DOE F 241.3
(2-01) p.1 of 2

UNITED STATES DEPARTMENT OF ENERGY (DOE)
Announcement of Scientific and Technical Information (STI)
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OMB CONTROL NO.
1910-1400

PART I: STI PRODUCT DESCRIPTION
(To be completed by Recipient/Contractor)

A. STI Product Identifiers

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Concept Engineering Group Inc., 15 Plum Street, Verona, PA 15147

C. STI Product Title
MAG-GATE System for Molten Metal Flow Control

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E. STI Product Issue Date/Date of Publication
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☒ *Final* ☐ *Other (specify)*

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I. Subject Categories *(list primary one first)*
32 Energy Conservation, Consumption and Utilization
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J. Description/Abstract

The need for improved active flow control of hot metal has been recognized for many years by the steel industry. Concept Engineering Group Inc. has developed MAG-GATE, an electromagnetic system for molten metal flow control. Two successful hot metal tests were performed to validate and enhance the predictive computer model created as part of the project.

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L. Recipient/Contract Point of Contact *Contact for additional information (contact or organization name To be included in published citations and who would Receive any external questions about the content of the STI Product or the research contained herein)*
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Report Documentation Page

Title and Subtitle:	AISI/DOE Technology Roadmap Program MAG-GATE System for Molten Metal Flow Control TRP 9808
Author(s):	Richard D. Nathenson, Principal Investigator
Performing Organization	Concept Engineering Group Inc. Verona, PA

Abstract:

The need for improved active flow control has been recognized as part of the Steel Industry Technology Roadmap. Under TRP 9808 for the American Iron and Steel Institute and the Department of Energy**,** Concept Engineering Group Inc. has developed MAG-GATE^{TM}, an electromagnetic system for active molten metal flow control. Two hot steel tests were successfully conducted in 2003 at the Whemco Foundry Division, Midland, PA. Approximately 110,000 pounds of 0.2% carbon steel were poured through the device subject to electromagnetic flow control. Excellent agreement between predicted and actual flow control was found. A survey of the molten metal flow control practices at 100 continuous casters in North America was also conducted in 2003. This report summarizes the results of the development program to date. Preliminary designs are described for the next step of a beta test at an operating billet/bloom or slab caster.

(RDP Standard Form, Form 298)

MAG-GATE^{TM}

System for Molten Metal Flow Control

Developed

For

American Iron and Steel Institute

Department of Energy

Contract DE-FC36-97ID13554

By

Richard D. Nathenson, P.E.

Concept Engineering Group Inc.

15 Plum Street

Verona, PA 15147

May 2004

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Abstract

The need for improved active flow control has been recognized as part of the Steel Industry Technology Roadmap. Under TRP 9808 for the American Iron and Steel Institute and the Department of Energy**,** Concept Engineering Group Inc. has developed MAG-GATE^{TM}, an electromagnetic system for active molten metal flow control. Two hot steel tests were successfully conducted in 2003 at the Whemco Foundry Division, Midland, PA. Approximately 110,000 pounds of 0.2% carbon steel were poured through the device subject to electromagnetic flow control. Excellent agreement between predicted and actual flow control was found. A survey of the molten metal flow control practices at 100 continuous casters in North America was also conducted in 2003. This report summarizes the results of the development program to date. Preliminary designs are described for the next step of a beta test at an operating billet/bloom or slab caster.

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Introduction

Today, nearly all of the world's yearly steel production, approximately 700 million tons, is by continuous casting. The American steel industry produces approximately 100 million tons of steel annually valued at close to $50 billion. The maturing of continuous casting in the US, the emphasis on "clean steel," the rise of ladle and tundish metallurgy, the trend to higher production machines, and the need for precise control in innovative casting processes have all increased the importance of flow control in modern continuous casting. The Steel Manufactures Association and the American Iron and Steel Institute have recognized this need for improved active flow control as part of their Steel Industry Technology Roadmap.

In a modern steel continuous caster, control of the flow of the molten metal from the tundish to the mold is the critical location. Active flow control can improve the quality of the metal by reducing turbulence, reoxidation, and impurity entrapment. Caster productivity is improved by the ability to compensate in an independent fashion for a number of adverse operational conditions including, for example, refractory erosion or clogging. The potential to increase sequence length leads directly to strand yield improvement, energy savings, and operating cost reductions.

Using an electromagnetic flow control device for a typical billet caster, the projected savings for the operator are on the order of several dollars per ton. Payback of the system's initial capital investment can be easily accomplished within the one to three year period generally used by the industry. Over the US steel continuous casting industry the total net savings could reach $500 hundred million dollars per year.

Although the introduction of continuous casting has improved the energy efficiency of steel making over conventional ingot casting, the use of an electromagnetic flow control offers the potential to increase process yield and, hence, energy savings. Each 10% increase in sequence length made possible by MAG-GATE^{TM} offers the possibility of a 0.1% reduction in steel production energy use. The mature energy savings to the US steel industry could be on the order of 2×10^{12} Btu annually.

Concept Engineering Group Inc. is developing MAG-GATE^{TM}, an electromagnetic system for active molten metal flow control. This report summarizes the results from the development program to date. Conclusions are drawn and recommendations made for next steps in the development program.

Problems with Today's Flow Control Technology

Although simple in construction, metering nozzles suffer from a number of operational problems. The only way to control flow with a metering nozzle is to control the tundish level height, but this is slow and insensitive. Inclusion float time and vortexing, also, tend to make changes in tundish level undesirable from a quality standpoint. Generally for a billet caster, the nozzle life primarily limits the sequence length and, hence, productivity. The nozzle erodes to the point that the flow rate increases over the allowable limit for the machine. On the other hand, for some grades alumina clogging tends to limit sequence length and also restricts the types of steel that may be cast. Finally, the only way to stop flow through a metering nozzle is to manually insert a chill plug to freeze the flow. Typically in the steel industry this plug must be burned out with an oxygen lance to restart the flow often damaging the nozzle.

Stopper rods have several operational problems. The first is the production of a rough stream. A rough stream has a higher surface to volume ratio and, hence, a higher propensity to reoxidize by direct contact with the air. Further, a rough stream will entrain more air and carry it into the mold causing disadvantageous turbulence, foaming, and sloshing. With a turbulent pool, new steel is continuously brought to the surface for further contact with air. Very little time is left for proper separation of impurities. Oxides, also, tend to be thrown to the outside of the mold where they can be trapped in the surface of the strand. Excessive turbulence in the molten crater of the strand can, also, be a potential cause of a breakout through the shell. Finally, toward the end of a sequence cast, the accuracy of flow control gets worse as the flow area between the rod and the nozzle block becomes fouled.

Slidegates, also, tend to produce rough streams. Extensive studies during teeming through a 3-inch slidegate carried out at Stelco, Lake Erie Works, determined that stream flaring occurred when the gate is in a semiopen position, i.e. 95% of the time during a heat sequence. The stream exiting the top portion of the slidegate at an angle translates into a circular motion through and exiting the gate. In 1991, Inland Steel reported that the slide gate generates in a submerged entry nozzle several recirculation loops due to the sharp geometry changes and significantly worsens the alumna clogging problem when casting aluminum killed steels.

Process Advantages

When compared to metering nozzles, an electromagnetic flow control:

- Offers the operator of a billet caster the opportunity to now control the flow through the caster rather than react to it.
- Provides independent control over the casting rate to meet tight specifications on the heat removal rates in all commercial grades.
- Provides a greater degree of control over that of changing the tundish level height.
- Offers independent flow control on each nozzle to compensate for uneven nozzle wear or clogging among the multiple strands in a caster fed from the same tundish.
- Gives the operator the capability to adjust flow independent of strand motion changes to maintain a constant mold level height, which is so important to good quality.
- Opens up markets currently not available to the minimills with the ability to counter the traditional nozzle blockage problem of aluminum-killed steels via the controlled flow and heat addition capabilities.

Since 2/3 of the flow control in the minimill market is still by metering nozzle, these advantages are particularly important. When compared to stopper rod or slide gates, the electromagnetic flow control:

- Regulates flow without introducing stream roughness and the subsequent mold turbulence, reoxidation, and impurity entrapment.
- Eliminate sites where stream velocity changes abruptly, which then causes inclusions to accumulate.
- Eliminates the mechanisms needed to move the rod or plates, which are subject to, wear and failure.

An electromagnetic flow control device can perform a number beneficial functions that current metering nozzles, stopper rods, or slidegates cannot including:

- Electromagnetically improves the steadiness of the pouring stream eliminating turbulence from the ladle stream and the tundish resulting in improved quality.
- Can provide additional heat directly at the nozzle to reduce the tendency for inclusion deposition and the possibility of freezing.
- Can apply heat at the nozzle electromagnetically to remelt a strand if it has been deliberately frozen off avoiding the damage typically done by an oxygen lance.
- Gives a greater capacity to deal properly with hot or cold heats.
- With the trend toward larger tundishes, provides a new capability to offset the extra head present with the greater depth that is desired to minimize vortexing and to maximize inclusion float.

The electromagnetic flow control is, also, expected to improve performance over the current state of the art in the following ways:

- Gives the computer better and more responsive control over the metal flow rate through the caster to better match to the furnace.
- Achieves more uniformity from cast to cast by reducing the reliance on individual operator's skill and potentially the number of operators needed.
- Reduces costly events such as breakouts, nozzle lancing, and caster turnarounds with the subsequent upturn in strand yield.
- Allows a higher number of sequential casts through increased nozzle reliability and performance, which results directly in higher productivity.

Mag-Gate™ Device

Figure 1 shows a cross-section of the prototype Mag-Gate™ device tested at Whemco. Along the vertical, axial centerline runs a ceramic tube through which the molten steel flows. Surrounding this pour tube are two, thin, polished stainless steel cylinders, which act as heat shields. One lies up against the inner diameter of the core; while the other is in the air gap between the core and the pour tube. Two electric coils, one above the other, surround all of the tubes. An iron core in turn surrounds both of the coils. The iron core serves to circulate the magnetic flux generated by the coils through the pour tube and molten steel. Overall dimensions of the unit are shown. Table 1 gives the performance parameters for the alpha test device.

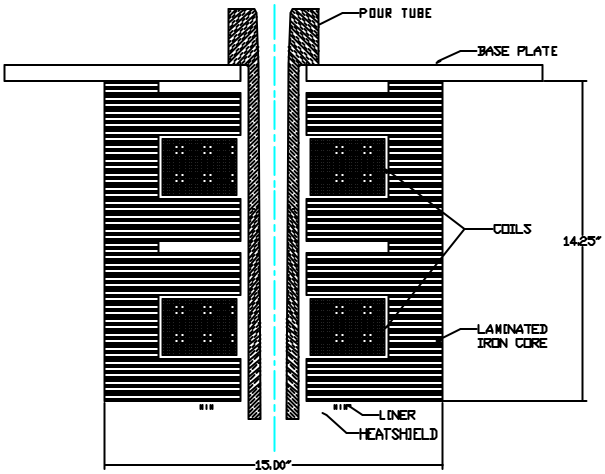

Figure 1. Schematic cross-section of Whemco Mag-Gate^{TM} device.

Table 1. Whemco Mag-Gate^{TM} Device Parameters

Design water inlet temperature	70 ^{o}F
Water temperature rise	100 ^{o}F
Design Pressure drop 2 coils	260 psig
Total Water flow rate 2 coils	34 gpm
Maximum coil current	2000 amps DC
Total power 2 coils	500 kW

Figure 2 shows the device mounted to the bottom of the test tundish. The pour tube sits with a tapered fit into a well block installed in the bottom of the tundish. The well block was installed first surrounded by rammed factory sand. A simple, hand operated stopper rod fit into the rounded inlet at the top of the pour tube to positively start and stop the flow at the beginning and the end of the test.

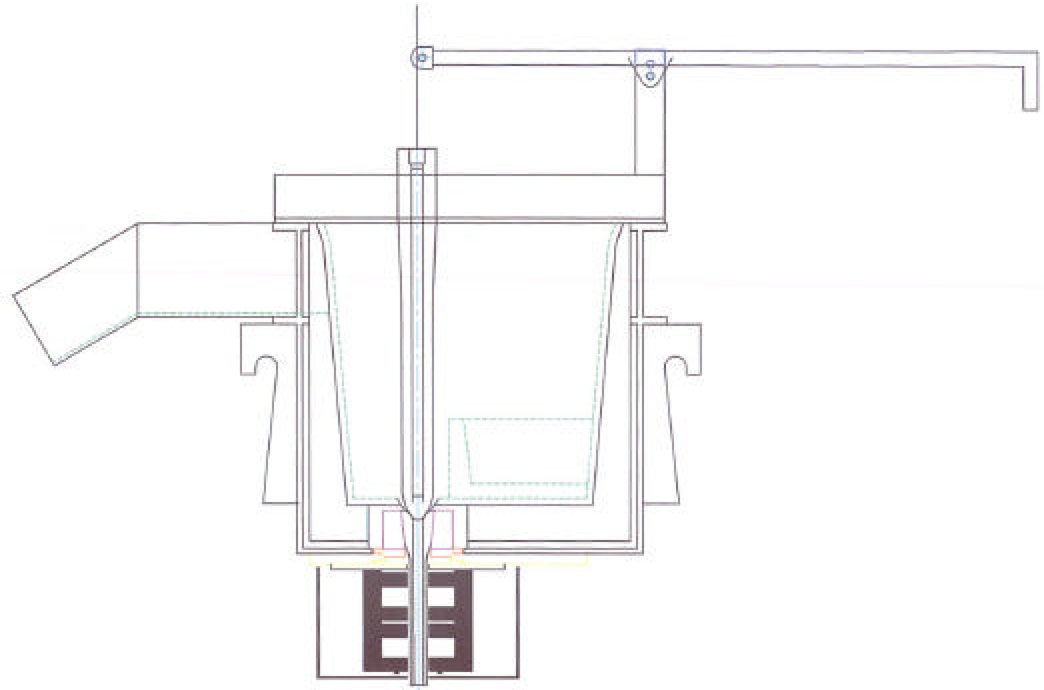

Figure 2. Schematic of Mag-Gate™ installed on bottom of test tundish including pour tube, well block, and stopper rod.

Theory

The theoretical performance the electromagnetic flow control device is described below.[i] The device is dc with the braking action being developed internally by the induced drag of a conducting fluid trying to move through a steady magnetic field. Ohm's Law in magnetohydrodynamic problems is given by:

$$J = s \cdot (E + V \times B) \qquad \textit{Equation 1}$$

where:
J = Current density
E = Electric potential
V = Velocity
B = Magnetic Field

The Lorentz body force, **F**, on the fluid is given by

$$F = J \times B \qquad \textit{Equation 2}$$

Combining these and rearranging the order of terms yields:

$$F = s \cdot ((V \times B) \times B) + s \cdot (E \times B) \qquad \textit{Equation 3}$$

For the Mag-Gate™ device, the following assumptions can be made.

- The externally applied electric field E is zero.

- The radial velocity is essentially zero.

Integrating over the volume of fluid subjected to the magnetic field, the induced drag or differential pressure drop in the flow tube becomes:

$$\Delta P = \frac{s}{A} \cdot \int V \cdot B_r^2 \cdot \partial Vol \quad \text{Equation 4}$$

ΔP = Differential pressure drop
A = Flow tube area
Vol = Volume over which field acts
B_r = Radial component of magnetic field

For the Whemco and commercial Mag-Gate™ devices the flow is turbulent. Therefore, the velocity is essentially constant across the section and goes to zero very close to the wall.

Hot Metal Tests

The actual Mag-Gate™ device as tested at the Whemco Foundry, Midland, PA is shown in Figure 3 attached to the bottom of the test tundish. Each coil has its own inlet and outlet aluminum water manifold. RTD's are mounted on each manifold to monitor temperature. Non-conducting "Shock-Safe" hoses connect each layer of the coils to these water distribution manifolds. 1-inch diameter, SAE 100R1AT water hoses from each manifold connect to the de-ionized water system. To bring the current from the power supply to the device, four 350 MCM stranded copper cables are used per lead. In open air each of these cables can carry 500 amperes. The cables terminate at the device on two copper plates to which the device's start and finish leads are in turn brazed. Fire sleeves protect the first 10 feet of each hose and cable away from the device and tundish. Lead wires for the high temperature thermocouples attached to each of the liner and heat shield respectively can also be seen in the photograph.

Two successful tests with hot metal have been performed at the Whemco Foundry Division, Midland, PA. Figure 4 shows steel being poured from the ladle through the Mag-Gate™ device mounted to the tundish in the test stand. Approximately 110,000 pounds of 0.2% carbon steel were poured through the device subject to electromagnetic flow control. A very smooth steel stream was achieved. Temperatures of the device surrounding the molten steel were stable and extremely good cooling of the electric coils was achieved. As shown in Figures 5 and 6, excellent agreement was seen between expected theoretical performance and actual test results.

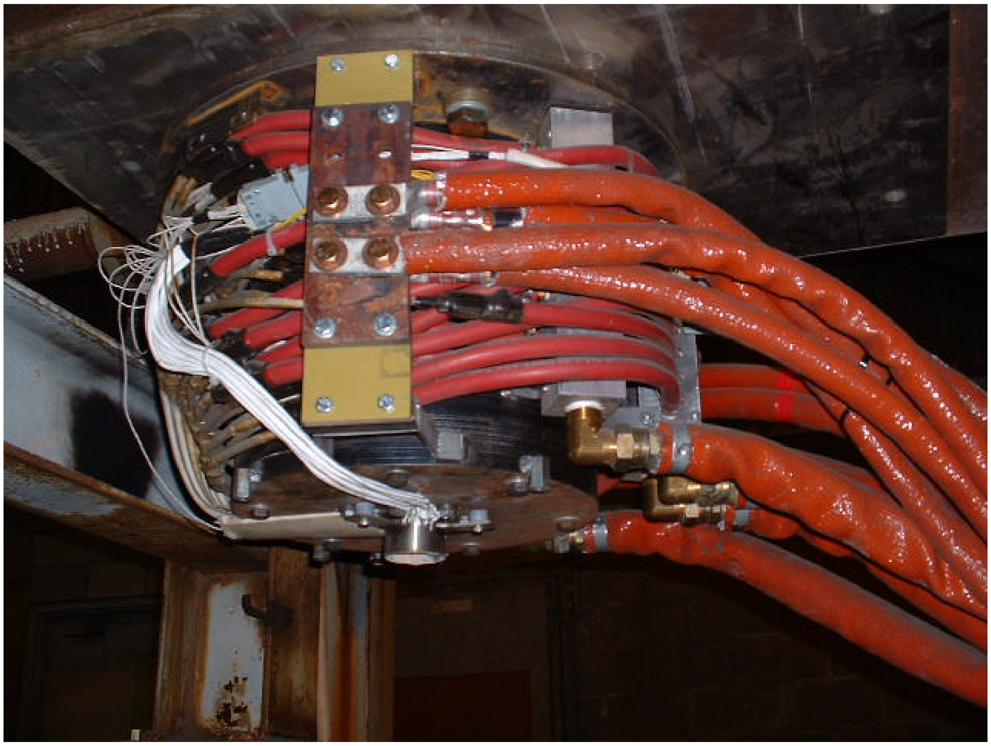

Figure 3. Prototype Mag-Gate™ device installed on tundish.

Figure 4. Overall view of the test site from across the plant's aisle during a pouring test.

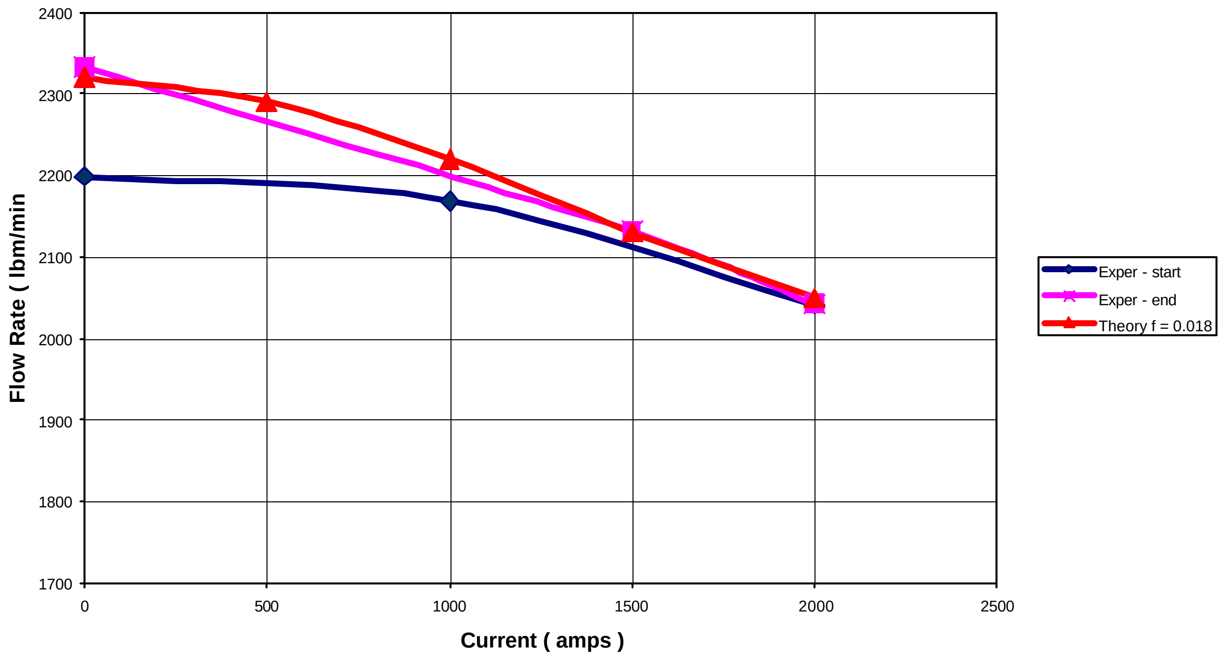

Figure 5. Results from 1st hot test with 14-inch head of steel in tundish.

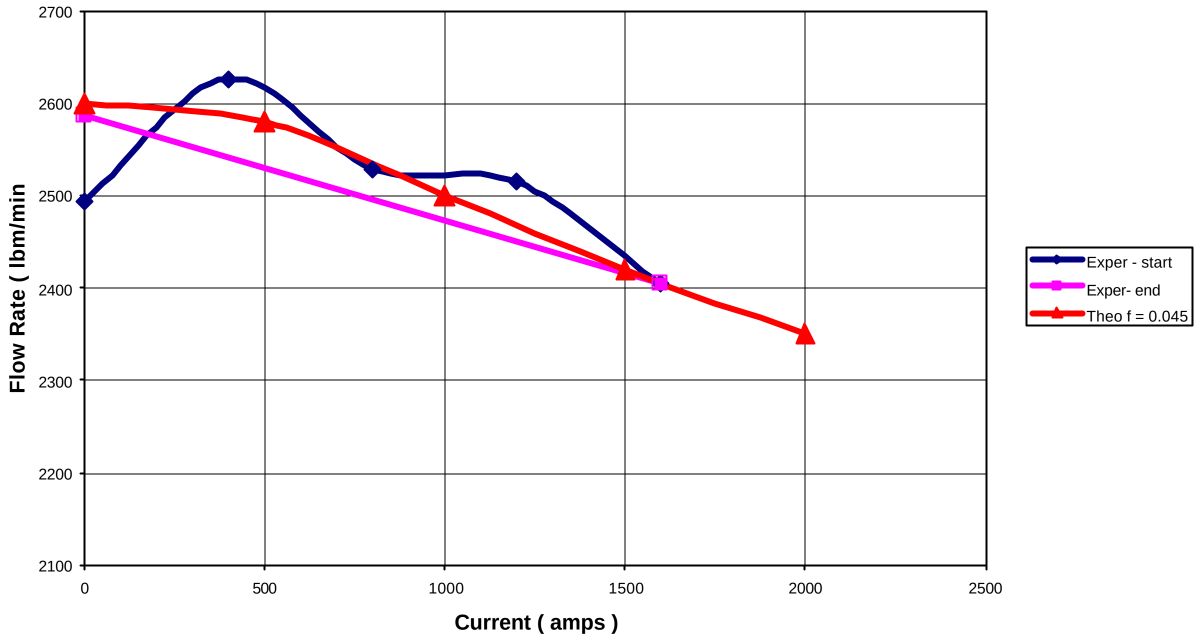

Figure 6. Results from 2nd hot test with 25-inch head of steel in tundish.

Continuous Caster Market Study

AISI and CEG jointly participated in a 2003 North American continuous caster survey conducted by AIM Market Research.[ii] The survey covered 100 casters from 23 casting machine builders scheduled to produce 89 million tons of steel in 2003. Topics included: production mix; operating parameters; product dimensions; age of equipment; priorities; tundish parameters, practices, preheating, and refractory; oscillators; tundish flow and level control; mold shape and level control; cut systems; bearings; and lubricants. Plans to upgrade or replace equipment, and maintenance were addressed. By type of caster 41 billet, 19 bloom, 33 slab, and 7 thin slab machines were covered.

Flow control parameters are listed in Table 2 by caster type. Average tundish depth ranged from a low of approximately 31 inches for billet machines to a high of 45 inches for slab machines. Average tons per strand per sequence ranged from a low of 300 for billet casters with open pouring to a high of 6100 for slab casters using slidegates or rotary gates. Pour rates for these same machines ranged from 760 to 6600 pounds per minute.

Table 2. Flow control Parameters by Caster and Flow Control Technology Type

Qnt'y	Caster Type	Flow Control	Tundish Depth (in)	Sequence Length (tons per strand)	Yearly Production (000 tons)	Sequence Length (Heats)	Pour Rate (lbs / min)
23	Billet	OP	30	300	460	14	760
18	Billet	SG, SR	34	590	560	26	900
16	Billet , Bloom, Round	SG, SR, OP	33	730	550	35	1100
17	Slab	SG, RG	45	6100	1740	46	6600
16	Slab	SR	41	1930	990	13	5400
8	Thin Slab	SR, OP	40	1190	1100	10	5500

Where: OP = Open pour; SG = Slidegate; SR = Stopper Rod; and RG = Rotary Gate.

Figure 7 shows the type of tundish flow control used by the casters surveyed. Overall the use of a slidegate, stopper rod, or open pouring is about evenly split among the casters. For billet casters, open pouring still dominates. For bloom casters, open pouring and stopper rods are about equal. For slab casters, use of either a stopper rod or a slidegate are about equal; while thin slab casters use only stopper rods.

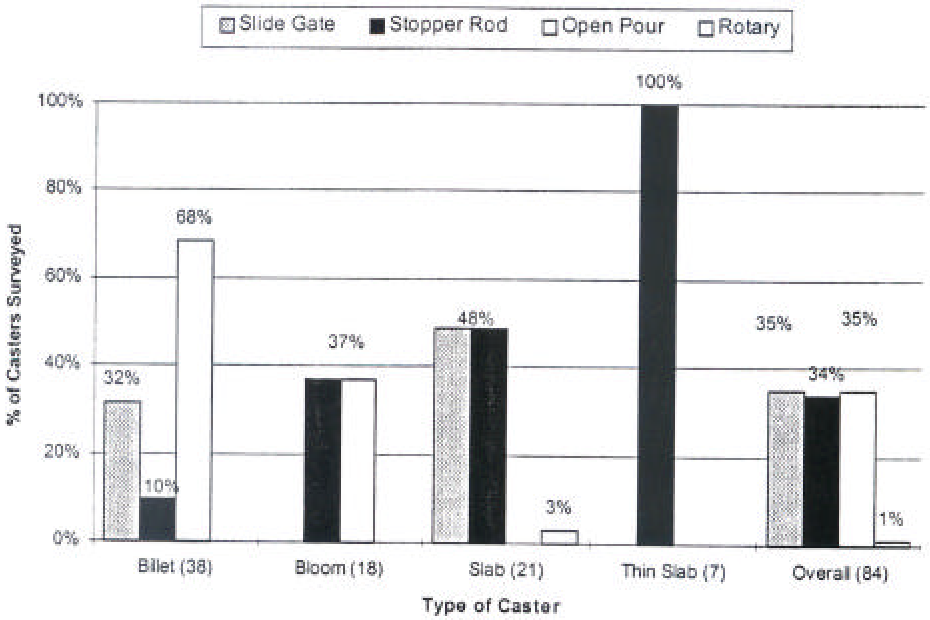

Figure 7. Type of tundish flow control.

The survey asked the caster operator when diminished flow through a nozzle dictated aborting the strand. Overall most of the casters responded that a 25% diminished flow dictated aborting a strand. Figure 8 summarizes the responses, mostly from operators of slab casters.

Interpreting the answer to this question is very important. A major benefit of the Mag-Gate™ device is that it can compensate for nozzle clogging when casting AL killed steels. By over-sizing the nozzle initially, as the nozzle clogs the flow retardation caused by the Mag-Gate™ device can be relieved thus maintaining a constant flow. The casting time could conceivably be <u>doubled</u> if the flow rate reduction by the device equals the level at which diminished flow terminates the cast. Since the majority of caster operators said a 25% reduction in flow would indicate termination of a strand, this would mean that the Mag-Gate™ device should provide a 25% flow turn down ratio to double casting time. Assuming a linear relationship of clogging with time, for each 5% turndown ratio, the casting time would increase 20%.

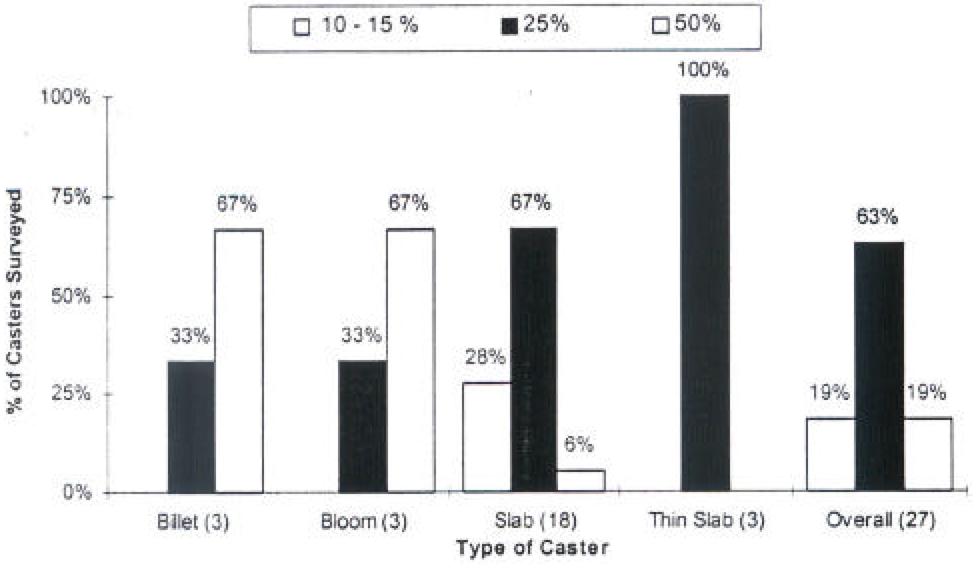

Figure 8. When diminished flow dictates aborting a strand/nozzle

Each of the operator were also asked about the required time over which the return on investment should be figured for adopting a new flow control technology. Figure 9 shows these results. 6 to 12 months was the most frequent answer overall among companies that responded. Many companies wanted to know more specifics about the nature of the new technology and its benefits before answering this question.

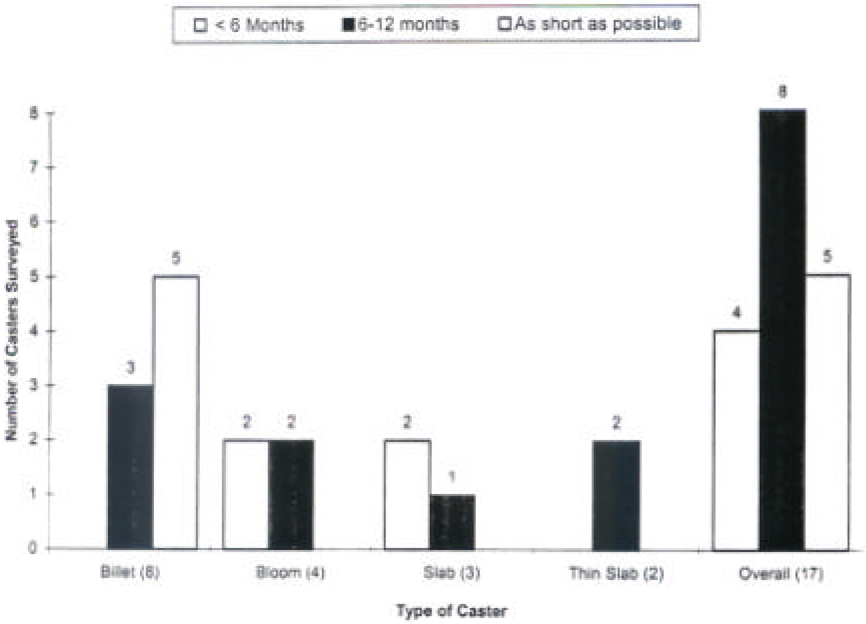

Figure 9. Pay back time required for investment for a new flow control technology.

Economic Analysis

Capital Costs

Costs for flow control technologies may be divided into capital and operating components. Capital costs for a typical stopper rod system for a tundish in a continuous caster are approximately $50,000 per strand. A typical tundish slidegate and level control system for a billet caster, such as Interstop currently markets, consists of: the slidegate, hydraulic cylinders, hoses, control valves, pumps, motors, reservoirs, racks, mounting plates, tools, tube changers, argon units, process control sensors, and computer interfaces. Costs for a slidegate for a billet caster are on the order of $100,000 per strand. Corresponding costs of a slide gate system for a bloom or slab machine may have an initial capital cost of from $175,000 to $250,000 per strand.

For the Mag-Gate™ system the main components are: the Mag-Gate™ itself, safety shutdown guillotine gate, power supply, water system, cables, hoses, and computer interface. Table 3 gives the projected capital costs for the beta Mag-Gate™ systems based on the lab and Whemco prototypes built to date. At a 25% flow reduction, the Mag-Gate™ costs are competitive with stopper rods and significantly less than slidegates for all types of casters. At a 50% flow reduction, the capital cost for a billet machine is greater than for a slidegate, but less than for a bloom unit. The major difference between the two flow reductions is due to the higher power required to achieve an additional 25% reduction, and, hence higher costs for the power supply and water system. The cost at 25% reduction for the slab caster is somewhat less than for the billet/bloom caster since less power is needed to affect the larger pour stream of the slab caster.

Table 3. Beta Mag-Gate™ Capital Costs per strand

	Slab 25% reduction	Billet / bloom 25% reduction	Billet / bloom 50% reduction
Mag-Gate™ device	$ 15,200	$ 18,000	$ 18,000
Guillotine safety gate	$ 5,000	$ 5,000	$ 5,000
Electric Power Supply	$ 16,600	$ 26,400	$ 78,300
Water System	$ 11,900	$ 15,000	$ 29,800
Hoses and cables	$ 3,500	$ 4,000	$ 7,500
Computer Interface	$ 1,600	$ 1,600	$ 1,600
Total	$ 53,800	$ 70,000	$ 140,200

Operating Costs

Operating costs are listed in terms of dollars per ton of steel cast. Typical operating cost for a stopper rod system is on the order of $ 1/ ton; while typical operating costs for a slide gate system are up to $ 4 to $5 / ton. Much of these costs are for the replacement of refractory. Table 4 lists projected operating costs for the beta Mag-Gate™ systems assuming no increase in sequence length. Electricity costs are based on a rate of 5.82 cents per kilowatt-hour.[iii] Refractory costs are based on the cost of the pour tubes produced by Vesuvius for the Whemco tests. For billet/bloom casters at a 25% reduction, the operating costs are comparable to a stopper rod and significantly less than for a slidgegate. For a 50% reduction, the costs are more than for the stopper rod, but still significantly less than for a slidegate. Because the tons per sequence are much higher for the beta slab caster (2900) than the billet/bloom caster (250), the projected operating costs are correspondingly lower.

Table 4. Beta Mag-Gate™ Operating Costs per ton

	Slab 25% reduction	Billet / bloom 25% reduction	Billet / bloom 50% reduction
Electricity	$ 0.04	$ 0.42	$ 1.22
Refractory	$ 0.04	$ 0.50	$ 0.50
Total	$ 0.08	$ 0.92	$ 1.72

Payback Period

The caster operators in the AIM survey indicated predominately a 6 to 12 month payback period for the adoption of a new flow control technology according to Figure12. This number may be conservative at the present due to the conditions in the US steel industry. Previously, many steel companies had used a one to three year payback period when evaluating new capital projects. For example, Mr. Tony Hickle, Director of Technology for North Star Steel Company, the second largest minimill in North America, stated that North Star generally uses a three-year payback rule. [iv] Additionally, Mr. Hickle indicated, in his opinion, most steel companies prefer to pay for new technologies outright in preference to entering licensing agreements, providing that the technology demonstrates the required returns.

Sequence Length Comparison

Today the length of life of the nozzle in a billet caster is a most significant factor in overall costs to the steel producer. An independent estimate by Zircoa of doubling the cast sequence from 12 to 24 hours results in a $ 1.6 million annual savings.[v] Table 5 forecasts operating costs for a 4 strand billet caster using conventional refractories for a 12 hour sequence cast and an improved 24 hour sequence cast with the Mag-Gate™ system.

Table 5. Operating Cost Comparison for 4 Strand Billet Caster

	Conventional Slidegate 12 hour sequence	Mag-Gate™ 24 hour sequence
Tundish cost	$ 1500	$ 750
Steel yield loss	$ 3200	$ 1600
Production loss	$ 2300	
Electricity		$ 300
Refractories	$ 2000	$ 125
Manpower	$ 200	$ 100
Total	$ 9200	$ 2875

At a production of approximately 1000 tons per day for the example caster, the operating cost savings is approximately $ 6 / ton. This is well in agreement with an independent analysis by a consultant with approximately 20 years experience in the continuous casting business. He indicated that an electromagnetic flow control device at the tundish in a steel continuous caster could result in at least $1 and as high as $10 per ton in overall cost reductions and process improvements to the steel maker.[vi] The net savings to the US steel industry is, thus, on the order of $500 million annually.

Energy Savings

The steel industry is the one of the largest industrial users of fossil fuels and electrical energy.[vii] Elliott has estimated that the total energy required to produce a ton of finished steel using strand casting is approximately 32.8 million Btu from a blast - basic oxygen furnace sequence and 17.9 million Btu from an electric furnace sequence.[viii] In 1994, the United States produced 55.9 million tons by basic oxygen furnace and 33.4 million tons by electric arc furnace. The annual energy consumption of the US steel industry on this basis is on the order of 2.4×10^{15} Btu.

A study by the International Iron and Steel Institute showed the primary causes of yield loss in continuous casting are front and back crops and tundish skull.[ix] The average yield over billet, bloom, and slab casters was reported to be 96.3%. Subtracting ladle steel returns and assuming the two primary yield losses are of comparable magnitude, the average front and back end loss for billet and bloom machines is 1.3%, while the loss for slab machines averages 1.0%.

The sequence length can be improved by the use of an electromagnetic flow control. As shown in Table 6, each 10% increase in sequence length across the US steel industry results in an annual energy savings of approximately 2.3×10^{12} Btu. This saving is consistent with the estimate published for the Advanced Process Control Project of 1.4×10^{13} Btu / year which included the benefits a Westinghouse proposed liquid steel feeding system for a slab caster.[x]

Table 6. Energy Savings for 10% increase in sequence length over US Steel Industry

	BF-BOF Sequence	EF Sequence	Total
Energy used (Btu / ton)	32.8×10^6	17.9×10^6	
Quantity made (ton / yr)	55.9×10^6	33.4×10^6	
Energy used (Btu / yr)	1.834×10^{15}	0.598×10^{15}	2.43×10^{15}
Avg front / back loss	0.975 %	1.3 %	
Waste reduction for 10% sequence length increase	0.1/1.1 = 9.09 %	9.09 %	
Savings	0.089 %	0.118 %	
Energy savings (Btu / yr)	1.625×10^{12}	0.707×10^{12}	2.33×10^{12}

Beta Test Designs

From the AIM survey, 18 beta test casters were identified. Table 7 gives the average tundish height, casting rate, and tons per strand per sequence for these machines.

Table 7. Parameters for Beta Test Casters

Caster Type	Tundish Height (in)	Casting Rate (lbm/min)	Sequence Length (tons/strand)
Billet / Bloom	31	850	250
Slab	39	5600	2900

Billet / Bloom Caster

About 2/3 of the billets caters in the survey use open pouring and abort the strand with a flow reduction of 50%; while the other 1/3 of the caster operators abort the strand after a 25% reduction in flow. By over-sizing the nozzle initially, as the nozzle clogs the flow retardation caused by the Mag-Gate™ device can be relieved thus maintaining a constant flow. Table 8 gives the design parameters for a billet/bloom unit designed to achieve a 50% reduction in flow. Figure 10 shows the predicted reduction in flow versus current. At zero current, the flow rate is predicted to be approximately 1210 pounds per minute. At a current of about 4700 amps per coil, the pour rate is reduced to 850 pounds per minute. Notice the pour rate is approximately linearly proportional to current.

Table 8. Design Parameters for Beta Billet / Bloom Caster

Device parameter	Value
Height (in)	16.0
Outer diameter (in)	9.0
Bore diameter (in)	2.0
Pour tube inner diameter (in)	0.82
Number of coils (-)	4
Maximum current (amps)	4700
Maximum voltage (volts)	300
Maximum output power (kW)	1400
Cooling water flow rate (gpm)	120
Coil pressure drop (psi)	230
Water temperature rise (^{o}F)	80

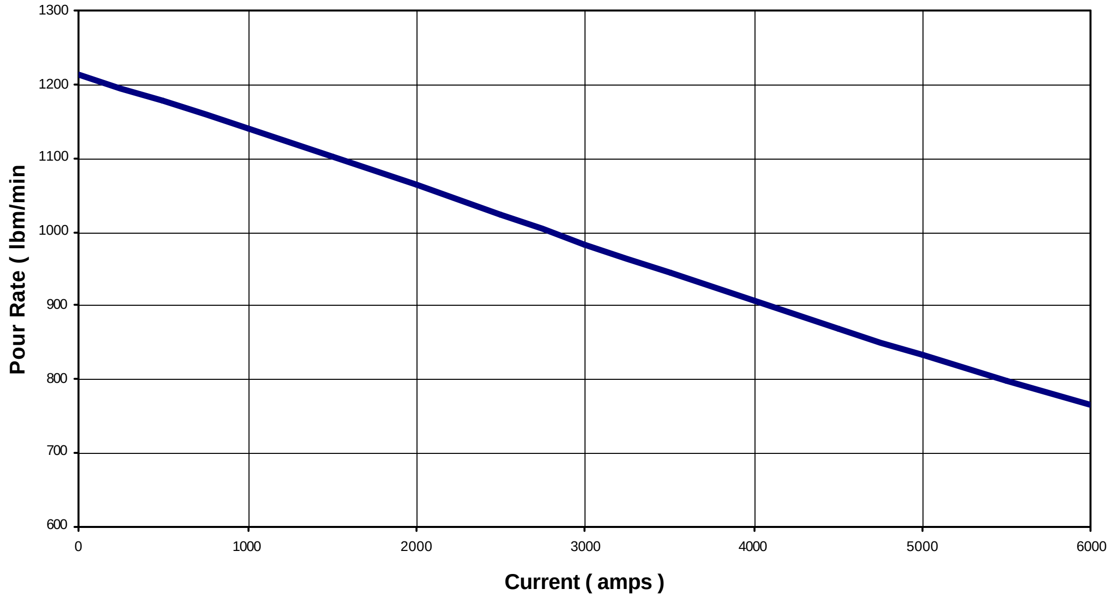

Figure 10. Pour rate versus current for beta billet/bloom caster.

Slab Caster

2/3 of slab caster operators reported the need to abort the strand after a 25% reduction in flow. At an average tundish height of 39 inches, 125% flow corresponds to 7000 pounds per minute with a nozzle size of 1.82 inches for the possible beta site units. Table 9 summarizes the Mag-Gate™ device preliminary design parameters based on the Whemco test device. The device contains three coils as opposed to two in the Whemco device. Figure 11 shows the predicted flow rate versus current for this device. At zero current the flow is about 6900 pounds per minute. At a current of about 3000 amps per coil, the flow rate is reduced to around 5600 pounds per minute. At 6000 amps per coil, the flow is reduced to about 4700 pounds per minute, a reduction of about 32%.

Table 9. Mag-Gate™ Design for beta site slab caster

Device parameter	Value
Height (in)	24.0
Outer diameter (in)	22.0
Bore diameter (in)	4.0
Pour tube inner diameter (in)	1.63
Number of coils (-)	3
Maximum current (amps)	6250
Maximum voltage (volts)	220

Maximum output power (kW)	1350
Cooling water flow rate (gpm)	120
Coil pressure drop (psi)	110
Water temperature rise (^oF)	80

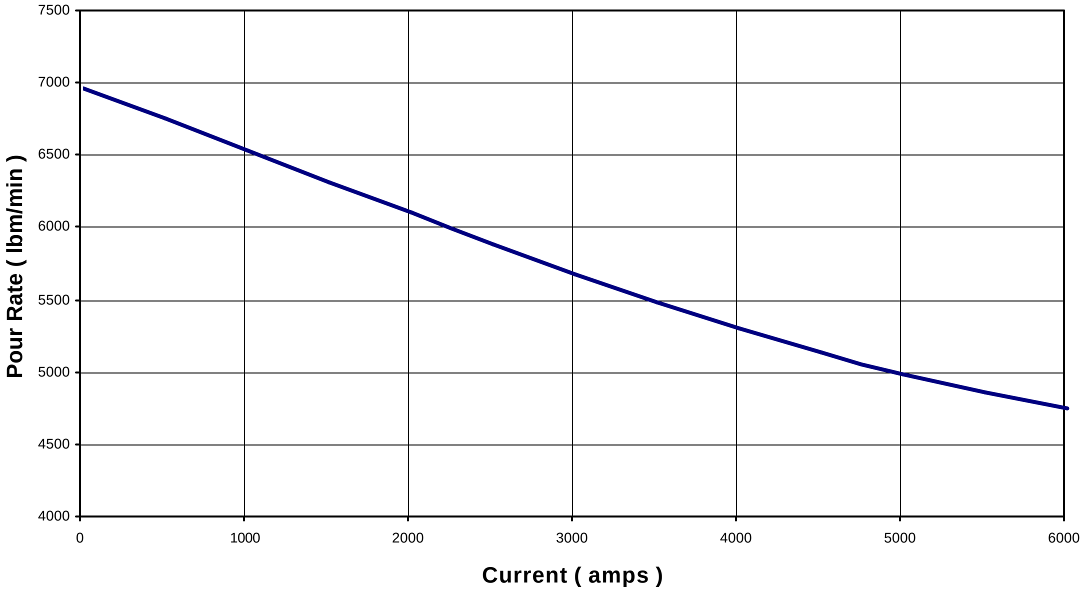

Figure 11. Pour rate versus current for Mag-Gate™ device for beta site slab caster.

Conclusions

The following conclusions may be drawn from the above work.

Hot Metal Tests

- Two safe and successful tests of the Mag-Gate™ device with molten steel were conducted in 2003 at the Whemco foundry.
- Over a total time of approximately 3/4 hours, 110,000 pounds of molten steel was successfully poured through the device.
- The stream of liquid steel emerging from the exit of the pour tube was very smooth and steady.
- During preheating of the tundish, temperatures at the device were all acceptable.
- The water-cooling of the coils kept the temperatures of the coils and shields well within acceptable limits.
- The DC power supply and special water systems functioned well.
- In general excellent agreement between theoretical and experimental results for flow rate versus current was seen over the range of currents tested.

- The combination of magnetic modeling using the finite element code Maxwell® along with the analytical Mathcad®7 flow model appears to work well to predict performance of the Mag-Gate™ device.
- The average friction factor for the flow through the pour tube was 0.03. The internal relative roughness of the pour tube varied from smooth to 0.02.
- The design and method of installation of the pour tube and well block into the tundish worked well.
- No leakage of molten steel was seen at any joint during or after the test.
- The RTD's at the bore of the device generally showed peak temperatures averaging about 200 °F during the tests, well below the 310 °F rating of the coil insulation.
- The fused silica pour tubes performed well during the pre-test and actual two runs.

Market Survey

- Average tundish depth ranged from a low of approximately 31 inches for billet machines to a high of 45 inches for slab machines.
- Average tons per strand per sequence ranged from a low of 300 for billet casters with open pouring to a high of 6100 for slab casters using slidegates or rotary gates.
- Pour rates for these same machines ranged from 760 to 6600 pounds per minute.
- For billet casters, open pouring still dominates.
- For bloom casters, open pouring and stopper rods are about equal in use.
- For slab casters, use of either a stopper rod or a slidegate are about equal; while thin slab casters use only stopper rods.
- Most of the caster operators responded that a 25% diminished flow dictated aborting a strand.
- Casting time could conceivably be doubled if the flow rate reduction by the device equals the level at which diminished flow terminates the cast.
- Assuming a linear relationship of clogging with time, for each 5% turndown ratio, the casting time would increase 20%.
- A 6 to 12 month return on investment period for adopting a new flow control technology was most frequently cited.
- 18 companies were identified as good prospects for the Mag-Gate™ system.

Economic Analysis

- At a 25% flow reduction, the Mag-Gate™ capital costs are competitive with stopper rods and significantly less than slidegates for all types of casters.
- At a 50% flow reduction, the Mag-Gate™ capital cost is greater than a slidegate for a billet machine, but less than a slidegate for a bloom unit.
- For billet/bloom casters at a 25% reduction, the operating costs are comparable to a stopper rod and are significantly less than for a slidgegate.

- For a 50% reduction, the operating costs are more than for the stopper rod, but still significantly less than for a slidegate.
- Comparing the Mag-Gate™ system to existing slidegates, the payback period is well under the desired range for all types of casters.
- For slab casters, the payback compared to stopper rods is also well under the desired range.
- For billet and bloom machines, if no increase in sequence length is assumed, the payback period is about 1 ½ years when compared to a stopper rod at a level of 25% reduction.
- At a level of 50% reduction, for billet and bloom casters, an 11% increase in sequence length offsets the cost of the Mag-Gate™ system with respect to a stopper rod.
- For billet and bloom casters with open pouring, an increase in sequence length of 14% offsets the cost of the Mag-Gate™ system at 25% flow reduction; while an increase of 27% balances the system at 50% reduction.
- For a caster producing about 1000 tons per day, the operating cost savings with Mag-Gate™ is approximately $ 6 / ton.
- The total savings to the US steel industry is on the order of $500 million annually.
- Each 10% increase in sequence length with Mag-Gate™ across the US steel industry results in an annual energy savings of approximately 2.3 x 10^{12} Btu.

Beta Designs

- A 4-coil billet/bloom Mag-Gate™ beta test device can be designed to achieve a 50% turn down ratio based on a nominal flow rate of 850 tons per minute at a head of 31 inches.
- A 3-coil slab Mag-Gate™ beta test device can be designed to achieve a 25% turn down ratio based on a nominal flow rate of 5600 tons per minute at a head of 39 inches.
- Carbon/alumina with zirconia may be an improvement in refractory composition over fused silica.

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[i] Shercliff, J.A. 1962. The Theory of Electromagnetic Flow-Measurement. Cambridge University Press. London

[ii] 2003 North American Continuous Caster Market Survey. AIM Market Research. Pittsburgh, PA. June 2003.

[iii] April, 2004 current hourly price by IMO, Independent Electricity Market Operator

[iv] Knutson, S.R. 1997. Market Assessment MAG/GATE – System for Molten Metal Flow Control. ERIP Recommendation # 717. Prepared for U.S. Department of Energy. Office of Inventions and Innovation. New Horizons Technologies, Inc. Center for Innovation. University of North Dakota.

[v] Engineering Analysis of DenZbor Nozzles. ZIRCOA. Salon, OH.

[vi] Personal Communication with Mr. Irvin Parker, New Jersey Steel.

[vii] Steel Industry Perspectives. 1984. Westinghouse Industrial Planning.

[viii] Elliott, J.F. 1973. Uses of Energy in the Production of Steel. The Steel Industry and the Energy Crisis. J. Szekely Ed. Marcel Dekker. N.Y. Pgs. 9-31.

[ix] Continuous Casting of Steel - 1985 A Second Study. 1986. International Iron and Steel institute. Brussels, Belgium.

[x] Fiscal Year 1993 Annual Report. Steel and Aluminum Energy Conservation and Technology Competitiveness Act of 1988. U.S. Department of Energy. Washington, D.C. DOE/EE-0030.