IMPROVED LIQUID STEEL FEEDING FOR SLAB CASTERS

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By
Brent S. Isaacson (WSTC)
Mike Slepian (WSTC)
Thomas Richter (NARCO)

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Authors

Brent Issacson (WSTC)
Mike Slepian (WSTC)
Thomas Richter (NARCO)

Performing Organizations:**Names****Addresses**

Westinghouse Science and Technology Center (WSTC)
1310 Beulah Road
Pittsburgh, Pennsylvania 15235 - 50989

North American Refractories Company
Technical Center
3127 Research Drive
State College, Pennsylvania 16801

Abstract

This report describes the completion of the development of an electromagnetic valve to control liquid steel flow for improved liquid steel feeding for slab casters. Achievements result from a joint research effort between Westinghouse Science and Technology Center, North American Refractories and U.S. Steel. This effort is part of the American Iron and Steel Institute's (AISI) Advanced Process Control Program, a collaboration between the U.S. Department of Energy (DOE) and fifteen North American steel makers.

Westinghouse Proprietary

This document contains information that is proprietary to Westinghouse Electric Corporation; it is submitted in confidence and is to be used solely for the purpose for which it is furnished.

Foreword

We wish to thank all those who in the past and up to the present have supported this project. Research partner(s) Westinghouse Science and Technology and North American Refractories Company. The sponsoring steel company - U.S. Steel Technical Center and the fifteen (15) AISI member companies who supported the Advanced Process Control Program on a cost share basis. The fifteen companies include: Acme, Bethlehem, Dofasco, Geneva, Georgetown, Inland, IPSCO, LTV, Lukens, National, Rouge, Stelco, Timken, U.S. Steel and Weirton.

We appreciate the personnel assistance received at the test site locations, the AISI-Direct Steelmaking group at US-Steel Pilot plant (Test Series I) and the personnel at the Whemco Foundry in Midland, Pennsylvania (Test Series II). We thank the contractors and vendors for their valuable services (Hatch Associates, Nick Istock, Thermojet, Ritter Engineering, Electro-Nite and UEC-Lab. Services).

Current mechanical liquid steel flow control devices have demonstrated a tendency toward premature clogging, particularly when pouring aluminum-killed steels.

However, improvements in other pouring technologies have greatly diminished the potential value to our industry. The Advanced Process Control Program Management Board has reviewed the progress of the project, and because of the participants have no interest in pursuing the project for billet casting, it was decided not to continue this project.

On January 20, 1995, Westinghouse Science and Technology Center at 1310 Beulah Road, Pittsburgh, PA 15235 was notified by Advanced Process Control that the Liquid Steel Feeding Project is terminated pursuant to paragraph four of the AISI-Westinghouse Subcontract dated July 26, 1993 and Appendix B, paragraph 10. We wish to make it clear that it is the circumstances surrounding the potential application of this technology that led us to this decision and not the performance of Westinghouse or NARCO.

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EXECUTIVE SUMMARY

The Improved Liquid Steel Feeding (ILSF) Program was lead by the Westinghouse Science & Technology Center as part of the American Iron and Steel Institute's Advanced Process Control Program. The goal of the Improved Liquid Steel Feeding program was to develop and test an electromagnetic valve to control the flow of molten steel in a continuous casting process. The electromagnetic valve was expected to exhibit fine flow control and excellent anti-clogging performance, especially in difficult to cast aluminum-killed steels. The economic benefits to be gained by the ability to more easily cast aluminum killed steels were analyzed by Westinghouse STC with input from industry experts and considered to be significant.

The Improved Liquid Steel Feeding Program ran from May 1993 to December 1994. Many of the technical issues in bringing the electromagnetic valve system to the steel industry were identified and resolved during the course of the program. However, the program was canceled by the American Iron and Steel Institute during the second of four planned project years.

During this time, significant hardware improvements in Westinghouse's electromagnetic valve were made to easily integrate it with existing casting processes. An improved refractory nozzle was developed and tested which had superior thermal shock and anti-cracking performance. In addition, several trials were conducted with molten steel to demonstrate and test the electromagnetic valve and its auxiliary equipment.

For each steel pouring trial, detailed reports were produced by Westinghouse STC to document and analyze the data. In addition, monthly and quarterly reports were produced to document the program's progress. An extensive study was performed by Westinghouse to assess the economic impact of the electromagnetic valve system on the continuous casting steel industry. All of these reports were transmitted to the American iron and Steel Institute as they were completed. This report provides an overview of the Improved Liquid Steel Feeding Program and is not intended to duplicate the extensive and detailed information contained in the reports developed during the course of the program and submitted to the American Iron and Steel Institute.

INTRODUCTION

This report describes the electro magnetic valve (EMV) approach to flow control of liquid steel from the tundish to the continuous caster mold. Figure 7 shows a photograph of a billet-size caster valve before molten steel testing, while figure 8 shows the projected slab caster valve. The valve consists of a non-conducting refractory shell through which flows the liquid steel and around which is wound a single-phase coil. Inside the shell is an insert, of similar refractory material, which is located axially in the same position of the coil. The insert (also called a torpedo), together with the shell, forms the nozzle. The EMV is similar in size to slide gates. This technology has no moving parts. The potential of the electromagnetic valve-based system is to reduce clogging of the liquid steel flow.

Equipment Modifications

In preparation for steel pouring trials and during the course of the program, the Westinghouse Science & Technology Center made extensive improvements and modifications to the Westinghouse electromagnetic valve system. These modifications include the following:

- The valve itself was improved to reduce the effects of local eddy current heating caused by the extremely high magnetic fields present during operation. The radial shield was extensively redesigned since it is in close proximity to the electromagnetic valve's coil and is subject to high local heat loads.
- For the first set of steel trials, performed in early 1994, the electromagnetic valve system was modified to use the freon replacement known as SUVA as a coolant for the electromagnetic coil. This was considered necessary because of operating difficulties associated with environmental concerns of releasing freon to the atmosphere. The auxiliary system that pumps coolant through the valve and cools it required extensive refurbishment and modification to accommodate the SUVA coolant.
- For the second set of pouring trials, performed in late 1994, the electromagnetic valve system was improved to safely use water as a coolant for the coil. The coil is in very close proximity to molten steel during valve operation, and design improvements were made to minimize explosion hazards. Chief among these changes was a liquid steel sensing device that detects molten steel flowing outside of the refractory nozzle near the coil. Upon sensing the presence of liquid steel outside of its intended flow path, the system automatically de-energized the electromagnetic valve coil and initiated an air purge of the coil to remove water from the coil. Also, an improved safety liner was developed to better protect the coil in the event of a refractory nozzle break.
- Significant functional and usability improvements were made in the electromagnetic valve nozzle retaining plate. Using sophisticated stress analysis techniques, the plate was redesigned to provide a more uniform and less position-dependent preload on the refractory nozzle.
- The refractory insert, or "torpedo", contained inside the refractory nozzle was improved significantly for the second set of pouring trials. Instead of the blunt end shape of the torpedo that was used for the first set of pouring trials, the improved torpedo employed a streamlined shape on both the leading and trailing edges. This was expected to result in improved anti-clogging performance because the more streamlined torpedo allows for smoother flow passages within the refractory nozzle. Extremely complex machining processes were developed and used by the Westinghouse Science & Technology Center to fabricate the improved torpedo. A less time-intensive process was planned for development and implementation in year 3 of the project.
- An improved data acquisition system was used for the second set of trials using the MS-Windows based LabView System. This improved data acquisition system allowed better real time monitoring of the electromagnetic valve system during operation and easy access to data for post-processing.

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Refractory Nozzle Development

A significant development program was successfully completed to design and test a refractory nozzle with excellent anti-cracking performance during thermal shock. Westinghouse Science & Technology Center and North American Refractories Company, NARCO, worked together to develop an improved refractory nozzle. The key feature of the refractory nozzle is its two-piece design. An inner liner of zirconia (for excellent erosion performance) was mortared to an outer liner of mulite which served as both a mechanical support and a thermal insulator to keep thermal stress low in the inner liner. By using a compliant mortar to join the two pieces of the refractory nozzle, the thermal stresses and thermal expansion generated in the inner liner during preheating and initial steel contact were isolated from the outer liner.

In several experiments performed during the project, not a single nozzle was found to suffer from thermally-induced cracking:

- Flame tests were performed in NARCO's laboratory to expose a nozzle to a thermal transient.
- NARCO exposed a nozzle to flowing molten steel. During post-testing examinations, no cracks were observed that were attributed to the thermal transient.
- Before the second set of steel pouring trials, Westinghouse Science & Technology Center exposed three nozzles to molten steel without causing any cracking failures.
- Finally, in steel pouring trials, no cracks occurred in the nozzles that could be attributed to thermally-induced stresses.

Molten Steel Pouring Trials

A total of five steel pouring trials were performed during the Improved Liquid Steel Feeding Program. The first three were performed in early 1994 at US Steel's direct steel making facility in Universal, PA, and the second two were performed in late 1994 at the Whemco foundry in Midland, PA.

The first three steel pouring trials used an earlier design of the refractory nozzle. This design was a monolithic piece of zirconia with a torpedo that had a blunt trailing edge design. This nozzle design demonstrated unsatisfactory thermal stress-induced cracking performance; the nozzle consistently failed from cracking.

The second set of pouring trials successfully addressed the issue of nozzle cracking by using the improved two-piece nozzle design discussed above. During the second set of steel pouring trials, a total of four nozzles were exposed to molten steel, and none of them cracked as a result of thermal shock.

However, the second set of steel pouring trials was not completely successful. In the first trial, pouring was terminated after molten steel was detected outside of the intended nozzle flow path. This breach was attributed to the presence of superheated steel melting the refractory nozzle during a remelting transient. The second trial was terminated early because of a molten steel leak in the nozzle-to-wellblock joint.

Both of the problems identified in the second set of steel pouring trials were considered by the Westinghouse Science & Technology Center to be resolvable with a few straightforward changes in the setup process. The Westinghouse Science & Technology Center recommended that a third trial be performed, incorporating minor process improvements, to successfully demonstrate the electromagnetic valve concept. However, the American Iron and Steel Institute's Advanced Process Control Program elected to terminate the Improved Liquid Steel Feeding Program.

Test Report: ILSF Test Series 2 -- Heat 2

Test Overview

The second test of the present ILSF test series was conducted at the WHEMCO Foundry in Midland, PA on the morning of December 10. The test plan called for a 35-T heat of 1020 steel tapped out at 3100 °F. There were two valve/nozzles attached to the tundish: one with a powered valve pouring through air (referred to as the EVS side) and one with an unpowered valve pouring through an SEN tube into a simulated mold (referred to as the SEN side). Each side has its own stopper rod for starting and stopping steel flow.

The overall chronology of events is shown below in Table 1. Preheaters were pulled off the tundish and simulated mold once the ladle was positioned over the pouring box. The SEN tube was then moved into position. The SEN side nozzle preheater was then removed, the SEN tube was installed, and the SEN side stopper rod was dropped. The EVS side preheater was then removed and the EVS side stopper rod was dropped. The interval between shutting off the nozzle preheaters is 1.4 minutes for the EVS side and 4.0 minutes for SEN side. At that time the ladle gate opened and steel started filling the tundish. The stopper rods opened when there was 5 inches of steel in tundish and flow immediately began in both the EVS and SEN side nozzles.

Steel was seen leaking outside the nozzle on the EVS side 13 minutes after the initiation of steel flow. During that time the valve was powered. After the steel leak was seen, power to the valve was stopped and air cooling of the valve began. The leak soon stopped and steel continued to flow normally through the nozzle. Later, at 15 minutes into the steel flow, steel was seen leaking through the chill on the SEN side. This leaking steel lead to a failure of the load cells used to determine steel flow rates at 20 minutes into the pour at which time the ladle was removed off the tundish. The remaining 15,000 lb in the tundish was drained through the valves during the following 14.5 minutes.

Stream Heating

The electrical heating is shown explicitly in the EVS Excitation graph on the first attached sheet. A sudden increase in power is shown at time $t=0$ when the steel flow is initiated and the nozzle is first filled. This increase represents 26 KW of additional dissipation and it is all due to the presence of the liquid steel within the nozzle. The amount of additional dissipation matches that found in previous tests at WHEMCO and Universal. When all of this power is used to increase the temperature of liquid steel, a 16 °F temperature rise is expected. This level of temperature rise is consistent with earlier predictions that were circulated to APC members during November.

Table 1. Test Chronology

Running Time	Elapsed Time (min)	Event
8:11.26	- 4.07	Attach Slidegate/Position Ladle
8:11.31	- 3.98	Remove SEN box & Tundish Preheaters
8:12.44	- 2.77	Position SEN Tube
8:12.51	- 2.65	Remove SEN Nozzle Preheater & Drop SEN Stopper Rod
8:13.26	- 2.07	Attach SEN Tube
8:14.05	- 1.42	Remove EVE Preheater & Drop EVS Stopper Rod
8:13.30	-2.0	Energize EVS (ground faults caused intermittent faults)
8:14.52	- 0.63	Open Ladle Gate
8:15.30	0	Open Stopper Rods (5 in of steel in tundish)
8:27	12	Leak seen from EVS Nozzle
8:29	14	Flow rate data lost
8:30	15	Steel leaking from SEN side chill
8:35.12	20	Ladle moved off tundish
8:59.30	44	Tundish empty/Test stopped

During the first 12 minutes of the test, when powered EVS operation was available, steady-state tundish temperatures were not reached (as seen in changing nozzle OD and wellblock temperatures in the accompanying graphs). As a result, steel stream temperatures varied with time without considering EVS effects. Stream temperatures were measured intermittently using insertion probes that have a rated accuracy of $\pm 5^{\circ}\text{F}$. The combination of these two effects leads to unpowered stream measurements differing by 30°F over 12 minutes and up to 20°F for measurements 1 minute apart. These effects masked the EVS stream heating effect.

Nozzle Performance

The improved preheating and flow-initiation procedures included adding nozzle preheaters below the tundish and moving the tundish preheater so the ladle could be spotted before turning of the tundish heaters. These procedures produced three results:

1. An increase of the nozzle preheat demonstrated by an increase of the two temperatures on the nozzle OD by 120°F .
2. A reduction in the axial temperature gradient of the nozzle. There is a 60% reduction in the difference between the two nozzle OD temperature measurements compared to the previous test. The two locations are axially separated by 2.0 in.

3. A reduction of the interval between preheating removal and flow initiation from over 9 minutes to 1.4 minutes for the EVS side and 4.0 minutes for the SEN side.

The nozzles were examined after the tests and only cool-down cracks were found. Significantly, no steel was found in any of the cracks that indicates that they formed after steel flow had stopped and solidified. The lack of cracks with steel shows that the nozzles successfully survived the thermal shock of flow initiation. This result confirms the NARCO work, both numerical studies and physical tests.

The leak that terminated the powered portion of the test was due to leaking through the nozzle/wellblock joint. Contributing factors to the leak may include loss of mechanical preload and/or improper assembly. The joint design uses as-cast nozzles with minimal mating area. During the start of the nozzle preheat, an unplanned incident (heater misalignment) caused temporary heating of the ductile iron, nozzle retaining springs. They were seen glowing red for nearly a minute. In addition, the person installing the EVS nozzle noted a different "feel" to the nozzle compared to other insertions even though deflections of the nozzle retaining plate fingers were consistent with other nozzles. The SEN side, which used a similar joint with different mechanical loading, showed steel between the nozzle and wellblock in some areas, but no through leak. It is unlikely that EVS operation would initiate a leak, but it could contribute to a leak continuing to flow without freezing.

Accompanying Graphs

The graphs on the following three pages include:

- Page 1 -- a graph with plots of tundish head, EVS and SEN flow rates and a graph with EVS current and power.
- Page 2 -- a graph with plots of nozzle OD, liner OD and wellblock temperatures and a graph with EVS power and voltage. The wellblock temperatures are measured in the ram material between the wellblock and the tundish lining.
- Page 3 -- a graph of the stream temperature and the graph with the EVS voltage and power.

All graphs have the same time axis for a period of 10 minutes before and 25 minutes after the start of EVS flow.

Figure 1 **Tundish Head and Flow Rates**

Figure 2 **EVS Excitation**

Figure 3 **Refractory Temperatures**

Figure 4 **EVS Excitation**

Figure 7 Photograph of billet caster valve before casting. Test have shown this valve can accommodate heats which ordinarily would evidence clogging in billet casters.

Figure 8 Configuration of the proposed slabcaster valve with 14 times the flow area of the billet caster valve. The large, fixed annular flow channel leads to reduced clogging, lower sensitivity to erosion and corrosion, lower operating frequency, and reduced power.

**POURING TRIAL
(TEST SERIES I)
at US-Steel Pilot Plant
Test Stand**

FIGURE 9: TEST STAND AT USS PILOT PLANT
(Test Series I)

POURING TRIAL
(TEST SERIES I)
at US-Steel Pilot Plant
Electromagnetic Valve

FIGURE 10: ELECTROMAGNETIC VALVE (EMV)
(Test Series I)

**POURING TRIAL
(TEST SERIES II)
at Whemco Foundry**
Test Stand

**FIGURE 11: TEST STAND AT WHEMCO FOUNDRY
(Test Series II)**

POURING TRIAL
(TEST SERIES II)
at Whemco Foundry
Electromagnetic Valve

FIGURE 12: ELECTROMAGNETIC VALVE
(Test Series II)

NARCO Nozzle Examination Report

Post Mortem Study - Composite Nozzles - Trial at WHEMCO Foundry

1. OBJECTIVE:

Post mortem study on the composite nozzles from the second casting trial at WHEMCO Foundry, Midland, PA.

2. INTRODUCTION:

The second trial of the Phase II test series was concluded at WHEMCO Foundry in Midland, PA on December 10, 1994. The experimental cast was performed on two strands. One of the strands was equipped with a fully functional electromagnetic valve (EVS), the second strand was unpowered and additionally was equipped with the SEN tube.

3. TRIAL CONFIGURATION:

Small, 5 tons, two strand tundish was used for the experiment. One strand utilized functional electromagnetic coil (referred as EVS strand). The second had similar configuration, it was equipped with the same refractory nozzle, though, the valve was not energized. In addition, the second strand had SEN tube and a simulated mold (referred as SEN strand). Stopper rods were incorporated as a part of the flow control assembly on both strands. The preload parameters of the valves were identical for both sides. However, the SEN attachment on the SEN strand contributed additional loading pressure on the refractory nozzle and subsequently on the mortar joint between the well block and the nozzle.

The tundish was preheated with two burners from the top and two burners from the bottom. The bottom burners were directed thru the bores of the refractory nozzles. The preheat, contrary to the first trial, resulted in good heat dissipation and adequate nozzle temperatures. The simulated mold in the SEN strand was preheated with a separate burner to avoid freezing after SEN. It was reported, that the bottom preheat on the EVS side overheated the loading plate of the "Electrovalve", possibly negatively influencing the preload on the refractory nozzle.

The melting sequence started at 6:20 AM. The top burners of the preheat were disconnected at 8:12 AM. The last burner of the preheat, bottom burner on the EVS side, was disconnected at 8:14 AM. The cast initiated at 8:15 AM, at the same time

the EVS was energized. The temperature drop on both strands was minimal because of the short duration between the end of the preheat and initiation of the cast.

At 8:27, twelve minutes in the casting sequence, a leak was discovered on the EVS side. The energizing of the EVS was discontinued. The leak immediately stopped.

At 8:29, the catch basin broke out on the SEN side. As a result, the scale and the capability of collecting flow data was lost. The attempt to close the SEN strand with the stopper rod was unsuccessful. At 8:59, after 44 minutes of casting time, tundish emptied and the test was stopped.

4. POST MORTEM STUDY:

EVS STRAND (energized):

The gap between the refractory nozzle and the safety ring was fully filled with a solidified steel. Even more, the safety ring exhibited one vertical crack, fully penetrated with the steel. The steel outside the safety ring contacted with the safety wire indicator (Figure13).

The mortar joint between the refractory nozzle and the well block exhibits large degree of steel finning and likely was responsible for the leak. The vertical sides of the mortar joint are steel free, which would suggest, that the leak propagated between the surface of the well block and the mortar. Unfortunately, the residues of the well block were not recovered for detailed post mortem analysis.

Close examination of the top portion of the nozzle shows clear evidence of steel penetration thru the mortar joint between the zirconia innersleeve and the mullite outersleeve (Figure14 and15). It appears, that the steel propagated from the top thru the joint between the two components of the nozzle.

The cross sectional views of the nozzle (Figure 16 and17) demonstrate cooling cracks in the zirconia innersleeve and destructive crack in the mullite outersleeve. Furthermore, the mortar joint between the sleeves shows large degree of steel penetration. It appears that the concentration of the steel progressively decreases at lower sections of the nozzle. The top section of the nozzle has the highest concentration of the steel (Figure16), the discharge end of the nozzle is steel free (Figure17).

Only two vertical cracks were discovered during the detailed examination of the zirconia innersleeve (Figure18). They imply two important conclusions. First, the cracks developed

during cool down (Figure18 top) - no steel residue visible). Second, the steel propagation was directed from the outside of the nozzle to the inside of the nozzle (Figure18 bottom). There was not evidence of any horizontal cracking of the innersleeve (Figure19).

Closer examination of the mortar joint between the sleeves has revealed spider type steel finning throughout the drying cracks in the mortar (Figure19).

The crack in the mullite outersleeve is full of steel (Figure 20) and likely served as the entrance for the steel. Vertical cut thru the crack (Figure19) doesn't show any continuation into the zirconia innersleeve. It suggests that the steel propagation was indeed from the outside of the nozzle toward the mortar joint between the sleeves.

Zirconia torpedo is horizontally cracked (Figure19), likely a result of the rapid cooldown. The cracks are full of solidified slag, steel free (Figure20).

SEN STRAND (not energized):

The nozzle survived the entire 45 minutes casting sequence and the refractory components manifest overall good integrity. (Figure21)

However, the finning in the mortar joint between the nozzle and the well block is apparent. (Figure 21) The steel quickly solidified in the joint and didn't propagate further. The freezing mechanism in the joint distinguishes the SEN strand from the EVS strand.

The cross sections of the refractory nozzle exhibit cracks in the zirconia innersleeve and cracking of the outersleeve.

The cracks are free of steel, which would suggest, at least for the zirconia innersleeve, that the initiation was during the cool down. The possibility, that the mullite outersleeve cracked on preheat, or during service could not be discounted.

The mortar gap between the innersleeve and the outersleeve, as designed, shows an evidence of compressive deformation.

The deformation is required to absorb the higher thermal expansion of the innersleeve in the steep temperature gradient. The mortar joint is free of steel.

5. RESULTS and CONCLUSIONS:

The preheating of the nozzles was adequate. Both zirconia innersleeves survived the thermal shock during the initiation of the cast and none of the strands froze.

The joint design between the well block and the refractory nozzle is inadequate and resulted in steel leak on the strand with the

energized EVS. The not energized strand didn't leak.

The loss of preload and the inability of the steel to solidify in high inductive field contributed to the joint failure.

RECOMMENDATIONS:

The joint between the nozzle and the well block must be redesigned prior to any further trial activity.

The improvement in the loading system of the "Electrovalve" must also be considered.

TOP END - MORTAR JOINT

DISCHARGE END

Figure 13 : NOZZLE FROM THE ENERGIZED STRAND

Figure 14 : DETAILS OF THE MORTAR JOINT.

Figure 15: DETAILS OF THE MORTAR JOINT.

EVS SIDE

Figure 16: HORIZONTAL CROSS-SECTIONS OF THE NOZZLE.

Figure 17 : HORIZONTAL CROSS-SECTIONS OF THE NOZZLE.

Figure 18: DETAILS OF CRACKS IN THE ZIRCONIA INNERSLEEVE.

EVS SIDE

Figure 19: VERTICAL CROSS-SECTION AND THE MORTAR GAP.

OUTERSLEEVE

TORPEDO

Figure 20: DETAILS OF CRACKS IN THE OUTERSLEEVE AND TORPEDO. EVS SIDE

SEN SIDE

Figure 21 : NOZZLE FROM THE NOT ENERGIZED STRAND.