Report Documentation Page Information

Title and Subtitle

AISI/DOE Advanced Process Control Program
Vol. 2 of 6: Improved Liquid Steel Feeding System for Slab Casters

Authors

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

Performing Organizations:	Names	Addresses
---------------------------	-------	-----------

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

North American Refractories Company (NARCO) Technical Center 3127 Research Drive State College, PA 16801		
---	--	--

Abstract

This report describes the development, construction and testing of the Electromagnetic Valve System (EVS), conducted as a project entitled "Improved Liquid Steel Feeding System for Slab Casters". This program ran from November 1992 to January 1995. Many of the technical issues in bringing the EVS to the steel industry were identified and resolved during the course of the program. During this time, significant hardware improvements in Westinghouse's electromagnetic valve were made to easily integrate it with existing continuous 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 verify the proof-of-principle of the electromagnetic valve and its auxiliary equipment.

However, improvements in other conventional pouring technologies have greatly diminished the potential value of this project to the steel industry. As such, the program was canceled by the American Iron and Steel Institute after the conclusion of Phase I (proof-of-principle).

Sponsor TBD Report No.:

AISI/DOE Advanced Process Control Program

Final Report

**Vol. 2 of 6: Improved Liquid Steel Feeding System
For Slab Casters**

11/30/92 - 1/20/95

Edited

By

Joe Vehce

June, 1999

Work performed under Cooperative Agreement
No. DE-FC07-93ID13205

Prepared by
American Iron and Steel Institute
for
Department of Energy

DISCLAIMER

“This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.”

“This report has been reproduced from the best available copy. Available in paper copy and microfiche.

Number of pages in this report: 22

DOE and DOE contractors can obtain copies of this report from: Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831. (615) 576-8401.

This report is publicly available from the Department of Commerce, National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161. (703) 487-4650”

TABLE OF CONTENTS

<u>Contents</u>	<u>Page</u>
TABLE OF CONTENTS	iii
FOREWORD	iv
LIST OF FIGURES	v
EXECUTIVE SUMMARY	vi
1.0 Introduction	1
2.0 Project Description	2
2.1 Background	2
2.2 Equipment Modifications	4
2.3 Refractory Nozzle Development	5
2.4 Molten Steel Pouring Trials	6
2.4.1 Test Series I	6
2.4.2 Test Series II	9
2.4.2.1 Test Results	13
3.0 Conclusions and Recommendations	16

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. Photograph of Billet Caster Valve	3
2. Configuration of Proposed Slab Caster Valve	3
3. Photograph of Test Stand, Test Series I	7
4. Photograph of EMV, Test Series I	8
5. Diagram of the Side-by-Side Test Arrangement	10
6. Photograph of Test Stand, Test Series II	11
7. Photograph of EMV, Test Series II	12
8. Simulated Test Results of Flow vs. Time	14
9. Tundish Head and Flow Rates vs. Time	14

EXECUTIVE SUMMARY

The Improved Liquid Steel feeding System for Slab Casters project was lead by the Westinghouse Science and Technology Center (WSTC) as a part of the Advanced Process Control (APC) Program [an American Iron and Steel Institute (AISI) and the Department of Energy (DOE) joint cooperative program]. The goal of this specific project was to develop and test an electromagnetic valve system (EVS) to control the flow of liquid 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 (AK) steels. The economic benefits to be gained by the ability to cast more easily AK steels were analyzed by WSTC with input from industry experts and considered to be significant.

The project ran from November 1992 to January 1995. Many of the technical issues in bringing the EVS to the steel industry were identified and resolved during the course of the program. During this time, significant hardware improvements in Westinghouse's electromagnetic valve were made to easily integrate it with existing continuous 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 verify the proof-of-principle of the electromagnetic valve and its auxiliary equipment.

However, improvements in other conventional pouring technologies have greatly diminished the potential value of this project to the steel industry. As such, the program was canceled by the American Iron and Steel Institute after the conclusion of Phase I (proof-of-principle).

This report provides an overview of the project and is not intended to duplicate the extensive and detailed information contained in progress reports developed during the course of the project and submitted to AISI.

FOREWORD

We wish to thank all those who in the past and up to the present have supported this project: research partners, Westinghouse Science and Technical Center (WSTC) and North American Refractories Company (NARCO); 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 steel companies are Acme, Bethlehem, Dofasco, Geneva, Georgetown, Inland, IPSCO, Lukens, National, Rouge, Stelco, Timken, US 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, PA (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 (APC) 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 APC that the Liquid Steel Feeding Project was 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.

1.0 INTRODUCTION

The AISI/DOE Advanced Process Control (APC) program was directed towards developing real-time, on-line, continuous control systems for the entire steelmaking, steelshaping and steeltreating process. Participants in the APC program included universities, national laboratories, advanced technology companies and the steel industry. The Improved Liquid Steel Feeding System for Slab Casters was one of the six projects under the APC program.

The overall aim of this particular project was to develop an electromagnetic valve-based flow control system (EVS) for continuous casters, especially for slab casters. The project was targeted to provide significant benefits to the steel industry by

- greatly reducing clogging of liquid steel flow control components when pouring aluminum-killed (AK) steels,
- improving the life of refractory components in the flow control system, and
- improving mold level control with resulting reductions in the formation of longitudinal surface cracks on peritectic steel grades.

The Westinghouse Science and Technology Center (WSTC) and North American Refractories Company (NARCO) were the research partners. The US Steel (USS) Technical Center was the sponsoring steel company.

2.0 PROJECT DESCRIPTION

2.1 Background:

Currently used flow control devices (slide gates and stopper rods) operate on the principle of mechanically constricting the flow area, and this action encourages clogging, particularly for AK steels. These devices utilize restricted flow area with high localized velocities and continuous jogging of the valve plates to prevent sticking, with the side effect of premature wear of the refractory material.

The electromagnetic valve approach to flow control provides a solution to these problems. The valve consists of a non- or weakly-conducting refractory shell through which flows the molten steel. Around this conducting refractory shell, a single-phase coil is wound. Inside the shell is an insert (covered by a Westinghouse patent) 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 electromagnetic valve system (EVS) nozzle. Figure 1 shows a photograph of a billet caster valve before molten steel testing, and Figure 2 shows the projected slab caster valve.

This whole project was designed to be conducted in four phases: Technology Assessment and proof-of-principle (Phase I), Development of Slab Caster Valve (Phase II), Slab Caster Trials (Phase III) and Commercialization (Phase IV). It was also designed to have major reviews at the end of each phase, before proceeding to the next .

At the end of Phase I, the project was terminated by AISI, as the improvements in existing flow control systems have greatly diminished the potential value of the project to the steel industry. This report summarizes, in general, the achievements in Phase I.

Figure 1 Photograph of billet caster valve before casting. Test have shown this valve can accommodate heats which ordinarily would evidence clogging in billet casters.

Figure 2 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.

2.2 Equipment Modifications:

During the course of the project, WSTC 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 (described in Section 2.4), performed in early 1994, the EVS 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 (described in Section 2.4), performed in late 1994, the EVS was improved to safely use water as 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 the refractory nozzle near the coil. Upon sensing the presence of liquid steel outside 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 should allow for smoother flow passages within the refractory nozzle. Extremely complex machining processes were developed and used by WSTC to fabricate the improved torpedo.
- 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 EVS during operation and easy access to data for post-processing.

2.3 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. WSTC and NARCO worked together to develop an improved refractory nozzle. The key feature of the refractory nozzle is its two-piece design. An inner layer of proprietary material (for excellent erosion performance) was mortared to an outer refractory liner 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 (described in Section 2.4), WSTC exposed three nozzles to molten steel without causing any cracking failures.
- Finally, in steel pouring trials (described in Section 2.4), no cracks occurred in the nozzles that could be attributed to thermally-induced stresses.

2.4 Molten Steel Pouring Trials:

A total of five pouring trials was performed during this project. The first three were performed in early 1994 at AISI's Direct Steel Making Facility at US Steel's Pilot plant in Universal, PA. The second two were performed in late 1994 at the WHEMCO foundry in Midland, PA.

2.4.1 Test Series I:

These anti-clogging experiments were conducted at AISI Direct Steelmaking Pilot Plant in Universal, PA between February 4 and March 16, 1994. The electromagnetic valves that were tested had been re-designed with a better cooling method for the flux shield and simpler co-axial connection. The first heat was a "wash" heat and did not shed any light on the performance of the flow control devices. The second heat turned out to be a non-killed low carbon (rather than AK) heat because the aluminum was lost in the ladle transfer from the furnace to the tundish. The EM valve performed well for over 30 minutes despite a minor crack in the nozzle; however, the slide gate did not open due to a sand plugging problem. The third test was a good AK heat (about 0.04% nominal carbon in the tundish). The EM valve nozzle cracked very early in the test, and the nature of the erratic flow stream(s) forced a premature shut-down of the EVS. On the other hand, the slide gate opened and operated normally for about 18 minutes until it started freezing at the bottom of its shortened SEN (submerged entry nozzle) tube. Further post-mortem analysis indicated significant clogging starting in the upper and middle plate areas. No further testing was performed because of the high-degree of uncertainty in the nozzle integrity. Figures 3 and 4 show two photographs of these pouring trials.

Problem Areas:

The first set of pouring trials confirmed the earlier tentative conclusions reached by Westinghouse during their development of the electromagnetic valve: a one-piece refractory nozzle is susceptible to severe cracking without proper pre-heating. However, the improved nozzle design must incorporate high strength back-up liner, and a proven pre-heat system must be developed prior to the second series of pouring trials.

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

FIGURE 3: TEST STAND AT USS PILOT PLANT
(Test Series I)

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

FIGURE 4: ELECTROMAGNETIC VALVE (EMV)
(Test Series I)

2.4.2 Test Series II:

Test series II pouring trials were all conducted at the WHEMCO foundry in Midland, PA in November-December, 1994. A total of two pouring trials was conducted.

The earlier trials could not evaluate the potential of the EVS for use as an anti-clogging device compared to conventional flow control devices, such as a tundish slide gate. The new test arrangements in these pouring trials called for two EVS to be tried side by side during the test: one with an SEN tube and simulated mold, and one without (only one EVS would be electrically energized at a time - see Figure 5).

The second test of the test series II was significant enough to be included here in some details. Figures 6 and 7 show two photographs depicting the general set up of the test and the electromagnetic valve.

The test was conducted at the WHEMCO foundry in Midland, PA on the morning of December 10, 1994. 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 had its own stopper rod for starting and stopping steel flow.

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 installed, and the SEN side stopper rod was dropped. The EVS side preheater was then removed and the EVS side stopper rod dropped. The interval between shutting off the nozzle preheaters was 1.4 minutes for the EVS side and 4.0 minutes for the 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 leaking through the chill on the SEN side. This leaking steel led 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.

Figure 5 *Diagram of the side-by-side test arrangement for the two EM Valves, one with SEN tube and simulated mold, showing the major steel handling equipment*

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

FIGURE 6: TEST STAND AT WHEMCO FOUNDRY
(Test Series II)

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

FIGURE 7: ELECTROMAGNETIC VALVE
(Test Series II)

2.4.2.1 Test Results:

It was expected that two types of useful information would be available from the second trial of the series II tests. The flow data, derived from the weight measurements of the tundish and catch basins, together with physical inspection of the flow channels would provide information on the extent and location of any clogging. In addition, there would be some general data on operating information of the devices which would prove useful in later design tasks, but would not significantly impact the clogging assessment.

Data from the catch basin weighing system would provide a flow rate history for each test device, while the weight data from the tundish could be scaled to provide information on the ferrostatic head driving the streams throughout the test. By normalizing flow data with the head information, the resulting flow-time history would be a measure of clogging performance. The processed data could only be used for this purpose if the nominal flow modulation (EVS power) was held constant or well known and wear of the channels was ignored. Wear was expected to be insignificant during these very short tests.

A sample of reduced data is given in Figure 8 showing three (of many) possible clogging histories. Curve 'A' shows no indication of clogging, Curve 'B' shows immediate clogging of a critical flow area being reduced in a linear fashion until complete shut-off occurs, and Curve 'C' shows either clogging similar to that of 'B' which is delayed in time or that which occurs in a non-critical part of the flow channel that later becomes the critical part when the normalized flow rate is seen to decline. For clarity, the three curves have been shown with different nominal flow rates (either different modulation or different form factors).

Knowledge of the location and extent of alumina deposition, obtained through dissection and physical inspection of the used refractory pieces (nozzles), would also be important. Such knowledge would lead to improved understanding of flow patterns and might identify possible changes to refractory design.

Figure 9 shows actual data collected on tundish head and flow rates as a function of time (for a period of 10 minutes before and 25 minutes after the start of EVS flow) during this trial. During the time when molten steel flowed through the EVS side (as well as the SEN side), the data suggest no clogging (very similar to Curve 'A' in Figure 8).

A sudden increase in power was seen when the steel flow was initiated and the nozzle was first filled. This increase represented 26 kW of additional dissipation and it was all due to the presence of the liquid steel within the nozzle. The amount of additional dissipation matched those found in previous test 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.

During the first 12 minutes of the test, when powered EVS operation was available, steady-state tundish temperatures were not reached. 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 ± 5 °F. The combination of these two effects led to unpowered stream measurement differing by 30 °F over 12 minutes and up to 20 °F for measurements 1 minute apart. These effects masked the EVS streamheating effect.

Figure. 8 Simulated results from a test heat showing three possible flow-rate/time histories. Each curve represents different clogging performance.

Figure 9 Tundish Head and Flow Rates

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;

- An increase of the nozzle preheat demonstrated by an increase of the two temperatures on the nozzle OD by 120 °F.
- A reduction in the axial temperature gradient of the nozzle. There was a 60% reduction in the difference between the two nozzle OD temperature measurements compared to the previous test. The two locations were axially separated by 2.0 in.
- 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. This is an indication that these cracks were 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.

3.0 CONCLUSIONS & RECOMMENDATIONS

The first three pouring trials used an earlier design of the refractory nozzle. This design was a monolithic piece 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 design. 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. During this trial, the preheating of the nozzles was adequate. Both inner sleeves survived the thermal shock during the initiation of the cast and none of the strands froze. The joint design between the wellblock and the refractory nozzle was inadequate and resulted in steel leak on the strand with the energized EVS. The non-energized strand did not leak. The loss of pre-load and the inability of the steel to solidify in high inductive field contributed to the joint failure.

Thus, it was concluded from these trials that the joint between the nozzle and the wellblock must be redesigned prior to any further trial activity. Moreover, the improvement in the loading system of the electrovalve must also be considered.

These problems identified in the second set of steel pouring trials were considered by WSTC to be resolvable with a few straightforward changes in the setup process. WSTC recommended that a third trial be performed, incorporating minor process improvements, to successfully demonstrate the electromagnetic valve concept. However, American Iron and Steel institute, and the fifteen project-supporting steel companies decided to terminate the project, as the improvements in existing flow control systems have greatly diminished the potential value of this project to the steel industry.