be used to replace traditional magnesium ferrosilicon (MgFeSi) as well as other magnesium containing master-alloys. Controlled laboratory tests show that Nodu-Bloc can replace up to 50 weight percent of MgFeSi. Field trials with Nodu-Bloc confirm these results and show that Nodu-Bloc replacement of MgFeSi can provide significant cost savings. Foundries converting to Nodu-Bloc will experience reduced melting costs because less MgFeSi is consumed, less steel and pig iron is required in the charge and far greater levels of foundry returns can be utilized. Foundries can easily save up to $10 or more per ton on molten ductile iron processing costs by incorporating Nodu-Bloc technology.

**Introduction**: Since the commercialization of ductile iron in 1948, foundries have used numerous methods to introduce magnesium into molten cast iron. **Figure 1** lists some of the approaches and techniques used over the years. Although some of these processes gained a brief following, and some have even been used successfully, most have fallen out of favor because of numerous shortcomings. Today, the majority of ductile iron castings made throughout the world are produced using ladle-metallurgy practices with MgFeSi alloys. It is estimated that MgFeSi alloys are used in 65 percent of all ductile irons produced worldwide. In the United States, MgFeSi alloys account for an estimated 75 percent of ductile iron production. The remaining ductile iron production is made using either the magnesium-converter process or magnesium containing wire injection.

During the first decade of the new millennium, ductile iron production is forecast to surpass U.S. gray iron production, with shipments exceeding 5 million net tons by 2006 [(1)]. The supply of domestically produced MgFeSi becomes important in assessing whether this important raw material will be available in sufficient quantities to sustain the forecasted growth.

With the International Trade Commission 1999 ruling to rescind dumping duties on ferrosilicon alloys, foreign-produced ferrosilicon alloys have flooded the market, setting near-record low prices and pushing domestic producers out of the market. See **Figure 2**. Just last year, American Alloys, a producer of MgFeSi as well as ferrosilicon, was forced into bankruptcy and has closed. Figure 2 shows the average production costs of 33 ferrosilicon producers taken from a recent survey conducted by the Commodities Research Unit, a British economic research firm.

At the present time, all five remaining U.S. ferrosilicon producers are operating at a profit loss. Their combined, before tax operating income for the last four years is summarized in **Table 1**.[(2)]

The U.S. producers provided this information at ITC hearings in an unsuccessful attempt to restore dumping duties on ferrosilicon-based products. In addition to increased competition from foreign firms, the slowing economy and rising energy costs have worsened the plight of domestic producers. Consequently, some haven't found continued operations to be financially worthwhile.

If, indeed, the supply of domestically manufactured MgFeSi is reduced or curtailed because of plant closures, alternate nodulizing approaches may be necessary to sustain the projected growth of ductile iron.

**Economics of Ferroalloy Production**: The U.S. ferroalloy industry was a major market force up until the early 1980s. **Figure 3** shows U.S. production of ferrosilicon alloys compared with imports for the time frame 1969 to the present. The decline in production can be linked to several factors. Because of electricity-rate increases, pollution-control costs and strong competition from foreign ferrosilicon producers, several domestic producers have gone bankrupt, have closed plants or reduced manufacturing output. **Table 2** shows the decline in installed furnace capacity to manufacture ferrosilicon alloys during the past 20 years.

In the United States, MgFeSi production is dependent on the production of 50 percent ferrosilicon. Fifty percent ferrosilicon is produced in a submerged-arc furnace and then alloyed with magnesium, calcium and rare earths, also known as mischmetal. The relative cost to produce 50 percent ferrosilicon, based on a nominal 25-mil power rate ($0.025/kilowatt), is shown in **Figure 4.** Electricity and raw materials represent 42.32 percent and 43.92 percent, respectively, of molten metal cost at the furnace spout; labor accounts for a modest 8.07 percent of the cost. Major cost reductions for producing 50 percent ferrosilicon can only be achieved by renegotiating electrical power rates. Reducing labor costs has only a minimal effect on overall production costs.

The amount of electricity needed to produce one ton of 50 percent ferrosilicon is 4,500 kilowatts. A single 22-megawatt submerged arc furnace using 25-mil electricity, running 24 hours per day, uses $11,500 of electricity per day, or $4.1 million annually. However, the current energy crunch doesn’t bode well for ferrosilicon producers to have access to such low-cost electricity in the future. In fact, during the summer of 2001, at least three plants have curtailed production of silicon-based alloys and have sold their contracted electricity back to the power generator.

MgFeSi is made by ladle treatment of 50 percent ferrosilicon. Magnesium ingots are plunged into the ladle, followed by additions of calcium silicon and rare earths. The relative cost to produce MgFeSi is shown in **Figure 5**. Two ingredients, magnesium ingot and related raw materials required for 50 percent ferrosilicon production account for 70.07 percent of the molten metal cost while electricity and labor now represent 20.65 percent and 4.14 percent, respectively.

Because electricity has such a significant effect on production costs, foreign ferroalloy producers that have inexpensive, government-subsidized electricity, have a distinct production-cost advantage. In the survey of ferrosilicon production costs at thirty-three Western World ferrosilicon plants by the Commodities Research Unit, high electricity costs were cited as the reason all U.S. ferrosilicon producers were ranked as high-cost producers. Two-thirds or twenty-four of the ferrosilicon producers surveyed by CRU had lower production costs. All of these overseas producers had significantly lower power costs.

Currently, only three producers of MgFeSi remain in the United States. Globe Metallurgical, Calvert City Metals and Alloys (CCMA) and Keokuk Ferro-Sil produce MgFeSi as well as other silicon-based alloys. Keokuk Ferro-Sil, Inc. just started to produce MgFeSi alloys in October 2000 while another, Globe Metallurgical in Beverly, Ohio[3], the largest domestic MgFeSi producer, is for sale. The owner, an investment-holding company, has decided that its return on investment isn't adequate and that there isn't much hope that market conditions will improve in the near term. Quite simply, there is an excess worldwide capacity to produce silicon-based ferroalloys. This oversupply will continue to depress world prices in the foreseeable future. If Globe Metallurgical is sold, and if the new owner decides to convert the plant to silicon metal production, future U.S. supplies of MgFeSi will be jeopardized[4] .

Although considerable production capacity still exists in the United States to manufacture MgFeSi, whether that capacity will be utilized for MgFeSi production remains to be seen. The various grades of U.S. ferrosilicon production are shown in **Figure 6.** It's apparent that capacity exists to convert much of the current 50 and 75 percent ferrosilicon production to MgFeSi should the need arise. However, this premise is based on U.S. ferrosilicon producers weathering the continued onslaught of imports and remaining in business.

U.S. ferrosilicon producers have recently (August 2000) appealed to the International Trade Commission to re-instate dumping duties and restrictions on ferrosilicon imports, but no ruling is expected soon. Even if a favorable ruling occurs, other non-affected ferrosilicon producing countries would probably step into the U.S. market. Favorable currency exchange rates and a strong dollar typically are excellent incentives for overseas producers to export ferrosilicon into the U.S. market. Further, there doesn't appear to be any shortage of ferrosilicon producers who can export to the U.S.

Without import restrictions, U.S. ferrosilicon production could disappear or be drastically reduced, possibly causing U.S. ductile iron producers to be totally dependent on foreign-produced alloys. If this occurs, the number of available grades and sizes of MgFeSi may be limited. Because ocean transportation is used to ship foreign produced MgFeSi to the United States, it is unlikely that multiple grades and sizes would be available because of the logistics problems associated with ocean transportation. Only one or two grades of the most commonly used alloy chemistries, of one specific size, would most likely be available.

**<u>MgFeSi Replacement:</u>** To meet the growing demand for ductile iron and to circumvent potential reliance on foreign-produced MgFeSi, progressive foundries need to explore alternate nodulizing methods. Nodulizing processes that utilize pure magnesium have attracted more attention in recent years. Eliminating or reducing the amount of silicon based nodulizers has a number of benefits for ductile iron producers. Silicon is often an unwanted element and at many foundries, control of silicon levels is an economic and technical challenge. High silicon levels typically are the result of one or more of the following: over-treatment with MgFeSi alloys, improper ladle design, treatment method, treatment temperature and base sulfur level.

ASI International, Ltd. has developed a new generation of iron-magnesium alloys (Nodu-Bloc) that address potential MgFeSi shortages and as well as provide improved ductile iron silicon control. These new iron-magnesium alloys can reduce or even completely eliminate dependence on MgFeSi alloys. The iron-magnesium alloys provide all the cost advantages of pure magnesium processes along with the ease and forgiving nature of ladle-treatment production techniques. More importantly, by using these low silicon alloys, higher levels of foundry returns can be used in the furnace charge make-up, resulting in significantly reduced melting costs.

Nodu-Bloc iron-magnesium alloys are manufactured using well-developed powder-metallurgy techniques. Pure magnesium, high-purity iron powder and other additives are carefully blended and compacted under extremely high pressure. Since a furnace smelting process isn't employed, magnesium levels can consistently be controlled in the range of +/- 0.05 percent. In addition, controlled amounts of calcium, barium, rare earths and copper can easily be incorporated into the briquettes for those applications requiring special chemistries.

Popular Nodu-Bloc iron-magnesium alloy chemistries are listed below:

Nodu-Bloc Grade 11 - 11% Mg, 0.7% Ca, 0.7% Ba, 3.0% Si, 0.7% C, Balance - Iron
Nodu-Bloc Grade 15 - 15% Mg, 3.0% Ca, 6.0% Si, 2.0% C, Balance - Iron
Nodu-Bloc Grade 20 - 20% Mg, 5.5% Ca, 13.0% Si, 2.0% C, Balance - Iron

Nodu-Bloc briquettes have an almond shape and measure 1.25 inch by 1.0 inch by 1/2 inch, each having a volume of approximately 5 cubic centimeters **(see Figure 7)**. Recently, a somewhat larger pressed disc measuring 4.75 inches in diameter and 1.25 inch thick (350 cc's) and containing either 11 percent or 15 percent magnesium has been developed. A schematic of two discs covering MgFeSi in a ladle bottom is shown in **Figure 8**. The Nodu-Disc's have a similar formulation to the smaller briquettes and can be used as a "reactive cover" material for either iron-magnesium tablets or standard MgFeSi. The consistent weight of the discs may be advantageous in some applications where weighing charge additions might prove cumbersome. The shape of the pressed disc also provides a more favorable surface area-to-volume ratio, which reduces reactivity in molten iron.

A comparison of Nodu-Bloc iron-magnesium briquettes with 5 percent MgFeSi is shown in **Table 3**. The density of Nodu-Bloc iron-magnesium briquettes, for a given magnesium level, is considerably higher than MgFeSi. However, as with MgFeSi, alloy floatation, especially with the 20 percent Nodu-Bloc product, may be a problem. Silicon deficiencies can simply be corrected by adding additional returns to the charge. In many cases, improved foundry return utilization can result in significantly reduced melting costs.

Although silicon control is necessary in producing high quality ductile iron, many ductile iron foundries are reluctant to add sufficient returns to their furnace charges for fear of high silicon. Sometimes, these returns are simply sold to scrap dealers at a significant loss. Utilizing these returns, in conjunction with Nodu-Bloc replacement of MgFeSi, allows more flexibility in post-inoculation. Higher addition rates of post-inoculants for improved structure and carbide reduction can now be made while maintaining nominal silicon levels. Higher-base silicon levels from improved return utilization will significantly improve refractory live. Lastly, by lowering silicon levels and precisely controlling these levels, foundries will have improved control over mechanical properties such as charpy impacts.

**Experimental Laboratory Testing and Development**: To investigate the effects of various levels of Nodu-Bloc substitution for MgFeSi, several experimental ductile irons heats were prepared. Three levels of Nodu-Bloc substitution (15%, 30% and 50%) were evaluated as partial replacement for a nominal 6 percent MgFeSi alloy. The effects of Nodu-Bloc substitution on slag and fume formation, magnesium recovery, sulfur removal and final microstructure were evaluated during this laboratory-testing phase [(5)].

Heats of ductile-base iron were prepared in a 2,500 pound induction furnace with the base iron charge shown below:

220 kilograms (485 pounds) pig iron (Sorel grade)
330 kilograms (727.5 pounds) ductile iron returns
550 kilograms (1212.5 pounds) steel scrap
25 kilograms recarburizer (55.1 pounds) (crushed electrode grade, 99.9% C, 0.05% S)
8 kilograms (17.63 pounds) 75% Ferrosilicon

Experimental ductile iron treatments were poured into a conventional, 300 kilogram (660 pound) tundish ladle. Two base iron sulfur levels were used, 0.013 percent and 0.033 percent. Treatment temperatures were 1,500 $^{o}$C (2,732 $^{o}$F), and tundish ladle filling times were 40 seconds. The tundish ladle had a removable lid and a sandwich divider wall in the ladle bottom. The nominal height to diameter ratio of the ladle was 2.5-to-1. Nodu-Bloc briquettes containing 21 percent magnesium were used for the trials along with a 5.9 percent magnesium containing ferrosilicon containing 1.0 percent total rare earths. The Nodu-Bloc briquettes were first charged into the ladle. The appropriate amount of MgFeSi was then added as a cover. Finally, 2 kilograms (4.4 pounds) of calcium-bearing 75 percent ferrosilicon was also used as a sandwich cover. Post-inoculation was accomplished using a 0.30 percent barium-containing ferrosilicon as a stream inoculant in a 68 kilogram (150 pound) transfer ladle.

Results for the 0.013% sulfur base iron tests are shown in **Table 4**. The 15% and 30% Nodu-Bloc replacement levels showed no significant change or reduction in magnesium recovery. However, magnesium recovery for the 50 percent replacement level declined somewhat. The relatively lengthy treatment ladle filling time may have accounted for this reduced recovery.

It was noted during testing that more surface dross was observed at the highest Nodu-Bloc replacement level of 50 percent. It was also noted was that with increasing Nodu-Bloc replacement level, treatment reaction intensity increased. Although more flashing and flaring were observed, the overall reaction is best described as being "brighter," not more violent. Since a tundish ladle was used, the increased reactivity would not be regarded as a problem in a normal tundish operation. However, with open sandwich ladles, the increased reactivity of 21 percent magnesium Nodu-Bloc could result in some risk of metal splashing. Although not laboratory tested, the 11 and 15 percent grades of Nodu-Bloc would provide reduced reactivity.

Test results for the higher 0.033% sulfur base iron are shown in **Table 5**. For these heats, 0.8 kg (1.76 lbs) of iron pyrites was added to the furnace. The 30% Nodu-Bloc replacement levels showed no change in magnesium recovery. However, magnesium recovery for the 50 percent replacement level declined somewhat. Nodu-Bloc replacement at both the 30% and 50% levels seemed to be much more effective in removing sulfur than 100% MgFeSi additions. Typically, with a 2.5 percent MgFeSi addition to a high (0.033 percent sulfur) base iron, final sulfur levels typically are above 0.02 percent. In these experiments, the addition of 2.5 percent MgFeSi decreased the base sulfur content from 0.033 percent to 0.023 percent. The 30 percent and 50 percent Nodu-Bloc replacement treatments reduced the final sulfur levels to 0.017 percent and 0.019 percent. These results tend to indicate that Nodu-Bloc has a somewhat more powerful capability to desulfurize a high sulfur base iron compared with just MgFeSi. In more practical terms, foundries running high base sulfur levels would benefit from using Nodu-Bloc since nodulizing and desulfurization can both be accomplished without any increase in silicon level.

Microstructural results for the series of experimental treatments are summarized in **Table 6**. The microstructures of all 25 mm section test bars poured with the 0.013% sulfur base iron were all normal and contained nodule counts ranging from 184 to 237/mm$^2$. Pearlite content was measured between 60 to 70 percent for all samples. No differences in nodule count or nodularity were noted even at the highest Nodu-Bloc replacement level. In fact, the 50 percent Nodu-Bloc replacement showed the highest nodule count (237 N/ mm$^2$ ) and best nodularity even though magnesium recoveries were somewhat reduced. Similar microstructural results were observed with the 0.033% sulfur base iron samples; nodule counts ranged from 164 to 178 N/ mm$^2$.

One of the subtler laboratory observations was reduced temperature loss when Nodu-Bloc was used. For example, at a 30 percent Nodu-Bloc replacement of MgFeSi, the nominal reduction in total alloy addition rate is 0.30 weight percent. Reducing additions of nodulizing alloys results in less temperature loss from the heating and melting of alloy additions. The heat conservation resulting from 0.30 percent less MgFeSi is estimated to be in the range of 20$^{o}$C to 30$^{o}$C (36$^{o}$F to 54$^{o}$F). Higher levels of Nodu-Bloc replacement would undoubtedly result in additional temperature conservation.

**Production Results:** To date, several foundries have substituted Nodu-Bloc for MgFeSi as an integral part of their daily production while many others are in the process of evaluating Nodu-Bloc. The production experience of three vastly different ductile iron foundries, each of which had different needs, is discussed in detail in this section.

Foundry A is a medium-sized, high-production foundry producing ductile iron parts for the automotive and truck industries. Daily production capacity is 280 tons. Although Foundry A has a casting yield which ranges from 45 percent to 55 percent, they generate more returns, in the form of gates, risers and pouring basins, than they can remelt. They needed an economical way to increase returns utilization without the accompanying increase in silicon levels. To accomplish these goals, an economical, low-silicon nodulizer needed to be found. Nodu-Bloc 15 met these goals.

Foundry A utilizes three 10-ton induction furnaces for melting. A 2,000 pound capacity open ladle with a height-to-diameter ratio of 2.5-to-1 is used for ductile iron treatments. Extensive tests with Nodu-Bloc iron-magnesium briquettes containing 15 percent magnesium were conducted. It was found that a 25 percent Nodu-Bloc replacement, based on total magnesium, allowed the foundry to use an additional 400 pounds of returns per furnace charge and reduce steel scrap levels by an equivalent 400 lbs.

Nodulizing is accomplished using the sandwich technique. The appropriate amount of MgFeSi is weighed and placed in a charging container. Next, the Nodu-Bloc iron-magnesium briquettes are place over the MgFeSi. The charge container is then dumped into a pocket in a completely empty, heated ladle. Foundry grade 75% ferrosilicon is then added to the pocket as additional cover material, followed by twelve pounds of cover steel. Residual magnesium levels ranged from 0.035 percent to 0.040 percent.

**Table 7** shows a comparison of the furnace charge makeup as well as levels of nodulizers employed prior to and after incorporation of Nodu-Bloc. Little-to-no difference in magnesium flare or reactivity was noted by operating personnel when Node-Bloc was used. The favorable height to diameter dimensions of the sandwich ladle most likely accounted for the modest reaction.

The 25 percent magnesium Nodu-Bloc replacement provided identical microstructural results compared to nodulizing with 100 percent MgFeSi. Nodule count, nodularity and matrix structures remained unchanged. Average nodule count is 275 with an average nodularity rating of 95 percent. Average casting section size is five-eighths of an inch with section sizes ranging between a quarter inch to two inches.

The foundry has realized significant cost savings by utilizing 11.21 percent more returns in the charge make-up. Production costs have been reduced by $7.45 per net ton. The level of daily savings achieved by using a combination of Nodu-Bloc, reduced levels of MgFeSi and increased foundry returns in the furnace charge is $1,489 daily. Annually, these savings approach $375,000. It should be noted that the level of savings is largely dependent on how the foundry values its returns. In this example, the foundry placed a value of $90.00 per ton on its returns. Thus, with these types of savings, Nodu-Bloc iron-magnesium briquettes have now been incorporated into daily production. Trials have been run with Nodu-Discs and have produced encouraging results. Additional trials with the discs are scheduled for in the near future.

Foundry B is a much smaller jobbing foundry producing a variety of ductile iron castings. Daily production is about 25 tons. Because of the jobbing nature of their business, optimizing casting yield becomes difficult due to the fluctuating nature of their production schedule. Foundry B melts with two 4,000-pound induction furnaces.

Twenty percent magnesium containing Nodu-Bloc briquettes were evaluated as a replacement for 6% percent MgFeSi for cost-reduction purposes. Foundry B also had a silicon problem and could not utilize all of the returns generated. It was often forced to liquidate excess returns by selling them to the local scrap yard. This practice had an adverse effect on their balance sheet since it involved a significant write-down of assets.

Nodulizing is accomplished in a 750-pound tundish ladle having a height-to-diameter ratio of 2-to-1. MgFeSi is first weighed into a charging container. Then Nodu-Bloc 20% iron-magnesium briquettes are place over the MgFeSi. The charge container is then dumped into the completely empty, heated tundish ladle. Foundry-grade 75% ferrosilicon is then placed over the nodulizers. Finally, 22 pounds of cover steel is added to the ladle.

**Table 8** shows the furnace charge makeup as well as levels of nodulizers employed by Foundry B both prior to and after incorporation of Nodu-Bloc. During the foundry trials, no appreciable difference in magnesium flare or reactivity occurred during the nodulizing operation.

The 46 percent magnesium Nodu-Bloc replacement provided identical microstructural results compared with nodulizing with 100 percent MgFeSi. This small foundry has realized significant cost savings by utilizing 10 percent more returns in the charge make-up. Ductile iron production costs have been reduced by $10.00 per net ton. The level of daily savings achieved by using a combination of Nodu-Bloc, reduced levels of MgFeSi and increased foundry returns in the furnace charge is $295 daily. On an annual basis, these savings approached $75,000, which pleased foundry management. Needless to say, Nodu-Bloc iron magnesium briquettes have now been incorporated into daily production.

Foundry C is also a small, jobbing foundry producing mostly ductile iron castings along with gray iron castings. The foundry uses two one-ton induction furnaces for melting. Foundry C's prime objective was to reduce ductile iron production costs by eliminating costly nodular grade pig iron and replacing it with its own foundry returns. This foundry, not unlike many other small foundries, tends to over treat their ductile iron with MgFeSi and, consequently, is always battling a silicon problem. The reasons for over treatment include MgFeSi is used for desulfurization since base iron sulfurs approach 0.02 percent, non-ideal treatment ladle dimensions, and lengthy ladle filling times due to the tilting mechanism on the induction furnaces.

Nodulizing is accomplished in a 2,000-pound open ladle using the sandwich process. The height to diameter ratio of the ladle is only 1.25-to-1. The treatment is completely empty and pre-heated. Nodu-Bloc 15% briquettes are added to the ladle first, then MgFeSi is placed over the iron-magnesium briquettes, and finally, one 3-pound Nodu-Disc is added as cover. Lastly, 22 pounds of foundry grade 75% ferrosilicon is placed over the nodulizers for "cover".

**Table 9** shows the furnace charge makeup as well as levels of nodulizers employed by Foundry C both prior to and after incorporation of Nodu-Bloc. During the foundry trials, only minor differences in magnesium flare and reactivity occurred during the nodulizing operation. However, some metal splashing has occurred on an infrequent basis, mainly due to the shallow depth of the treatment ladle. Residual magnesium levels continued to be in the range of 0.05 to 0.055 percent.

The 57 percent magnesium Nodu-Bloc replacement provided identical microstructural results compared with nodulizing with 100 percent MgFeSi. This small foundry has realized significant cost savings by completely eliminating over 1,000 pounds of nodular pig iron from its charge make-up. Production costs have been reduced by $33.49 per net ton. The level of daily savings achieved by using a combination of Nodu-Bloc, reduced levels of MgFeSi and increased foundry returns in the furnace charge is $502 daily. On an annualized basis, these savings are in excess of $126,500. As with Foundries A and B, Nodu-Bloc iron-magnesium briquettes and discs have now been incorporated into daily production.

**Discussion:** Laboratory testing of Nodu-Bloc replacement for MgFeSi confirmed that it is a viable replacement for MgFeSi alloys up to 30% substitution. Magnesium recovery and microstructure evaluations showed that Nodu-Bloc replacement was identical to 100% MgFeSi treatment. At higher replacement levels, the nodulizing reaction was more vigorous and some reduction in magnesium recovery occurred. However, microstructures were identical or slightly better than the lower 30% substitution level. The laboratory findings also suggest that Nodu-Bloc is a more potent desulfurizer that MgFeSi, particularly when base iron sulfur levels are 0.025 percent and higher. Although the laboratory trials utilized the most potent form of Nodu-Bloc, (21 percent magnesium content), the 11 percent and 15 percent grades would show reduced reactivity.

The summary of production results at three different foundries mostly confirmed the laboratory findings. Two of the three foundries used a higher replacement level than 30 percent level and continued to produce high-quality ductile iron castings with excellent microstructures. The three case history foundries all were able to increase their use of ductile iron returns in their charges. The savings levels achieved ranged from $7.50 per ton to over $30.00 per ton. It should be noted that the savings level calculations greatly depends on what value the foundry places on its ductile iron returns.

Nodu-Bloc replacement of MgFeSi allows foundries to continue to use time-proven ladle metallurgy practices while also realizing the cost savings of pure magnesium processes. All of this is achieved without the need for costly wire feeding equipment and alloys or installation of a converter. Additionally, should supplies of U.S. produced MgFeSi be reduced due to producer plant closings, Nodu-Bloc replacement of MgFeSi is one method to stretch supplies. Additional research work continues to strive for methods that will allow even greater replacement levels of MgFeSi.

**Conclusions:**

1.) Extensive laboratory testing of Nodu-Bloc 21% iron-magnesium briquettes has shown that up to 30 percent replacement of MgFeSi could be accomplished. Good and comparable magnesium recovery and microstructures were obtained from substituting 1.5 weight percent addition rates of MgFeSi with 1.0 weight percent MgFeSi and 0.10 weight percent Nodu-Bloc. Higher addition rates may result in increased reactivity, possible metal splashing and reduced recoveries, but these are dependent on ladle design and other foundry variables.

2.) Nodu-Bloc is a very attractive product for silicon control in ductile iron production, since the iron-magnesium briquettes will introduce only trace contributions of silicon to the final castings. This may be of great advantage to foundries producing ferritic ductile iron with requirements for impact resistance where final silicons of 2.5 percent are often necessary to avoid brittleness.

3.) Production results from three different foundries, showed that Nodu-Bloc replacement of MgFeSi of up to 50 percent was feasible.

4.) Nodu-Bloc iron-magnesium briquettes appear to be provide greater efficiency in desulfurization than MgFeSi in medium sulfur base irons (0.02 to 0.05 percent). In such cases, Nodu-Bloc may be an attractive alternative to competitive treatment processes such as converter and cored wire. The mixture Nodu-Bloc and MgFeSi will still provide the most best advantages of MgFeSi versus pure magnesium when it comes to facilitating good nucleation response of the treated metal.

Part II of this paper will address new advances in post-inoculation practices of ductile iron using newly developed inoculants that contain a significant amount of oxy-sulfide forming elements.

References:


1.) Modern Castings, January 2000
2.) Ryan's Notes, April 12, 1999
3.) Ryan's Notes, March 19, 2001
4.) Ryan's Notes, July 30, 2001
5.) T. Skland, Elkem Research Laboratory, Norway


Figures 1 through 6 are Powerpoint v. 2000

## Table 1. “Plight of the U.S. Ferrosilicon Industry”
## U.S. FeSi Producer Statistics
(International Trade Commission Questionnaire Responses)

| | **2000 est.** | **1999 est.** | **1998 actual** | **1997 actual** |
|---|---|---|---|---|
| Shipments<br>(Metric tons of contained silicon for both 50% and 75% Ferrosilicon) | 180,000 | 180,000 | 186,497 | 189,755 |
| 75% FeSi Prices<br>(Price per lb. of contained silicon) | $0.3483* | $0.3991 | $0.4281 | $0.4765 |
| Operating Income<br>(Loss) in Millions | ($30.7) | ($10.6) | ($2.8) | $15.4 |

- Average 75% FeSi for Year 2000

## Table 2. U.S. FeSi Producer Statistics
## Ferrosilicon Production - 20 years of contraction

| | **1980** | **2000** | **+ / - %** |
|---|---|---|---|
| Ferrosilicon Producers | 7 | 5 | |
| No. of Furnaces | 39 | 9 | (77%) |
| Installed KVA Capacity | 804 | 224 | (72%) |
| Production (Metric Tons) | 585,551 | 408,000 | (30.3%) |

### Table 3. Comparison of Nodu-Bloc Iron-magnesium Briquettes to MgFeSi

| | | **MgFeSi** | **Iron-magnesium Briquettes** |
|---|---|---|---|
| Melting Temperature | | 2,350 to 2,450°F | <2,050°F |
| Size (typical) | | 1 in. x 1/4 in. | 1.25 x 1.0 x .5 in |
| Magnesium % | | 3.5% to 11% | 11%, 15% and 20% |
| Density | 5.5% grade | 4.05 grams/cc | |
| | 11% grade | 3.50 grams/cc | 4.55 grams/cc |
| | 15% grade | | 4.1 grams/cc |
| | 20% grade | | 3.3 grams/cc |
| Reactivity in Open Ladle | | Moderate | Moderate & "brighter" |
| Alloy chemistry control capability | | Fair | Excellent |

## Table 4. Research Laboratory Test Results
## 0.013% Sulfur Base-Iron

| Tap No. | **Mg Substitution Level** | **% Mg** | **% Sulfur** | **Recovery** |
|---|---|---|---|---|
| #1 - 1.5% Addition or 9.9 lbs MgFeSi | 0% - Base | 0.042 | 0.010 | 48.70% |
| #2 - 8.36 lbs MgFeSi & .44 lbs Nodu-Bloc | 15% | 0.044 | 0.009 | 53% |
| #3 – 7.04 lbs MgFeSi & .88 lbs Nodu-Bloc | 30% | 0.038 | 0.007 | 49% |
| #4 - 4.84 lbs MgFeSi & 1.43 lbs Nodu-Bloc | 50% | 0.031% | 0.008 | 40% |

Notes:
1.) Magnesium FeSi alloy – 5.9% Mg, Nodu-Bloc – 21% Mg
2.) 300 kg Tundish Ladle, Base Sulfur Level - 0.013%
3.) Treatment Temperature - 1,500°C (2,732°F), Tundish filling time - 45 sec.
4.) Post-inoculation - 0.30% Ba containing 75% FeSi stream inoculation into transfer ladle
Magnesium Recovery calculations based on the formula:

$$\% \text{ Mg recovered} = \frac{(\%) \text{ Mg residual + base iron sulfur reduction}}{\% \text{ Mg addition}} \times 100\% \ (\%)$$

## Table 5. Research Laboratory Test Results
## 0.033% Sulfur Base-Iron

| **Tap No.** | **Mg Substitution Level** | **% Mg** | **% Sulfur** | **Recovery** |
|---|---|---|---|---|
| #1 - 2.5% Addition or 16.5 lbs MgFeSi | 0% - Base | 0.056 | 0.0235 | 44% |
| #2 – 10.67 lbs MgFeSi & 1.474 lbs Nodu-Bloc | 30% | 0.055 | 0.017 | 47% |
| #3 – 8.25 lbs MgFeSi & 2.36 lbs Nodu-Bloc | 50% | 0.039 | 0.019 | 35% |

Notes: 1.) MgFeSi alloy – 5.9% Mg, Nodu-Bloc – 21% Mg
2.) 300 kg Tundish Ladle, Base Sulfur Level - 0.033%
3.) Treatment Temperature - 1,500°C (2,732°F), Tundish filling time - 45 sec.
4.) Post-inoculation - 0.30% Ba containing 75% FeSi stream inoculation into transfer ladle
5.) Magnesium Recovery calculations based on the formula:

$$\% \text{ Mg recovered} = \frac{(\%) \text{ Mg residual + base iron sulfur reduction}}{\% \text{ Mg addition}} \times 100\% \ (\%)$$

## Table 6. Research Laboratory Microstructure Results
## 0.013% Sulfur Base-Iron – 25 mm Section Size

| **Nodu-Bloc Substitution Level** | **0%** | **15%** | **30%** | **50%** |
|---|---|---|---|---|
| Nodule Count (mm$^2$) | 184 | 188 | 201 | 237 |
| Nodularity % | 85% | 86% | 89% | 89% |
| Ferrite Content % | 41 | 42 | 42 | 46 |
| Pearlite % | 59 | 58 | 58 | 54 |
| Shape Factor | 0.80 | 0.80 | 0.81 | 0.81 |
| Mean Diameter (in microns) | 21.0 | 21.3 | 21.2 | 19.5 |

Notes:
1.) Test casting section size - 25 mm

## Table 7: Production Experience of Foundry A using 15% Nodu-Bloc Iron-magnesium Briquettes

| | **Original Charge** | **Nodu-Bloc Modified Charge** |
|---|---|---|
| Foundry Returns | 2,100 lbs | 2,500 lbs |
| Steel scrap | 1,500 lbs | 1,100 lbs |
| Carbon | 55 lbs | 40 lbs |
| Silicon Carbide | 4 lbs | 4 lbs |
| MgFeSi | 27 lbs | 21 lbs |
| Nodu-Bloc 15% | 0 lbs | 2.9 lbs |
| 75% Foundry FeSi | 11 lbs | 11 lbs |
| Cover Steel | 11 lbs | 11 lbs |
| | | |
| Final Chemisty | | |
| % Carbon | 3.70% - 3.85% | 3.70% - 3.85% |
| % Silicon | 2.60% - 2.70% | 2.60% - 2.70% |
| % Sulfur | 0.007% - 0.009% | 0.007% - 0.009% |
| % Magnesium | 0.030 - 0.040% | 0.03 - 0.040% |
| Nodule Count (mm$^2$) | 275 | 275 |
| Nodularity | 95% | 95% |
| Carbides | None | None |

Notes:
1.) 1,900 lb. open ladle, sandwich treatment method

Table 8: Production Experience of Foundry B using 20% Nodu-Bloc Iron-magnesium Briquettes

| | **Original Charge** | **Nodu-Bloc Modified Charge** |
|---|---|---|
| Foundry Returns | 750 lbs | 900 lbs |
| Steel scrap | 750 lbs | 600 lbs |
| Carbon | 28 lbs | 23 lbs |
| Silicon Carbide | 5 lbs | 5 lbs |
| MgFeSi | 12 lbs | 6.5 lbs |
| Nodu-Bloc 20% | 0 lbs | 2.1 lbs |
| Proprietary Inoculant | 3.25 lbs | |
| 75% Foundry FeSi | ---- | 3.75 lbs |
| Cover Steel | 22 lbs | 22 lbs |
| | | |
| Final Chemistry | | |
| % Carbon | 3.60% - 3.75% | 3.60% - 3.75% |
| % Silicon | 2.50% - 2.65% | 2.50% - 2.65% |
| % Sulfur | 0.0075% | 0.0075% |
| % Magnesium | 0.035 - 0.045% | 0.035 - 0.045% |
| Nodule Count ($mm^2$) | 225 | 250 |
| Nodularity | 95% | 98% |
| Carbides | None | None |

Notes:

1.) 750 lb. tundish treatment ladle

Table 9: Production Experience of Foundry C using 15% Nodu-Bloc Iron-magnesium Briquettes

| | **Original Charge** | **Nodu-Bloc Modified Charge** |
|---|---|---|
| Foundry Returns | 0 lbs | 1,000 lbs |
| Steel scrap | 200 lbs | 200 lbs |
| Nodular Pig Iron | 1,800 lbs | 800 lbs |
| Carbon | 2 lbs | 6 lbs |
| 75% FeSi lumps | 16 lbs | 0 lbs |
| MgFeSi | 49 lbs | 21 lbs |
| Nodu-Bloc 15% | 0 lbs | 8 lbs |
| Nodu-Disc 15% | 0 lbs | 3 lbs |
| 75% Foundry FeSi | 20 lbs | 20 lbs |

Notes:

1.) Base iron sulfur level – 0.025%

Figure 1: Ductile Iron Treatment Processes
50 Years of Innovation

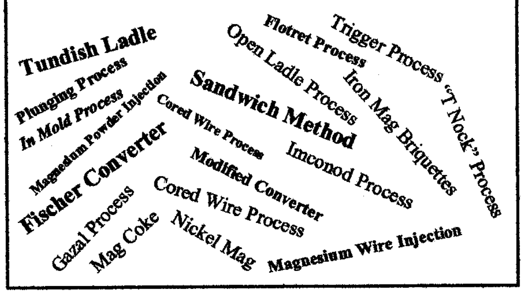
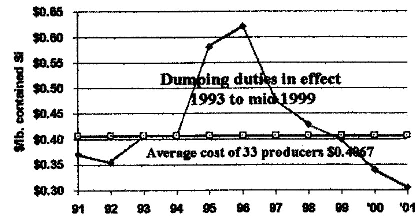
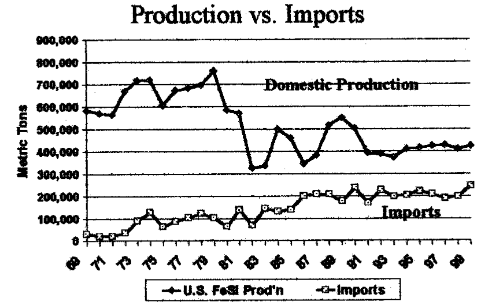



Figure 2: 75% Ferrosilicon Average Yearly Price vs. Production Cost




Sources: CRU International Ltd. , Metals Week, Ryan's Notes

Figure 3: U.S. Ferrosilicon Production vs. Imports




Source: U.S. Geological Survey

Figure 4: 50% Ferrosilicon Cost Components

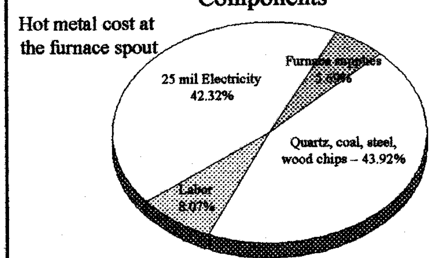



Figure 5: Magnesium Ferrosilicon Cost Components

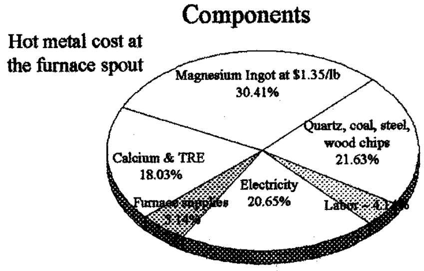
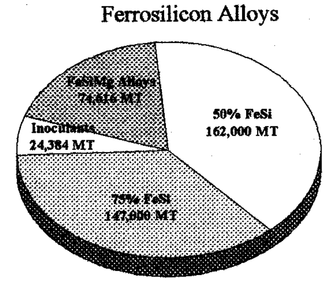



Figure 6: U.S. Production of Ferrosilicon Alloys




1998 Total U.S. Production - 408,000 MT, Source: U.S. Census Bureau

Figure 7. Photograph of Nodu-Bloc iron-magnesium briquettes magnification 1.25x

Figure 8. Illustrations of Nodu-Disc iron magnesium nodulizing discs covering magnesium ferrosilison. Magnification 0.5x